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# Development of limestone modified cements for high performance concretes

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**DEVELOPMENT OF LIMESTONE MODIFIED CEMENTS  
FOR HIGH PERFORMANCE CONCRETES**

**A thesis submitted in fulfilment of the requirement  
for the award of the degree of**

**Doctor of Philosophy**

**from**



**UNIVERSITY OF WOLLONGONG**

**By**

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**(B.Eng (Hon.), M.Eng.)**

**DEPARTMENT OF CIVIL, MINING AND ENVIRONMENTAL ENGINEERING**

**1999**

## **DECLARATION**

This is to certify that the work presented in this thesis was carried out by the author during the Ph.D. study at the Department of Civil, Mining and Environmental Engineering, University of Wollongong. The results obtained from this study and the conclusions drawn therefore are the author's effort, except where otherwise stated. The work contained in this thesis has not been submitted for a degree to any other university or similar institution.

Van Khanh Bui



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## **ABSTRACT**

This study has developed limestone modified cements to be used for self-compacting and vibrated high performance concretes. The study has also placed emphasis on the development of rapid testing methods for determining quality of self-compacting concrete. In addition, a mix design method that can be applicable for different materials was proposed to ensure high durability and economic efficiency for self-compacting high performance concrete. The effect of aggregate maximum size, coarse to total aggregate ratio, water to binder ratio and paste volume on superplasticizer requirement, compressive strength and drying shrinkage of high performance concretes also were investigated in the study.

The test results showed that the use of limestone modified cements, consisting of portland cement and milled limestone with suitable content and fineness, can result in reduced superplasticizer requirement, improved compressive strength, reduced heat of hydration and drying shrinkage as well as reduced cement content of high performance concretes. These benefits would therefore enable high-performance concrete to be produced more economically.

Rapid testing methods for determining blocking behaviour, deformability and segregation resistance of self-compacting concrete were developed. Test results showed that the proposed method and developed apparatus are useful in the rapid evaluation of quality of self-compacting concrete.

The proposed mix design method combines the criteria for aggregate blocking and liquid phase (deformability, segregation resistance and flow velocity as well as superplasticizer requirement), criteria for selection of optimum coarse to total aggregate ratio and construction criteria. The method can be used to design self-compacting concrete having high durability, economic efficiency and application for different materials. The developed criteria should also reduce the need for repeated mixing trials, the times and extent of laboratory procedures and practices.

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## NOTATION AND ABBREVIATION FORMULAE

$\alpha$	= Factor from diaphragms (section 2.2.6 in Chapter 2)
$\Phi$	= Ratio between reinforcement diameter
$\Gamma_m$	= Deformability index of mortar
$\alpha_p$	= Material constant of water retainability
$A$	= Volume of air ( $l/m^3$ ) (section 2.2.6 in Chapter 2)
$B$	= Mass of binder content (kg) (Chapters 4, 5, 6, 7 and 8)
BFC1, BFC2	= Blast furnace slag cements
BFS	= Blast furnace slag
$C$	= Mass ( $kg/m^3$ ) of cement
$C_k$	= Coefficient depended on ratio ( $K$ ) between reinforcement diameter and maximum aggregate size
$D_{af}$	= Three-quarter dimation of each aggregate fraction
$D_{av}$	= Average particle diameter, which is given by:
$D_{ca}$	= Ratio between reinforcement clear spacing ( $c$ ) and the three-quarter dimension of each aggregate fraction ( $D_{af}$ )
$D_i$	= Average size of aggregate fraction $i$
$D_{max}$	= Maximum size of aggregate
$D_{ss}$	= Average spacing between particle surfaces (particles are assumed to be spherical)
$D_{ssmin}$	= Minimum required average spacing between aggregate particle surfaces
F20	= Slump flow value of 20 cm
F50	= Slump flow value of 50 cm

$F_c$ :	= 28-day compressive strength of concrete
$F_d$	= Slump flow diameter of self-compacting concrete
$\rho_g$	= Bulk specific gravity of coarse aggregate
$G$	= Total coarse aggregate content by weight
$G_b$	= Dry mass of coarse aggregate in the concrete at bottom (section 2.2.5 in Chapter 2)
$G_t$	= Dry mass of coarse aggregate in the concrete at top (section 2.2.5 in Chapter 2)
$H$	= Height (m) (section 2.2.6 in Chapter 2)
$H_a$	= Average depth of aggregate particles
$H_d$	= Filling head drop of self-compacting concrete
$H_f$ :	= Final depth
HPC	= High performance concrete
$K$	= Ratio between reinforcement diameter ( $\Phi$ ) and maximum size of aggregate ( $D_{max}$ )
$K_1$	= Pozzolanic coefficient;
$K_2$	= Limestone filler activity coefficient.
$K_g$	= Aggregate coefficient
$K_w$	= Effective coefficient
$LS$	= Mass ( $kg/m^3$ ) of milled limestone
$LS_1$	= Milled limestone LS1
$LS_2$	= Milled limestone LS2
$LS_3$	= Milled limestone LS3
$m$	= Experimental coefficient



$M_c$	= Mass of mortar contained in 2 litres of concrete
$M_f$	= Mass of mortar passing through screen
$M_i$ and $M_{i-1}$	= Upper and lower sieve dimensions of aggregate group $i$ , respectively
$M_i$	= Percentage of aggregate mass retained between upper and lower sieve sizes (obtained from sieve analysis) in fraction $i$
$n$	= Number of aggregate size groups
$N_{bi}$	= Blocking volume ratio of aggregate group $i$ ,
$N_{ga}$	= Coarse to total aggregate ratio (by mass)
$N_{opt}$	= Optimum coarse to total aggregate ratio
$n_{sbi}$	= Blocking volume ratio (i.e. the volume ratio which causes blocking) of the aggregate of single-size group $i$
$n_{si}$	= Volume ratio of an aggregate of single-size group $i$
OPC	= Ordinary portland cement
$P$	= Pressure for pumping (section 2.2.7 in Chapter 2)
$P_d$	= Penetration depth
PFA	= Mass ( $\text{kg/m}^3$ ) of fly ash
$P_l$	= Pressure for pipeline (section 2.2.7 in Chapter 2)
$P_m$	= Mass of powder materials (section 2.2.3 in Chapter 2)
$P_{vgm}$	= Ratio of volume of coarse aggregate group $m$ to total coarse aggregate volume
$P_{vsn}$	= Ratio of volume of fine aggregate group $n$ to total fine aggregate volume
$r_1, r_2$	= Flow diameters of mortar
$R_c$	= 28-day cement strength measured on ISO mortar

Rh	= Difference between the average masses of coarse aggregate in front of the reinforcement set and at the end of L-box
RLs	= Percentage reduction of heat of hydration of mortar containing limestone
Rm	= Viscosity index of mortar
$r_o$	= Flow cone diameter
RS1	= River sand RS1
RS2	= River sand RS2
Rv	= Variation of the masses of the coarse aggregate in the vertical direction
$\rho_s$	= Bulk specific gravity of fine aggregate
S	= Total fine aggregate content by weight
SCC	= Self-compacting concrete
SC-HPC	= Self-compacting high performance concrete
SF	= Mass ( $\text{kg/m}^3$ ) of silica fume
SI	= Segregation index
SP	= Superplasticizer
SPC1, SPC2	= Shrinkage limited portland cements
t	= Measured time (seconds) for mortar to flow through the funnel
T50	= Flow time when self-compacting concrete reaches slump flow value of 50 cm
U	= Unit weight of concrete ( $\text{tonne/m}^3$ ) (section 2.2.6 in Chapter 2)
V	= Average of mass of the coarse aggregate with particle size larger than 9.5 mm
V50	= Average flow velocity of self-compacting concrete

$V_a$	= Total aggregate volume
$V_{abi}$	= Blocking volume of aggregate group $i$ ( $V_{abi}$ is the volume of aggregate group $i$ that retains prior reinforcement set in L-box apparatus),
$V_{abm}$	= Blocking volume of coarse aggregate group $m$
$V_{abmax}$	= Total maximum allowable aggregate volume by which the blocking risk equals to 1
$V_{abn}$	= Blocking volume of fine aggregate group $n$
$V_{ai}$	= Volume of aggregate group $i$
$V_{am}$	= Volume of coarse aggregate group $m$
$V_{an}$	= Volume of fine aggregate group $n$
$V_g$	= Total coarse aggregate volume
$V_{gi}$	= Mass of the coarse aggregate with particle size larger than 9.5 mm in each piece cut from concrete specimens used in assessment of segregation resistance of self-compacting concrete in the vertical direction
V-HPC	= Vibrated high performance concrete
Void	= Volume of voids in the densely compacted aggregate
$V_{opt}$	= Paste volume ( $V_{opt}$ ) at optimum coarse to total aggregate ratio ( $N_{opt}$ ), which satisfies both blocking criteria (solid phase) and liquid-phase criteria
$V_{pmin}$	= Minimum required paste volume in considering criteria of liquid phase
$V_{pw}$	= Paste volume
$V_{pwmin}$	= Minimum required paste volume in considering blocking criteria of aggregate phase (solid phase)
$V_s$	= Total fine aggregate volume
$V_t$	= Volume of the concrete mixture

W = Water content of concrete ( $\text{kg/m}^3$ ) (section 2.2.6 in Chapter 2)

W/B = Water to binder ratio

W/C = Water to cement ratio

W<sub>p</sub> = Water retained by powder materials

X<sub>L</sub> = Percentage of limestone (by mass) in the binder

## **LIST OF PUBLICATIONS WRITTEN DURING THE STUDY**

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- Bui K. V. and Montgomery D. "Drying Shrinkage of Self-Compacting Concrete Containing Milled Limestone", Accepted for RILEM Symposium on Self-Compacting Concrete, Stockholm, Sweden, September 13-15, 1999.
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## CHAPTER 1

### INTRODUCTION

#### 1.1. GENERAL BACKGROUND

High-performance concretes are defined as concretes which meet special performance and uniformity requirements (Rangan, 1998). The performance requirements may include ease of placement and compaction without segregation, enhanced short-term and long-term mechanical properties, high early-age strength and long life in severe environment.

High performance concretes can be classified into two types, namely: vibrated high-performance concrete (V-HPC) and self-compacting high-performance concrete (SC-HPC). High strength concrete as vibrated high performance concrete has been developed over many years, beginning with the relative low compressive strengths of 40 MPa in the 1960s, up to strengths of 100 MPa that are commercially available today (Russell, 1998).

Self-compacting concrete (SCC) is considered to be a new generation of concrete technology. This type of concrete can fill all corners of formwork without vibration since it is of excellent flowability. Self-compacting concrete was originally developed in Japan in the late 1980s, and it has attained increasing interest in recent years throughout the world. Its research and development is currently being undertaken in many countries such as Japan, Thailand, Korea, Sweden, United Kingdom, France, Netherlands, Spain, Canada, Australia and United States. Applications of self-compacting concrete in different structures have also increased in number.

High performance concretes have various advantages, namely: high durability, reduced construction time, less labour cost. Beside these advantages, self-compacting high performance concrete facilitates a decrease in noise impact during the building process which contributes to an improved working environment for workers and surroundings. However, high performance concretes, especially self-compacting concrete, usually require high dose rates of high-range water reducing admixtures (superplasticizers) and high paste volumes which often result in high shrinkage, high heat of hydration and high costs for the concrete. In an attempt to reduce these effects, mineral additives such as silica fume, fly ash, blast furnace slag, etc. are often used in concrete, however several problems have arisen with the use of some of these. Some mineral additives such as industrial by-products are not always of consistent quality, not always available locally and require additional silo at the batching plant.

## 1.2. OBJECTIVES AND SCOPES

Blended limestone-portland cements are available and widely used for normal concrete in Europe. However, little has been published on blended limestone-portland cements used for high-performance concretes. The aims of this study are to develop limestone modified cements which will:

- reduce drying shrinkage,
- reduce heat of hydration,
- reduce required dose of superplasticizer,
- reduce cement content and
- decrease the total cost of self-compacting and vibrated high performance concretes.



Self-compacting concrete is a new type of concrete which is quite sensitive to quality control and requires high degrees of accuracy in batching of constituent materials. Therefore, this study also aims to:

- develop rapid testing methods for segregation resistance, deformability and blocking behaviour which are the main properties of self-compacting concrete in the fresh state;
- develop a mixture proportioning method for self-compacting concrete aimed at ensuring high performance, economic efficiency and which can be applied for different kinds of raw materials.

### 1.3. OUTLINE OF THESIS

The thesis consists mainly of nine chapters. Below is a summary of these chapters.

*Chapter 1* introduces a definition and classification of high performance concretes that include self-compacting and vibrated high performance concretes. The reasons, objectives and scopes for this study are also given in this chapter.

*Chapter 2* reviews the literature concerned with cement paste, mortars and vibrated concrete containing milled limestone. This chapter also presents literature relating to research, development and application of self-compacting concrete throughout the world. A major emphasis is placed on presentation of literature relating to self-compacting concrete containing milled limestone, testing methods and mix design procedures for self-compacting concrete.

*Chapter 3* outlines the methodology for development of limestone modified cements, rapid testing methods for quality and a mix design procedure for self-compacting high performance concrete. Also, a summary of experimental programs and materials used is given.

*Chapter 4* presents test results for consistency and setting time of pastes. Test results on compressive strength, drying shrinkage and heat of hydration of mortars containing milled limestones are discussed. This chapter also reports results of a study on microstructure and mineral compositions of pastes containing milled limestones.

*Chapter 5* presents and discusses test results for superplasticizer requirement, compressive strength and drying shrinkage of vibrated high performance concrete (V-HPC) containing limestone modified cements. A developed model predicting 28-day compressive strength of the V-HPC and some test results on normal concrete containing milled limestone are also discussed in the chapter.

Complementing *Chapter 5*, *Chapter 6* reports and discusses test results on superplasticizer requirement, compressive strength and drying shrinkage of self-compacting high performance concrete (SC-HPC) containing limestone modified cements. Moreover, test results on effect of maximum aggregate sizes, different coarse to total aggregate ratios and water to binder ratio as well as effect of paste volumes on properties of self-compacting concrete are discussed in this chapter. A developed model predicting 28-day compressive strength of the SC-HPC and microstructure of interface between coarse aggregate and mortar in SC-HPC are also presented in the chapter.

*Chapter 7* describes the developed rapid testing methods for quality assessment of self-compacting concrete, with major emphasis focusing on the method for rapid testing of segregation resistance.

*Chapter 8* presents a proposed mix design method for self-compacting high performance concrete. A summary on blocking criteria for solid phase (aggregate phase) of SCC is made. Development of liquid-phase criteria is discussed, and mix design procedures for SC-HPC are also presented in the chapter.

*Chapter 9* summarises conclusions of this study on development of limestone modified cements for high performance concretes, rapid testing methods and mix design method for self-compacting high performance concrete from the view point of high durability, economic efficiency and applicability for different materials.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1. CEMENT, MORTAR AND VIBRATED CONCRETE CONTAINING MILLED LIMESTONE

Soroka and Stern (1976) studied the effect of two calcareous fillers (milled limestone and reagent quality calcium carbonate) on the compressive strength of Portland cement. It was concluded that fillers affect strength through their accelerating effect on the cement hydration. This effect was found to be essentially the same for all the fillers studied irrespective of their specific chemical composition. It was concluded that the formation of calcium carboaluminate, if it took place, did not necessarily affect the cement compressive strength.

Soroka and Setter (1977) published a paper about the effect of fillers on strength of cement mortars. The fillers, which were milled limestone, dolomite and basalt, had fineness from 1,150 to 11,200 cm<sup>2</sup> per g (115 to 1120 m<sup>2</sup>/kg). The filler content ranged from 10 to 40% of the cement weight replacing a corresponding volume of the sand (e.g. cement content was unchanged for all mixes). Mortar mixes with cement - sand ratio of 1:2.75 and W/C ratio of 0.70 were studied. The results confirmed the authors' earlier conclusions that the fillers effect on strength is primarily an accelerating effect on cement hydration. The improvement in strength was essentially the same for all three types of fillers, increasing with both filler content and fineness.

Larrard (1989) carried out a study on the use of ultrafine particles in very high strength concrete. The fillers included:

- limestone filler with particle size between those of cement and ultrafine particles;
- limestone ultrafine filler (average particle size of 1  $\mu\text{m}$ );
- ground siliceous ultrafine filler (average particle size of 1  $\mu\text{m}$ );
- two types of silica fume.

The author concluded that, in comparison with concrete containing pure ordinary portland cement, the use of ultrafine particles (average size of about 1  $\mu\text{m}$ ) improves the strength of the concrete; and silica fume was found to be the most effective addition (superplasticizer that was based on naphthalene sulfonate formaldehyde was used in this study).

Krstulovic et al. (1994a) evaluated the limestone filler effect with cement from the aspects of strength and workability of mortar and concrete. Mortar and concrete specimens of equal bulk modulus were tested. The study concluded that compressive strength decreases linearly with the increase of filler proportion in the volumetric concentration of cementitious component when bulk modulus of specimens is unchanged. Generally, filler was found to improve workability of both mortar and concrete when added in quantities of 5 and 12% of binder content. The same authors (1994b) also studied the effect of filler fineness and blending procedure. They suggested that addition of small quantities of fine filler improves the efficiency of portland cement, and the intimacy of mixing with clinker particles is a decisive factor for this positive effect.

Wallevik et al. (1995) studied the effect of different types of filler material on the rheological properties of fresh concrete. The results showed that different filler

materials, which had approximately the same particle-size distribution and consisted mainly of quartz, potassium feldspar, plagioclase feldspar and ground limestone, respectively, did not affect the rheological properties of the fresh concrete significantly.

The diffusion of chloride ions in neat cement pastes and mortars made with and without limestone filler was investigated by Hornain et al. (1995) who stated that the addition of a limestone filler reduces the diffusion coefficient of chloride ions; and this reduction is attributed to the effect of the limestone filler particles on the tortuosity of the system. It was noted that the specific area of the limestone filler was of the same order of magnitude as that of ordinary portland cement; and water to cement ratio of 0.55 was kept constant (the respective water to binder ratios were different).

Nehdi et al. (1996) investigated the effect of limestone microfiller replacement of cement on the mechanical performance and cost effectiveness of low water to cement ratio superplasticized portland cement mortars. Cement pastes with different water to binder ratios and incorporating various proportions of limestone powder and/or silica fume were designed to have a constant flow. The mean particle sizes of ordinary portland cement (OPC), silica fume (SF) and limestone filler (LF) were 14  $\mu\text{m}$ , 0.18  $\mu\text{m}$  and 3  $\mu\text{m}$ , respectively. The authors concluded:

- LF replacement did not significantly affect the strength of mortars at early ages up to about 10 to 15% by volume. Higher levels of LF caused significant strength losses which were more pronounced in the SF mixes. At later ages, LF replacement of cement beyond 10 to 15% caused strength losses which were more significant.

- Blending silica fume and limestone powder simultaneously with cement was efficient in maintaining high 28-day compressive strength for some LF proportions compared to an OPC + 10% SF system.
- The early age strength of cement mortars was most cost effective in an OPC system containing about 10 to 15% LF, and can be improved in an OPC + 10% SF triple blended cementitious binder by adding up to 10% LF.

Recently, Nehdi et al. (1998) also reported results of an investigation on the effect of ultrafine particles used as partial replacement for cement on the rheology of high strength concrete (HSC). Various proportions of 3  $\mu\text{m}$  and 0.7  $\mu\text{m}$  mean particle size limestone fillers, finely ground silica, and silica fume were individually used as partial replacement for cement in concrete mixtures with water to binder ratio of 0.33. In addition, concrete mixtures were made with triple-blended composite cements containing different proportions of limestone filler and silica fume. The authors concluded that high strength concrete can be made easier to place by substituting proportions of ultrafine particles for cement. In the presence of superplasticizers, the finer the microfiller the lower the flow resistance and torque viscosity of the mixture. Up to 20% ground silica or limestone did not require an increase in the superplasticizer requirement to achieve a constant workability, even though one of these fillers had a surface area as high as 10,000  $\text{m}^2/\text{kg}$ ; silica fume, however, while being the most effective filler from a rheological point of view, increased the superplasticizer demand at a constant workability. Microfillers were advantageous in some instances in maintaining better workability over time. They were also successful in inhibiting the induced bleeding of fresh concrete. No data on compressive strength and drying shrinkage were reported.

Blended limestone - portland cements are available and used in Europe complying with ENV 197-1 "Standard Specifications for Cements". The limestone content is 6 - 20% and 21 - 35% in CE II A/L and CE II B/L type, respectively, and these cements have been used for normal concrete. However, there is little published data on the use of milled limestone in vibrated high performance concrete, in which not only high compressive strength (between 50 MPa to 100 MPa), but also requirement of high range water reducing admixture (superplasticizer), drying shrinkage and heat of hydration play an important role. These properties for vibrated high performance concrete containing milled limestone have been investigated in this study.

## **2.2. RESEARCH AND DEVELOPMENT OF SELF-COMPACTING CONCRETE**

Research and development of self-compacting concrete has been carried in many countries such as Japan, Thailand, Sweden, United Kingdom, France, Australia, Korea, The Netherlands, Spain, Canada and United States.

The research and development of SCC has mainly focused on the following areas:

- Behaviour of SCC in its fresh state, of which deformability, segregation resistance and blocking property are the principal mechanisms (Ozawa et al, 1992; Ozawa et al, 1993; Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al, 1996);
- Mixture proportioning methods (Okamura and Ozawa, 1994; Bui, 1994; Okamura and Ozawa, 1995; Petersson et al, 1996; Domone and Chai, 1996; Sedran et al, 1996 and Ouchi et al, 1998)
- Quality testing and control methods, including tests in laboratory and on site, as well as rapid testing methods, in order to monitor the main properties of SCC



namely: deformability, segregation resistance, flow velocity and blocking behaviour around reinforcement (Ozawa et al, 1992; Tangtermsirikul et al, 1992b; Hayakawa et al, 1993; Ozawa and Nagamoto, 1995;);

- Hardened properties of SCC such as compressive strength, drying shrinkage, surface property, etc. (Ozawa et al, 1992; Sakamoto et al, 1993; Hayakawa et al, 1993; Furuya et al, 1994);
- Development of supplementary materials and admixtures in order to reduce cost and to improve properties of SCC (Ozawa et al, 1992, Sakamoto et al, 1993; Yoshino et al, 1993; Bui, 1994; Nagataki and Fujiwara, 1995; Petersson et al, 1996); and
- Formwork, mixing, pumping and placing procedures (Hayakawa et al, 1993, Petersson et al, 1996).

In 1996, an international technical committee on self-compacting concrete (TC-SCC) was created under the umbrella of the International Union of Testing and Research Laboratories for Materials and Structures (RILEM). The committee has been working actively in drafting a State of the Art Report and Testing Methods for self-compacting concrete. Four research organisations in France, UK, Spain and Sweden, together with two major contractors, have recently commenced a 3.5-year long research project on self-compacting concrete.

### **2.2.1. Behaviour of Self-Compacting Concrete in Its Fresh State**

Self-compacting concrete was initially developed at the University of Tokyo, Japan. Ozawa et al. (1992a, 1992b) extensively studied the filling mechanism of self-compacting

concrete, especially in relation to deformability, segregation and blocking mechanism around obstructions such as reinforcement bars. The authors stated the following:

- Filling capacity, controlled by the deformability and segregation resistance, is also affected by the shape of members, spacing between reinforcement bars and placing method. With an increase in slump value of fresh concrete, the deformability increases and the segregation resistance decreases. Maximum filling capacity results from an appropriate combination of deformability and segregation resistance. For lower slump concrete, the filling capacity is controlled mainly by the deformability, while for higher slump concrete it is controlled mainly by the segregation resistance. The relation between water cement ratio, flowability, deformability and segregation resistance of fresh mortar is illustrated in Fig. 2.1.

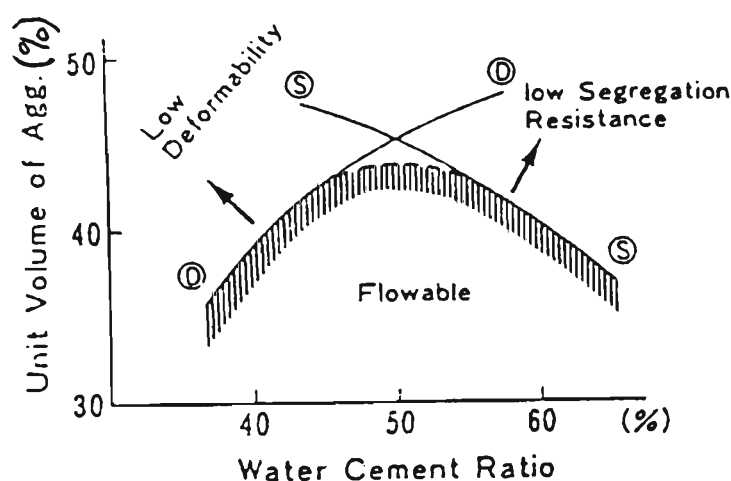


Fig. 2.1: Relation between water cement ratio, flowability, deformability and segregation resistance of fresh mortar (after Ozawa et al, 1992b)

- Free water content in fresh concrete is one of the governing factors for not only the deformability but also the segregation resistance; and hence for filling capacity (the free water in fresh concrete is defined as the water which is not retained by sand and powder materials). On the other hand, the amount of free water in concrete is also

controlled by added superplasticizer, as superplasticizer tends to release the water retained by powder particles and fine sand particles due to the transformation of coagulation structures of particles in water. The free water content is linear to deformability of self-compacting concrete, while segregation resistance of concrete has a non-linear relationship to the free water content.

- Particle contact restrains the deformation of particles, which produces localisation of shear deformation; this tends to promote the segregation between solid particles and liquid phase and resultant blocking due to high inter-particle stress transferred in the solid phase.
- Blocking of fresh mortar flowing through constricted opening is influenced by the sand content and flowing speed. The influence of sand on blocking depends on the mean size of sand particles. The risk of blocking can be estimated by the summation of the effect of each size on blocking. In this sense sand is defined as particles that have diameters greater than one tenth of diameter of the holes. Particles smaller than this size, including powder particles, have different role on blocking from the bigger particles such as sand. The relation between blocking volume and size ratio of hole to sand can be seen from Fig. 2.2.
- Flowability of concrete through narrow spacings is controlled not only by the deformability but also by segregation resistance related to the blocking. Both properties depend on the properties of powder materials, such as their size, shape and grading.
- Shear transfer mechanism of paste between solid particles, which is one of the roles of powder materials, depends on the water to powder ratio. For the shear resisting mechanism of the paste with appropriate amount of free water, the frictional mechanism of powder paste as solid is converted to the shear resisting mechanism of

a viscous liquid, and the amount of free water is controlled by the size, shape and grading of powder materials.

- Material segregation resistance can be obtained without reducing the deformability of concrete by the proper use of a thickening agent, and the desired viscosity of the paste with a small amount of water can be obtained by properly combining fly ash with powder components.

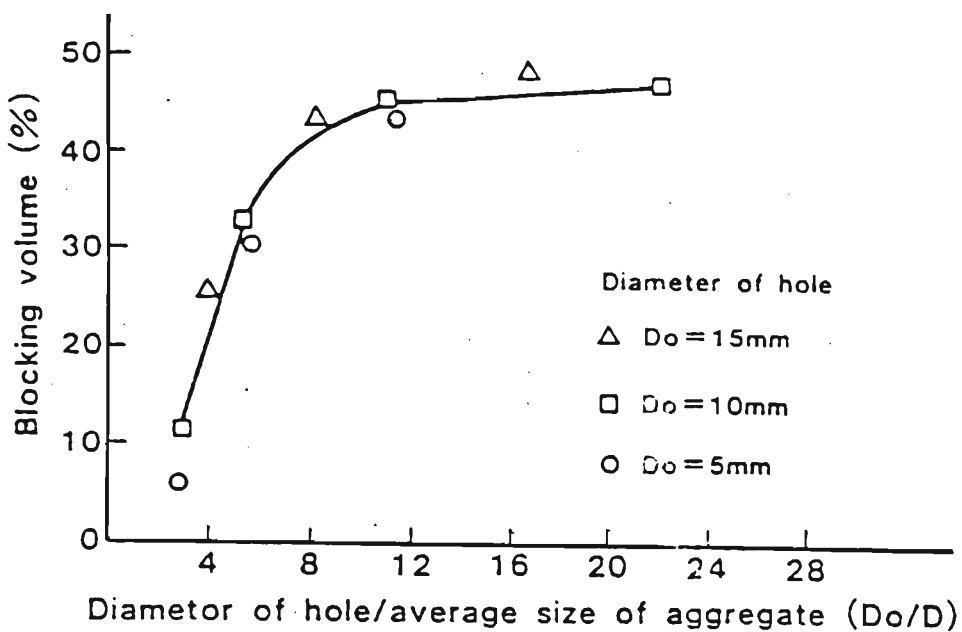


Fig. 2.2: Relation between blocking volume and size ratio of hole to sand (after Ozawa et al, 1992b)

Domone and Chai (1996) summarised the roles of the components in SCC as follows:

- **Water content** - This is typically between the range 160 - 185 kg/m<sup>3</sup>. If it is too low, there is insufficient fluidity, even with admixtures; if it is too high, the segregation resistance reduces and the paste or mortar will easily separate from the larger aggregate particles which can then form arches across gaps, e.g. between reinforcing bars, hence blocking the flow.

- *Admixtures* - The fluidity is provided by superplasticizers, most being based on either a naphthalene or melamine formaldehyde, often modified to provide extended retention of fluidity and set times.
- *Binders* - Binder contents are high, typically 450 - 550 kg/ m<sup>3</sup>, but it would seem that, at the required high fluidity, the use of portland cement alone will result in inadequate cohesion for satisfactory segregation resistance. Ground granulated blast furnace slag is beneficial in this respect, typically replacing 40% by weight of the portland cement. In some mixes fly ash and/or microsilica have also been used, and limestone powder as an inert filler seems particularly useful in enhancing cohesion.
- *Water to binder ratios* - It follows from the above that water/binder ratios are normally in the range 0.30 - 0.36. Sufficient segregation resistance has been achieved at higher values by including small quantities of a viscosity agent in addition to the plasticizer or superplasticizer. It is suggested that this works by restricting the movement of the free water in the mix, hence ensuring that it is fully available to provide lubrication between the particles. It also increases the viscosity of the free water, and so high doses are detrimental. It is also claimed that it reduces the sensitivity of the self-compacting properties to variations in mix proportions.
- *Aggregates* - SCC has been successfully produced with both gravel and crushed rocks, normally with maximum size of 20 mm. Lightweight SCC has been produced using an artificial lightweight coarse aggregate (Hayakawa et al, 1993; Umehara et al, 1994).

Since slump flow is measured when concrete is in a static condition, yield value can be considered as the controlling factor (Murata, 1993). Further, the yield value of concrete can be considered as being determined mainly by the volume of coarse aggregate and

yield value of mortar (Wami, 1990); and yield value of mortar increases, while slump flow value decreases as volume of coarse aggregate increases (Nagataki and Fujiwara, 1995).

### **2.2.2. Properties of Hardened Self-Compacting Concrete**

Sakamoto et al. (1993) presented test results of the use of SCC in steel-tubular columns. Concrete was placed up to the height of 40 m with a mobile concrete pump without difficulty. Core specimens were taken from a test column, which was set above an actual constructed steel-tubular column, in the vertical direction and tested for compressive strength at 91 days. The compressive strength of the outer cores were lower (average strength of  $61.1 \text{ MPa} \pm 3.7 \text{ MPa}$ ) than those of the center cores (average strength of  $66.2 \text{ MPa} \pm 4.5 \text{ MPa}$ ). The authors explained that this seems to be due to non-uniformity of the concrete because of loss of flowing ability at the top of the columns; nevertheless, the value of compressive strength satisfied the value of specified concrete strength (34.3 MPa) and the state of filling was good.

Hayakawa et al. (1993) reported properties of hardened SCC which was called Biocrete 21. The concrete contained about  $500 \text{ kg/m}^3$  of powder (ordinary portland cement, blast furnace slag and fly ash). Concrete with higher content of ordinary portland cement exhibited higher compressive strength. The compressive strength of Biocrete 21 can be controlled by selecting proper mix proportions. It was reported that Biocrete 21 usually exhibits 28-day compressive strength greater than 40 MPa. The authors also reported that, due to very low water to powder ratio and low water content, Biocrete 21 exhibited drying shrinkage less than or equal to, that of general concrete with the same water

content; and concrete containing 4% or more air entrainment showed superior resistance to freezing and thawing.

Furuya et al. (1994) studied compressive strength of highly flowing concrete in the field. The authors reported that compressive strength of core specimens was about 85% of standard specimens, and variation of compressive strength was larger in vertical direction than in horizontal direction. Variation of coarse aggregate area in core specimen became large when distance of flow reached 10 m. Therefore, the authors recommended that it is desirable to cast concrete as thinly as possible and at distance as short as possible.

### **2.2.3. Self-Compacting Concrete Containing Mineral Admixtures**

Ozawa et al. (1992b) and Nagataki et al. (1995) considered that one method of providing the concrete with resistance to segregation is the addition of a large volume of powder material. However, if the entire volume of powder consisted of cement, problems such as increased cost of materials and high heat of hydration would result. Therefore, to eliminate these problems, ground granulated blast furnace slag, fly ash and limestone powder are used.

#### **2.2.3.1. Self-Compacting Concrete Containing Limestone Powder**

Limestone powder (or milled limestone) has been used in self-compacting concrete because of its relatively uniform quality and wide availability. Also, its cost is relatively low.

Furuya et al. (1994) and Tanaka et al. (1993) reported development and application of highly-flowing concrete for mass concrete in the prestressing anchorages of the Akashi

Kaikyo Bridge in Japan. Anchorage blocks for long-span suspension bridges consist of large scale mass concrete structures heavily reinforced with structural steels and steel bars. To date, portland blast furnace slag cement has generally been used to prevent temperature cracking. However, since it is difficult to control the occurrence of thermal cracking even in conjunction with the use of subsidiary cooling, the authors developed highly flowing concrete using low-heat cement for the anchorages of the Akashi Kaikyo Bridge. Concrete with good flowability and segregation resistance, respectively, was ensured by the use of air-entraining high range water-reducing agent and limestone powder with different fineness. It was reported that the use of limestone having high degree of fineness was effective for reduction of bleeding. Also, for the same water to cement ratio, highly flowing concrete had higher compressive strength development compared to 11-cm slump concrete, and the tendency became more remarkable as limestone powder content was increased.

Yoshino et al. (1993) carried out a study on SCC containing 0%, 30% and 50% of limestone powder with water to binder ratios of 0.32, 0.34 and 0.36. The fineness (surface area) of limestone powder was reported as 3560 cm<sup>2</sup>/g, 5010 cm<sup>2</sup>/g and 7260 cm<sup>2</sup>/g. All mixes were designed to have the same sand to aggregate percentage of 49%, the same water content of 170 kg/m<sup>3</sup> and slump flow of 60 ± 5 cm. The fluidity of the concrete was measured using the L-shape flow test. The study found that fluidity of concrete containing limestone with the highest fineness was highest for the three kinds of limestone powder. No results on drying shrinkage and superplasticizer requirement were reported in this study.



A study aimed at reducing shrinkage of highly-flowable concrete was carried out by Ogawa et al. (1995). Limestone powder, viscosity agent, shrinkage reducing agent and expansive additive were used in the concrete. Limestone powder replaced a part of the aggregate content in the concrete. It was confirmed that, for the same water to cement ratio (water to powder material ratios were different), drying shrinkage and autogenous shrinkage of highly-flowable concrete is less than that of ordinary concrete. The compressive strength of concrete ranged from 33 MPa to 48 MPa. The unrestrained drying shrinkage strain of highly flowable concrete containing limestone powder, shrinkage reducing agent and expansive additive was reduced to less than the assumed limit value for cracking (400 microstrain).

Ayagano et al. (1993) used limestone powder with fineness index of 3,600 cm<sup>2</sup>/g in SCC mixes. The limestone powder replaced a part of the aggregates. It was found that, when limestone powder replaced a part of either sand, or coarse aggregate or both sand and coarse aggregate, there were optimum contents that produced the highest slump flow values. The maximum 28-day compressive strength obtained was about 58 MPa. No data on drying shrinkage and superplasticizer were reported.

Limestone powders were also used in the other studies (Sedran et al, 1996; Petersson et al, 1996; Sakata et al, 1996; Nishibayashi et al, 1996). However, the effect of limestone powder on properties of SCC were not reported in detail.

*Comments* - A number of studies on the use of limestone powder in SCC were carried out. However, the main reported results have focused on flowability and compressive strength of the concrete, which, in many cases, was not greater than 50 MPa. The effect

of limestone powder with different fineness indices and contents on the properties (drying shrinkage, superplasticizer requirement, heat of hydration) of self-compacting high performance concrete was not thoroughly studied. Therefore, a part of this present study has focused on the effect of different fineness and contents on superplasticizer requirement and drying shrinkage of self-compacting high performance concrete (SC-HPC) which has compressive strength between 50 MPa and 100 MPa.

#### 2.2.3.2. Self-Compacting Concrete Containing Blast Furnace Slag and Fly Ash

Blast furnace slag and fly ash were used in a number of studies (Kuroiwa et al, 1993; Ozawa et al, 1992a; Ozawa et al, 1992b; Yoshino et al, 1993; Miura et al, 1993; Hayakawa et al, 1993, 1995; Tangtermsirikul and Bui, 1995; Kosaka et al, 1996; Kim et al, 1996).

Ozawa et al. (1992b) used blast furnace slag in SCC in order to study the role of powder materials in mortars. The fineness indices of the blast furnace slag in details were 8000 cm<sup>2</sup>/g and 3200 cm<sup>2</sup>/g for slag B8000 and B3200, respectively. The water retained by powder materials,  $W_p$ , was computed as follows (Tsuji et al, 1987):

$$W_p = \alpha_p * P_m$$

where  $P_m$  is the mass of powder material and  $\alpha_p$  is a material constant of water retainability that equals to 0.24, 0.30 and 0.21 for ordinary portland cement, slag B8000 and B3200, respectively. The authors stated that the finer powder such as slag B8000 had a tendency to give higher segregation resistance and the coarse powder such as slag

B3200 exhibited lower segregation resistance. The authors also used slag powder with fineness indices of 7860 cm<sup>2</sup>/g and 3290 cm<sup>2</sup>/g to study the effect of the properties of powder materials on the shear resistance in SCC. In regard to the size of the powder material, the water to powder ratio which was required to obtain a minimum shear resistance was higher for SCC containing slag powder with fineness index of 7860 cm<sup>2</sup>/g in comparison with that containing slag powder having fineness index of 3290 cm<sup>2</sup>/g; and this is due to the increase of water retained by powder particles, caused by the increase of surface area in unit volume powder (this is in contrast to the results obtained by Yoshino et al. (1993) who found that fluidity of concrete containing limestone with the highest fineness was highest for the three kinds of limestone powder used. Therefore, it seems that the calculation of free water in SCC should consider not only the specific surface area (shape and size), but also other factors such as particle packing in the binder which might be related to shape and size of powder materials as well as water to binder ratio and ratio of mineral admixture and cement).

The use of granulated blast-furnace slag fine powder in self-filling light-weight high performance concrete was carried out by Umehara et al. (1994) who reported that the light weight concrete with high fluidity which satisfies the conditions that the yield value of paste is below 65 Pa and its viscosity is above 1.8 Pa is suitable for manufacturing of light-weight precast panels with reduced thickness. Concrete exhibited satisfactory strength when it reached the target strength at age of 7 days, and its drying shrinkage is about half of that of ordinary concrete. For the cases of actual application, no deficiency of filling was found at any part in the form and leakage of paste from the joints of tiles that were attached in form-work was observed.

#### 2.2.4. Self-Compacting Concrete Containing Chemical Admixtures

High range water reducing admixture (superplasticizer) is usually used to enhance deformability or flowability and flow velocity of SCC. Sometimes, a viscosity agent is used to reduce the tendency of segregation and quality sensitivity of concrete. Also, drying shrinkage reducing admixture has been experimented with to reduce the drying shrinkage of SCC.

Hayakawa et al. (1993) reported on the use of a viscosity agent based on biopolymer material, in SCC that is called Biocrete 21. The viscosity agent, combined with superplasticizer, was used to improve both deformability and resistance to segregation of fresh SCC.

According to Nagataki et al. (1995), in order to provide concrete with high fluidity, the addition of an superplasticizing admixture is required; in Japan, naphthalene sulphonic acid, polycarboxylic acid type polymer, etc. are generally used. In addition, concrete may be provided with resistance to segregation by the addition of viscosity-controlling admixtures such as an acrylic-or cellulose-based water soluble polymer or a polysaccharide polymer. Addition of a large volume of powdered material is not required if a viscosity-controlling admixture is used. The authors reported that viscosity and yield value of mortar increased linearly as the amount of viscosity-controlling admixture added was increased.

The use of a viscosity-modifying admixture to reduce top-bar effect of anchored bars cast with fluid concrete was studied by Khayat (1998) who claimed that, regardless of the slump, specimen height, and mode of consolidation, the reduction in surface

settlement (that is related to bleeding and segregation) resulting from incorporating a viscosity-modifying admixture (welan gum) can significantly reduce the top-bar factor (the reduction in bond with horizontally embedded bars located in the upper sections of structural elements as opposed to those located near the bottom is known as the top-bar effect, i.e., top-bar factor). The author also found that highly stable, self-compacting concrete with low settlement had low top-bar factors compared to conventional concrete specimens cast with 190- and 220-mm slump concrete. The incorporation of 0.07 percent of welan gum (by mass of cementitious materials) in concrete made without any silica fume resulted in concrete having greater stability and lower top-bar factor than similar concrete containing 0.035 percent of welan gum and 8 percent silica fume replacement (by mass of cementitious materials).

### **2.2.5. Testing Methods for Determining Quality of Fresh Self-Compacting Concrete**

Fresh self-compacting concrete requires testing methods that are different from vibrated concrete. The main properties of SCC include deformability capacity, velocity of deformability, segregation resistance and non-blocking characteristics. Several testing methods for these properties are summarised below.

#### **2.2.5.1. Flow Testing**

The slump flow test is widely used to evaluate the workability of SCC since it is easily conducted on site (Ozawa et al, 1992a; Hayakawa et al, 1993; Tangtermsirikul and Bui, 1995; Petersson et al, 1996). The procedure is similar to that of conventional slump testing for vibrated concrete, except that the SCC is not consolidated by rodding. The

workability of concrete is then related to the average diameter of SCC when it stops flowing.

An other flow test is carried out with the use of L-shape apparatus (Yoshino et al, 1993) (Fig. 2.3). In the test, the L-shape flow value (LF) is measured (the test procedure was not described in the reference). Larger values of LF indicate better flow.

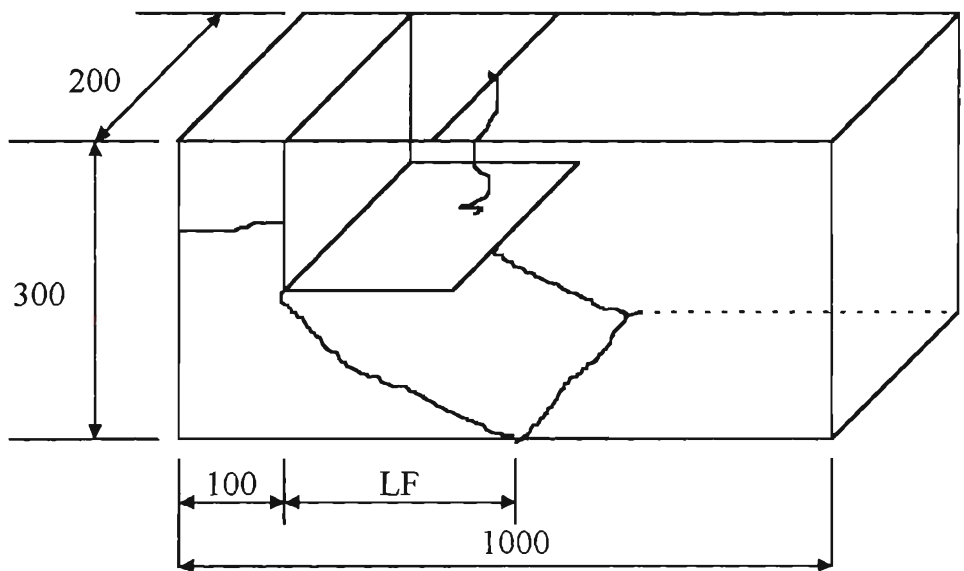


Fig. 2.3: L-shape flow test (after Yoshino et al, 1993)

#### **2.2.5.2. Evaluation of Filling Ability**

There are several methods for evaluating filling ability of SCC, in which different types of apparatus have been developed and used. These include:

- a) U-shape apparatus
- b) L-shape apparatus
- c) Funnel apparatus
- d) Vertical fill apparatus

The methods are summarised below.

### a) Test with U-shape apparatus

Hayakawa, et al. (1993) and Kuroiwa et al. (1993) have developed an apparatus for evaluating the filling ability of SCC. The apparatus is a vessel which is divided by a middle wall into two chambers indicated as R1 and R2 in Fig. 2.4. The bottom of the apparatus is circular. At the bottom of the central wall, a gate is made and installed with a sliding door. Deformed reinforcing bars with nominal diameter of 13 mm are installed at the gate with centre to centre spacing of 50 mm. This creates a clear spacing of 37 mm between the bars. To conduct the test, the concrete sample is initially placed in R1, to fill the compartment. A pressure of about 2400 Pa is applied to the concrete by placing a mass on the concrete in order to obtain sufficient filling height of concrete in chamber R2 after opening the gate (which is conducted by sliding the door upward to let the concrete flow through the clearance between the reinforcing bars installed at the gate and partially fill chamber R2). The filling height of the concrete in R2 is then measured and denoted as the filling ability of the concrete. Concrete is considered to have satisfactory filling ability if it produces filling height greater than 30 cm. The authors also presented a relationship between the filling height and slump flow value (Fig. 2.5). According to the authors, when the slump flow is less than 50 cm, the concrete will not reach the filling height of 30 cm; in this case, deformability of the concrete is insufficient for it to perform as self-compacting concrete. When the slump flow value is larger than 70 cm, the filling height of some concretes can be less than 30 cm; in this case, resistance to segregation may be insufficient. Some limitation of this method are:

- The clear spacing was fixed at 37 mm, but in actual practice, there can be many different values;
- It is not possible to conclude that SCC with slump flow value larger than 70 cm always has poor segregation resistance, especially when it contains aggregate of

small maximum size where concrete can exhibit low filling height due to large volume of aggregate, but still have good segregation resistance. Therefore it is necessary to determine whether the low filling height is caused due to too high volume of aggregate or poor segregation resistance of SCC. Thus, it is necessary to use another method to evaluate the segregation resistance of the concrete.

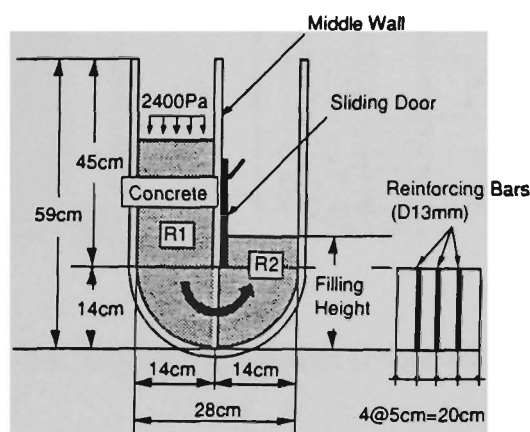


Fig. 2.4: U-shape apparatus for evaluating filling ability (after Hayakawa et al, 1993)

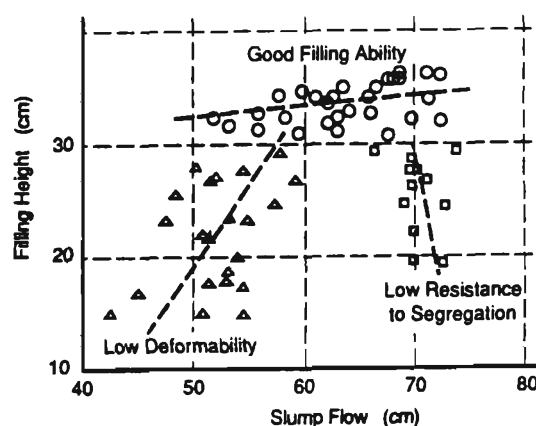


Fig. 2.5: Relationship between filling ability and slump flow (after Hayakawa et al, 1993)



Nagataki et al. (1995) also used another U-shape apparatus with clear spacing of 37 mm (diameter of reinforcement bars was 13 mm) (Fig. 2.6). The corners at the bottom of apparatus are square. The filling height of concrete was measured and evaluated. As before, higher filling height means better filling ability.

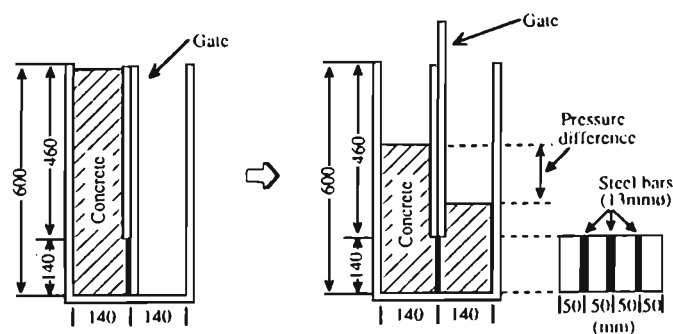
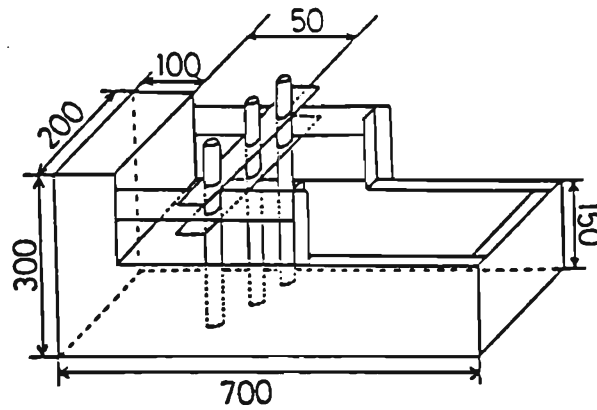


Fig. 2.6: U-shape apparatus (Nagataki, 1995)

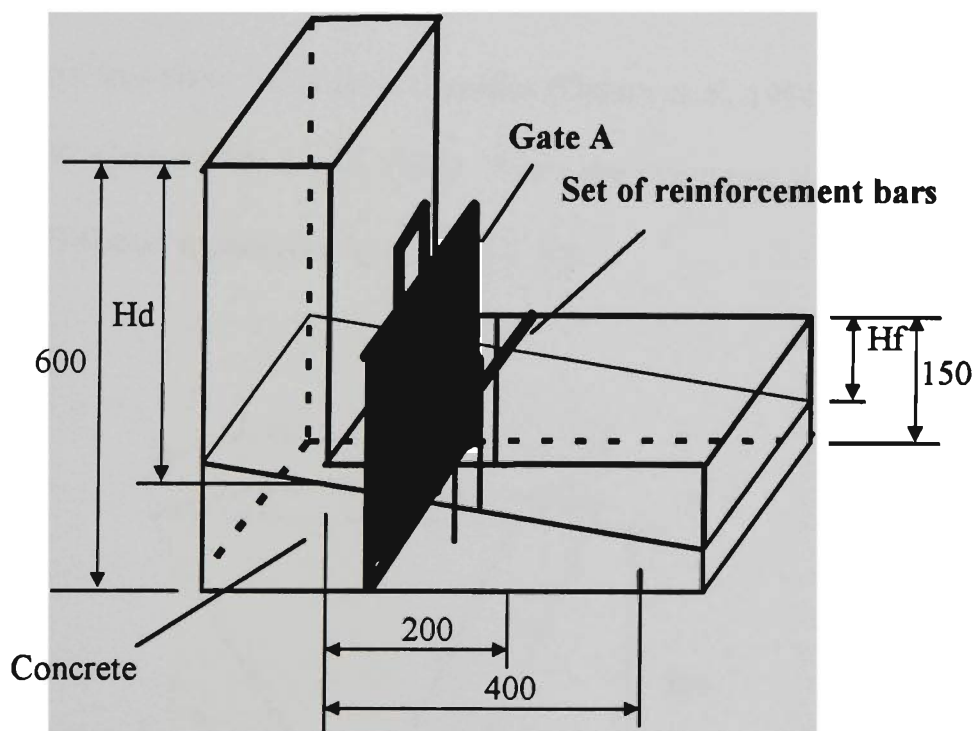
#### b) Test with L-shape apparatus

The L-shape apparatus was used in a number of studies (Yoshino et al, 1993; Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al, 1996; Goto et al, 1996; Kim et al, 1996; Van et al, 1998a). Typical forms of the L-shape apparatus are shown in Fig. 2.7 and 2.8. In the test with the L-shape apparatus (Fig. 2.8), with gate A of the L-box closed, fresh concrete is placed into the vertical leg of the L-box. The upper surface of the concrete is levelled. Then gate A is lifted in a vertical direction to allow the concrete to flow through the clear spacing between the reinforcement bars. When the concrete stops flowing, the filling head drop  $H_d$  (defined as the height difference between the L-box height and upper surface of concrete) is measured (Fig. 2.8). The filling head drop is used to evaluate the filling ability and, in particular, the blocking behaviour for self-compacting concrete.



(All dimensions in mm)

Fig. 2.7: L-shape apparatus (after Yoshino et al, 1993)



(All dimensions in mm)

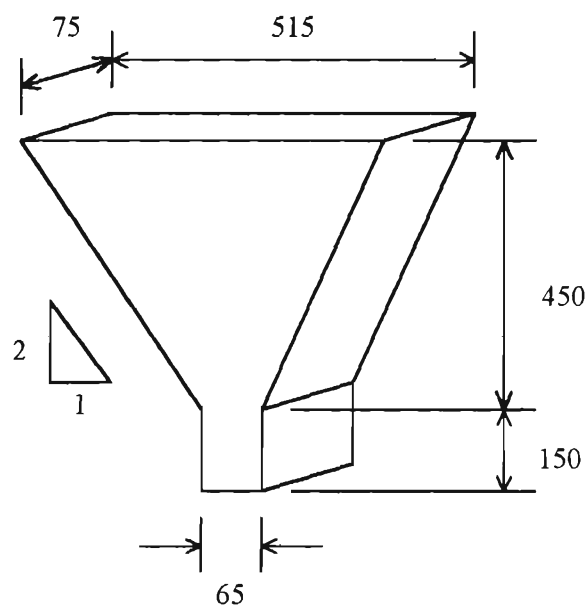
Fig. 2.8: L-shape apparatus (after Petersson et al. 1996)

The L-shape apparatus is useful for evaluating blocking around reinforcement. However, in previous studies, the clear spacing between reinforcement bars was usually

fixed and could not be easily adjusted. Therefore, in this study, the L-shape apparatus was modified. So that the set of reinforcement bars of the L-shape apparatus was manufactured in such fashion as to permit: adjustment of the clear spacing between the reinforcement bars; replacement of the bars with different diameters; and easy removal of the reinforcement bars from the box. In addition, the L-box and a Penetration Apparatus developed in this study were used in rapid tests for segregation resistance, deformability and blocking behaviour of self-compacting concrete. The rapid testing methods are described in Chapter 7.

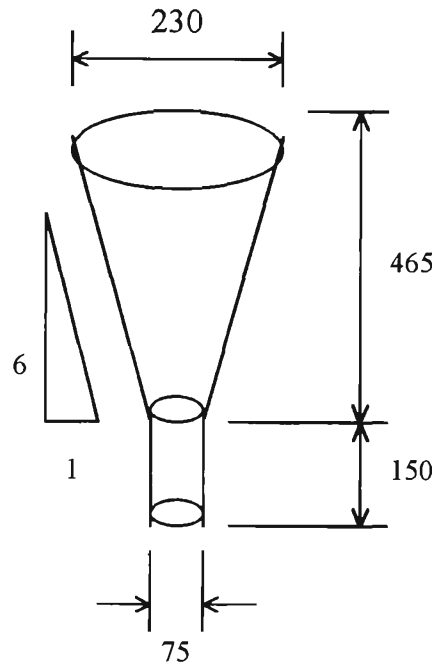
### c) Test with funnel apparatus

The funnel apparatus was used in several studies (Ozawa et al, 1994; Sakata et al, 1996; Kim et al, 1996; Chu and Machinda, 1998). There are two types of funnel, identified as V-funnel and O-funnel apparatus (Fig. 2.9 and 2.10).



(All dimensions in mm)

Fig. 2.9: V-funnel apparatus (after Ozawa et al, 1994)



(All dimensions in mm)

Fig. 2.10: O-funnel apparatus (after Kim et al, 1996)

In the test with the funnel apparatus, the time for concrete flowing out from the apparatus was measured. Longer flow-out time means concrete is of low viscosity and poor segregation resistance for concrete having slump flow of more than 70 cm; and it was found that when the concrete has slump flow of less than 50 cm, the flow-out time is either extremely long or the concrete is not able to flow because of blocking in the bottom of funnel (Sakata et al, 1996)

#### d) Apparatus for vertical fill

The vertical fill apparatus was first used at the University of Tokyo (Ozawa et al, 1992a) (Fig. 2.11). Concrete with a pressure about  $0.1 \text{ kg/cm}^2$  flows through a mesh of reinforcement bars, and the volume of concrete that passes the mesh is measured. Higher passing volume means better filling ability.

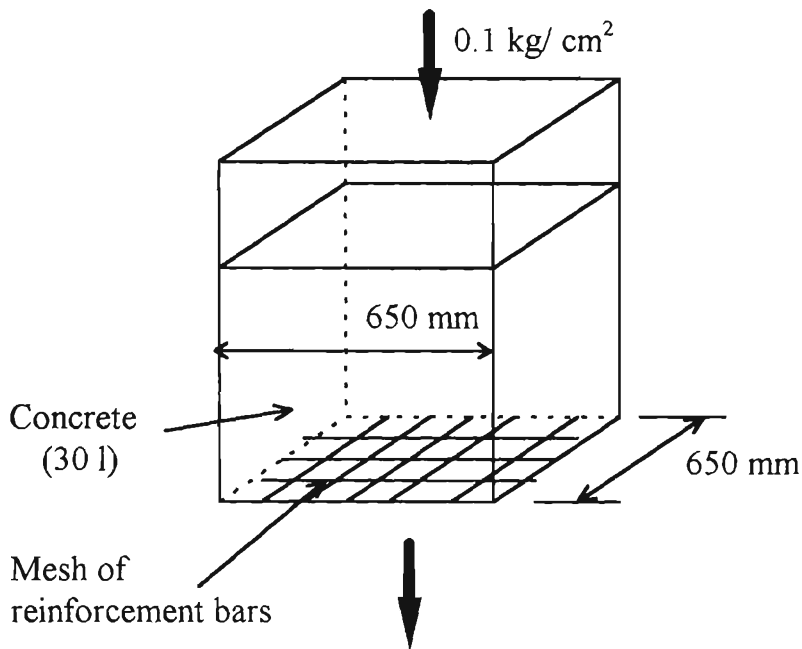


Fig. 2.11: Apparatus for vertical fill (after Ozawa et al, 1992a)

### 2.2.5.3. Evaluation for Segregation Resistance of SCC

According to Ozawa et al. (1992b), it is thought that workability of SCC is mainly affected by flowability (or deformability) and segregation resistance (that is obviously affected with viscosity); these being the most dominant properties required to obtain good filling capacity. Flowability is generally estimated by slump flow, defined as an average diameter of concrete after slump flow test. Segregation resistance, as discussed here, refers to separation of mortar and coarse aggregate. Direct and indirect methods have been developed in an attempt to evaluate the segregation resistance of SCC.

#### a) Direct methods

Nagataki et al. (1995) and Ogawa et al. (1995) proposed a method to evaluate segregation resistance of SCC. Concrete was gently poured from a two-litre steel container, 14 cm in diameter and 13 cm deep, onto a 5-mm mesh screen and left there for

five minutes. Then, the mortar which passed through the screen was weighed and the segregation index was calculated using Eq. 2.1 (Kimura, 1990).

$$SI = \frac{M_f}{M_c} \times 100(\%) \quad (\text{Eq. 2.1})$$

where

SI: Segregation index

M<sub>f</sub>: Mass of mortar passing through screen

M<sub>c</sub>: Mass of mortar contained in 2 litres of concrete

The authors (Nagataki et al, 1995) found that when the SI was about 5% or lower, no sinking of coarse aggregate or other segregation occurred. For each volume of coarse aggregate, the yield value of mortar giving an SI of approx. 5% was obtained and superimposed, resulting in Fig. 2.12. In the area to the right of the boundary line of segregation, no segregation is demonstrated, while the area to the left is the range in which segregation occurs.

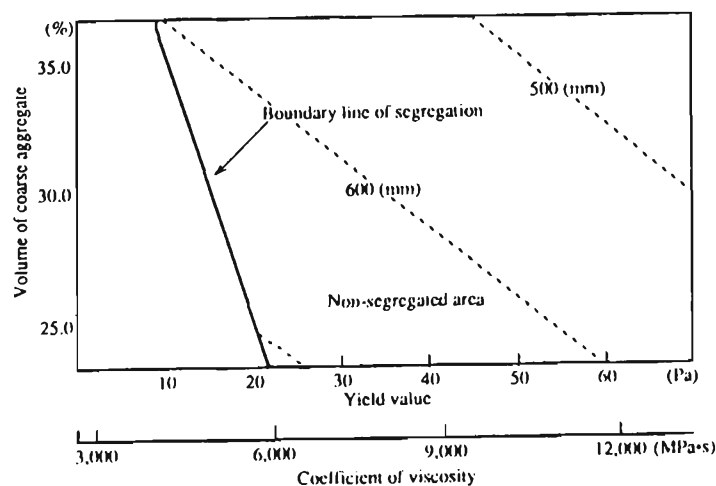
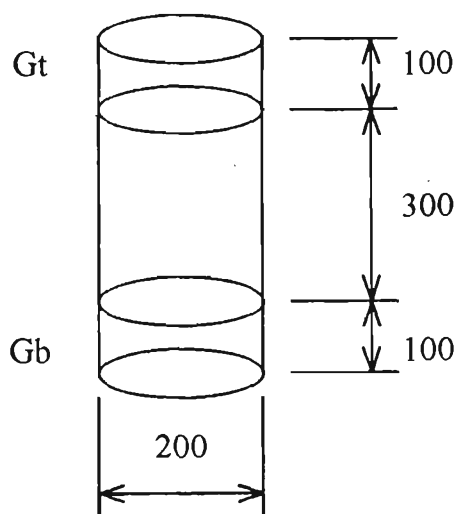


Fig. 2.12: Boundary line between segregation and nonsegregation (after Nagataki et al, 1995)

The other apparatus (Fig. 2.13) for evaluating segregation resistance of light weight SCC was used by Umehara et al. (1994). The apparatus consists of a cylindrical vessel. After placing concrete slowly into the vessel, slight vibration of 10 Hz is applied for 30 seconds with a table vibrator of 3000 rpm frequency. After keeping it still for one hour, concrete with height of 10 cm from the top and bottom is cut off and mortar is washed away (it is unclear, how the concrete specimen can be cut after 1 hour, since it is likely to be still soft). Then dry mass of coarse aggregate  $G_t$  and  $G_b$  in the concrete at top and bottom, respectively, is measured. Then segregation resistance of concrete is calculated as follows:

$$\text{Segregation resistance (\%)} = \frac{G_t}{G_t + G_b} \times 2 \times 100 \quad (\text{Eq. 2.2})$$

If segregation resistance is larger than or equal to, 95%, concrete is considered to be of satisfactory segregation resistance, because it was found that a drop in the strength becomes conspicuous suddenly when segregation resistance is less than 95%.



(All dimensions in mm)

Fig. 2.13: Cylindrical vessel for testing segregation resistance of light-weight SCC (after Umehara et al, 1994)

### b) Indirect methods

The above direct methods are quite slow and laborious. Therefore, several indirect methods were developed. Below is a summary of these methods.

#### Pulling test for evaluating segregation resistance

Tangtermsirikul et al. (1992a) used an apparatus (Fig. 2.14) to evaluate viscosity of mortar. The test is called as the pulling test. A cylindrical vessel is filled with mortar and a cruciform shaped steel blade (see Fig. 2.14), which is regarded as an imaginary aggregate, is pulled upward at three different values of constant velocity. The pulling force is measured by fixing a load cell to the axle of the steel blade. The value of viscosity is obtained by calculating the slope of the pulling velocity vs. load curve (Fig. 2.15 shows an example of the curve). The intercept of the vertical axis is denoted as the apparent resistance to segregation and represents the minimum force required to separate aggregate (steel blade in this test) from mortar. It is not the actual resistance to segregation because it is not the actual force between real aggregate and mortar. However, the authors regarded that for qualitative evaluation purposes, it is comparable because it increases and decreases in accordance with the actual resistance to segregation. Note that mortar samples for deriving viscosity are not obtained from the concrete mixtures but are mixed separately. However, they have the same proportions as mortars in the corresponding concrete mixtures, for which viscosity needs to be measured. As described, the method does not directly measure segregation resistance of SCC; however, quantitative values, which can be used to evaluate if the SCC sample has satisfactory or unsatisfactory segregation resistance, were not given in the literature.



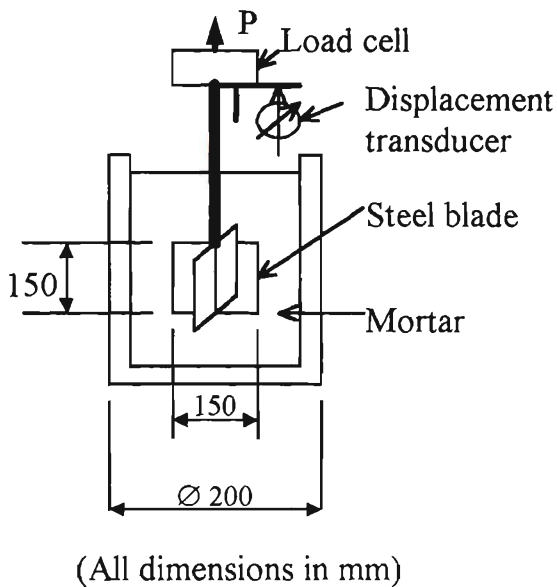


Fig. 2.14: Blade apparatus for segregation resistance of mortar (after Tangtermsirikul et al, 1992a)

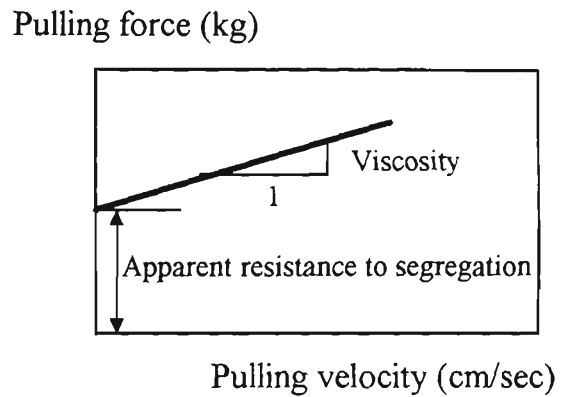


Fig. 2.15: Example of test result of pulling test (after Tangtermsirikul et al, 1992a)

### Segregation resistance test with funnel apparatus

Segregation resistance has been estimated by measuring the mean flow-out rate at the lower straight duct in the funnel apparatus shown in Fig. 2.9 (Ozawa et al, 1994), taking an average of three measurements. Fig. 2.16 (Miura et al, 1993) shows the relationship between slump flow and flow-out time for three typical mixtures, which are extremely different in unit powder content (here, “powder” includes cement, mineral admixtures and inactive fillers) or water to powder ratio that affect viscosity. According to the authors, while the flow-out times of these three mixtures are different, that of each mix is almost constant even when slump flow changes. The authors also claimed that the degree of fluctuation of the measured values shows the degree of segregation trend (the fluctuation is the difference between flow-out times for different durations (see Fig. 2.17)). Fig. 2.17 (Miura et al, 1993) shows the influence of unit coarse aggregate volume on flow-out time. When unit aggregate volume becomes as large as  $380 \text{ l/m}^3$ , coarse aggregate is condensed at the bottom of the funnel during flowing, so collision or blocking may often happen, and the degree of fluctuation of the three measured values

may increase; consequently with an increase of mean flow out time. Similarly, when segregation resistance of the mix is extremely low, partial collision or blocking occurs, so concrete flow becomes unstable and the degree of fluctuation becomes very high. However, there are some limitations relevant to this testing method for segregation resistance of SCC:

- To date, there are no published data on difference of flow-out times, based on which we can evaluate the segregation resistance of a mix;
- How can segregation resistance of a mix be evaluated if the mix contains low coarse aggregate volume, which will not in itself cause blocking at the bottom of funnel, however the mix may segregate in the vertical direction (i.e., the flow-out time difference may be low even after a certain period for SCC standing in the funnel) ?;
- Blocking at the bottom of the funnel can be caused by either: 1) too large a coarse aggregate volume for the mix having good cohesion between mortar and coarse aggregate; 2) segregation for mix having proper coarse aggregate volume, but poor cohesion between mortar and coarse aggregate; or 3) both too a large coarse aggregate volume and poor segregation resistance. If case 3) occurs, the difference of flow-out times will not be large, and this causes a difficulty in evaluating segregation resistance of the mix;
- The method is based on the evaluation of the difference of flow-time which is dependent on many factors such as water to binder ratio, water content, surface texture of aggregates, superplasticizer properties, volume of different components in concrete etc., and it is difficult to predict universal value of flow-out time difference that can be applicable for all mixes. Also, the test would need to be carried out at least two times to produce meaningful results.

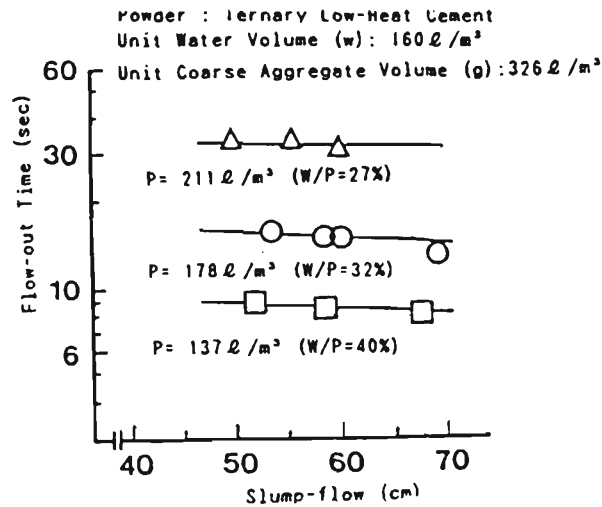


Fig. 2.16: Relationship between slump flow and flow-out time (after Miura et al, 1993)

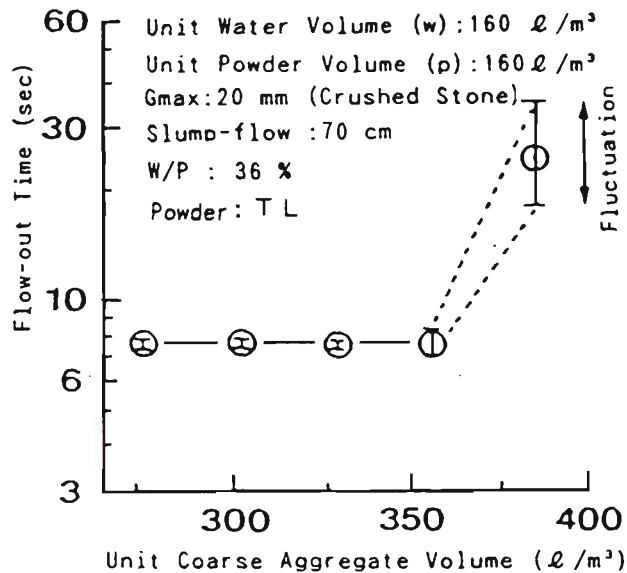


Fig. 2.17: Effect of unit aggregate volume on flow-out time (after Miura et al, 1993)

The above analysis indicates that it is necessary to develop another method which can evaluate more directly and more quickly segregation resistance of SCC, and which can be applied for different mixes. A major aspect of the current study has been to develop such a method for rapidly evaluating segregation resistance of SCC. The method is presented in Chapter 3 and Chapter 7.

#### **2.2.5.4. Flow Velocity of SCC**

Self-compacting concrete requires no vibration to fill all corners and spaces in the formwork due to its good deformability and segregation resistance. However, two concrete mixtures which are judged by an appropriate non-consolidation filling test to have equal filling ability, may fill a specified formwork at different speeds (Tangtermsirikul et al, 1992b). The process of filling takes time, even though the concrete can fill the formwork perfectly, if the concrete is relatively high in viscosity. Good velocity of deformation of the concrete is essential especially when rapid speed of construction is required. It is therefore considered that the velocity of deformation is one of the major parameters which has to be considered in the quality control of the concrete. Tangtermsirikul et al. (1992b) have proposed a method for evaluating the deformation velocity of SCC, including a simple test for measuring flow velocity of the concrete. In the simple test, V50 is defined as the average flow velocity, taken from the time just after removing the slump cone to the time when the concrete flow reaches 50 cm. The V50 is calculated as follows:

$$V_{50} = \frac{F_{50} - F_{20}}{T_{50}} = \frac{30}{T_{50}} \quad (\text{Eq. 2.3})$$

where F50 and F20 are slump flow values of 50 cm and 20 cm, respectively, and T50 is the flow time when concrete reaches 50 cm.

#### **2.2.6. Mix Design Methods for Self-Compacting Concrete**

Several mix design procedures have been proposed in recent years, being identified as:

a) General Purpose Mix Design, b) Further Modifications and Additions to the General Purpose Mix Design, c) LCPC Approach and d) Optimisation of Aggregate Quantity and Composition Mix Design.

### 2.2.6.1. General Purpose Mix Design Method

This approach was proposed by Okamura, Ozawa and co-workers at the University of Tokyo (Okamura and Ozawa, 1994; Okamura and Ozawa, 1995; Ouchi et al, 1998). The methods for achieving self-compactability by controlling mix proportions are summarised in Fig. 2.18. The self-compacting concrete achieves high deformability without segregation. The use of both limited aggregate volume and reduced water-powder ratio, with resulting high viscosity due to effect of superplasticizer, are effective in inhibiting collision between aggregate particles, leading to high segregation resistance.

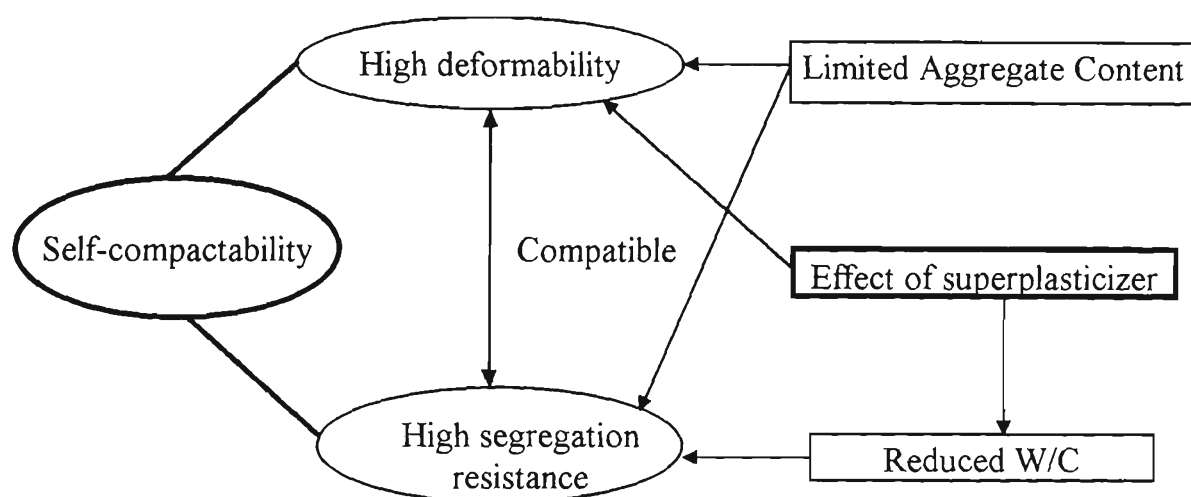


Fig. 2.18: Method for achieving self-compactability of SCC

(after Ouchi et al, 1998)

A rational mix design method for self-compacting concrete was then proposed (Fig. 2.19). Concrete is assumed to be two-phase material, consisting of coarse aggregate and mortar, in the mix design method. Coarse aggregate content was proposed to be around 50% of solid volume of the compacted coarse aggregate; while fine aggregate volume was designed to be about 40% of mortar volume. At the given aggregate contents, both superplasticizer dosage ( $Sp/P$ ) and water to powder ratio by volume ( $V_w/V_p$ ) are varied to achieve proper deformability and viscosity of the mortar. The mix design procedure is as follows:

- a) Fine aggregate content is set at 40% of the mortar volume;
- b) Vary the water to powder ratio and superplasticizer dosage to achieve proper deformability and viscosity of mortar (using a mortar flow spread test). The indices for the deformability and viscosity of mortar were defined as  $\Gamma_m$  and  $R_m$  (Eq. 2.4 and 2.5):

$$\Gamma_m = (r_1 r_2 - r_o^2) / r_o^2 \quad (\text{Eq. 2.4})$$

$$R_m = 10/t \quad (\text{Eq. 2.5})$$

where

$\Gamma_m$ : Deformability index of mortar,

$R_m$ : Viscosity index of mortar,

$r_1, r_2$ : Measured flow diameter (Fig. 2.20),

$r_o$ : Flow cone diameter (Fig. 2.20),

$t$ : Measured time (seconds) for mortar to flow through the funnel (Fig. 2.21)

Larger  $\Gamma_m$  indicates higher deformability and smaller  $R_m$  shows higher viscosity. Mortar with  $\Gamma_m$  of 5 and  $R_m$  of 1 was considered to be the most appropriate for achieving self-compacting concrete (Ozawa and Nagamoto, 1995).

- c) The coarse aggregate is then set at 50% of its solid volume (i.e. 50% of the coarse aggregate's dry rodded unit weight). This means that the volume of coarse aggregate will be greater if well graded and well shaped particles are used.
- d) Concrete then is tested in a U-type apparatus (filling height  $\geq 300$  mm), and if unsatisfactory, the water/powder ratio and admixture dosage is modified until satisfactory slump flow, V-funnel value and U-test result are obtained.

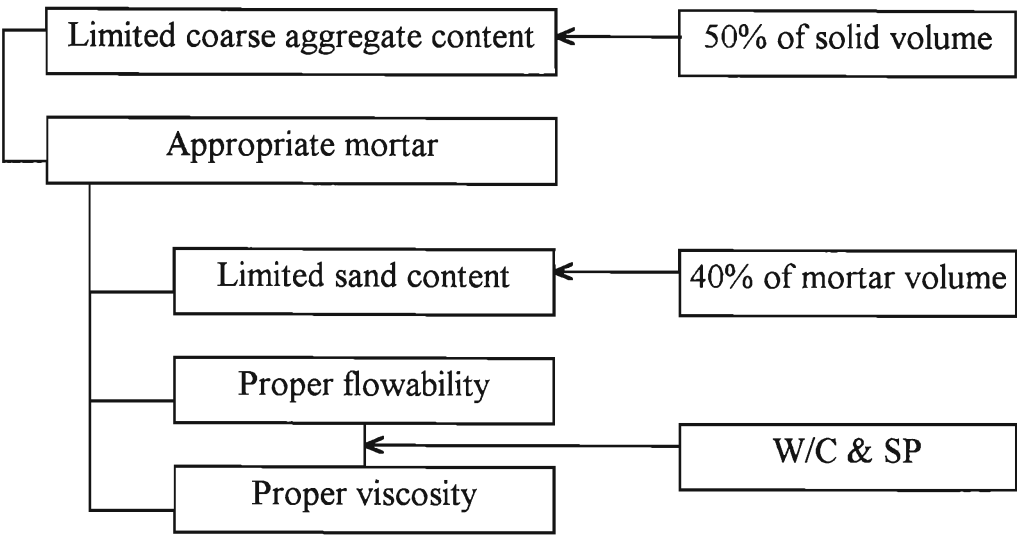


Fig. 2.19: Outline of a rational mix design method for SCC (after Ouchi et al, 1998)

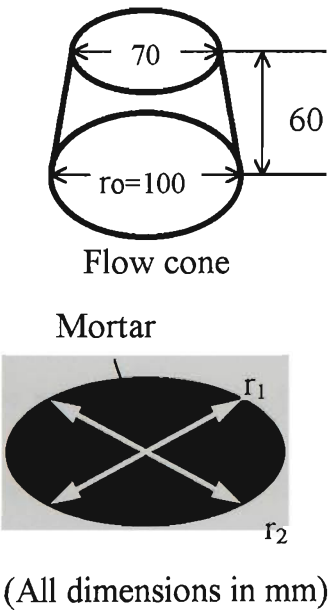


Fig. 2.20: Mortar flow test (after Ozawa and Nagamoto, 1995)

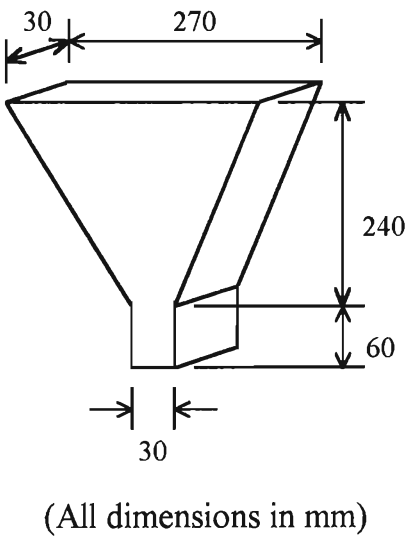


Fig. 2.21: Mortar funnel test (after Ozawa and Nagamoto, 1995)

This method can be used to design concretes which have more than adequate self-compacting properties for most applications. However, the method does not take into account the effect of different clear spacing between reinforcement bars in mixture proportioning, and does not always result in minimum paste volume needed to enhance self-compaction of the concrete.

### 2.2.6.2. Further Modifications and Additions to The General Purpose Approach

This approach has been being developed by Domone et al. (1996) who proposed some refinements and extensions to the approach at the University of Tokyo as follows:

- The circumstances in which cement replacement materials can be of benefit;
- Limits to water content and water/binder ratio as well as water/total fines with and without a viscosity agent;
- Proportions of aggregate and the required slump flow for 20mm and 10mm maximum aggregate size;
- Paste content and slump flow to avoid surface voids.

### 2.2.6.3. LCPC Approach

This approach was proposed by Sedran et al. (1996). The authors have applied a mix design method developed for high performance concrete in general to the particular case of SCC. The method uses the BTRHEOM rheometer and a mathematical model called the Solid Suspension Model in the mix design for SCC:

- The BTRHEOM rheometer is used to provide rheological parameters of SCC (and particularly its plastic viscosity);
- The Solid Suspension Model is used to optimise the granular skeleton of concrete. The model accounts quantitatively for the component nature (grading, packing, density and bulk density) and real confinement of the concrete (diameter of pumping pipes, density of reinforcement). Based on the model, the voids content of the granular skeleton, i.e. the aggregate plus binder, can be predicted. This void content is then minimised, hence minimising the water requirement for workability.



The detailed stages of this approach are as follows:

a) The initial data (at least) include:

- Slump flow between 60 and 70 cm (or shear yield stress measured with the BTRHEOM rheometer should be less than 500 Pa);
- Plastic viscosity should be less than 200 Pa to ensure good workability and a fast casting process on site, but greater than 100 Pa to avoid segregation; (There is a question as to whether this range of viscosity can be applied for different types and volume of coarse aggregate, as type and volume of aggregate can affect segregation of SCC)
- Mean compressive strength at 28 days;
- Restricting confinement e.g. dimension of pipe or clear spacing between reinforcement.

b) Suitable materials are chosen based on previous experience (aggregate types, cement/superplasticizer combination, mineral admixtures, retarders).

c) Mixture proportioning starts according to the following:

- Combination of binder is chosen based on experience; then maximum amount of superplasticizer for the chosen binder combination is determined, and half this amount is tentatively chosen.
- Water demand for the binder in the presence of the superplasticizer is determined.
- Calculations are performed with the Solid Suspension Model taking into account the confinement. An arbitrary value of relative viscosity is fixed according to experience and the water content is minimised. The mineral admixture/cement ratio(s) are kept constant, at the levels chosen, while the proportions of aggregates and binder combination are optimised.

- Concrete is batched and its water content is adjusted to obtain the target viscosity.
- The superplasticizer dosage is adjusted to find a suitable slump flow (or yield stress);
- Compressive strength of concrete is measured or estimated with an empirical formula that was modified from the classical Feret's formula:

$$F_c = \frac{K_g R_c}{\left( 1 + 3.1 \frac{W + A}{C(1 + K_1 + K_2) + BFS} \right)^2} \quad (\text{Eq. 2.6})$$

where

$F_c$ : 28-day compressive strength

$K_g$ : Aggregate coefficient. Two typical values of  $K_g$  are 5.4 and 4.8 for crushed and rounded aggregates, respectively;

$R_c$ : The 28-day cement strength measured on ISO mortar (sand:cement:water proportions: 3:1:0.5);

$W$ : The water content of concrete ( $\text{kg/m}^3$ );

$A$ : The volume of air ( $\text{l/m}^3$ );

$C$ ,  $PFA$ ,  $SF$ ,  $LS$  and  $BFS$ : Mass ( $\text{kg/m}^3$ ) of cement, fly ash, silica fume, milled limestone and blast furnace slag, respectively.;

$K_1 = 0.4PFA/C + 3 SF/C$  ( $K_1 \leq 0.5$ ): Pozzolanic coefficient;

$K_2 = 0.2 LS/C$  ( $K_2 \leq 0.07$ ): Limestone filler activity coefficient.

If the strength is too high or too low, a new combination of binders is chosen, and mix design steps are restarted.

- A filling ability test is carried out.

#### 2.2.6.4. Optimisation of Aggregate Quantity and Composition Mix Design

The method has been developed by the author and co-workers (Bui, 1994; Tantermsirikul and Bui, 1995 and Petersson et al., 1996) from 1993, and prior research has been focused on the aggregate phase in self-compacting concrete. In this approach concerning the Optimisation of Aggregate Quantity and Composition, concrete is considered as two-phase material, namely solid and liquid phases. The solid phase consists of fine and coarse aggregates. The liquid phase includes powder (cement, fillers), water, admixtures and air. The paste fills the voids in the aggregate matrix and provides a lubricating layer around each aggregate particle. The author and co-workers have focused on the solid phase (the aggregate phase), and the blocking criteria for the aggregate phase in SCC was developed based on the condition that the concrete does not segregate and has sufficient deformability. The blocking criteria relates the aggregate blocking volume ratio to the ratio between reinforcement clear spacing and diameter of aggregate fraction and ratio between reinforcement diameter and maximum aggregate size. From the blocking criteria, a minimum required paste volume (or maximum allowable aggregate volume) can be calculated in order to obtain self-compaction of concrete without causing blocking around the reinforcement. The test results that were reported in a number of publications (Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al., 1996; Montgomery et al., 1998) showed that the blocking criteria is useful for predicting the minimum required paste volume and can be applied for different materials. Further description of this method is given in section 8.1 of Chapter 8.

#### **2.2.7. Technology of Self-Compacting Concrete**

Sakamoto et al. (1993) reported a method for manufacturing and placing the concrete. The SCC was manufactured by using two-axial forced mixing type mixer in an ordinary

ready-mixed concrete plant. Agitator trucks were used to transport the concrete and it took about 30 minutes to transport from the plant to the placing site. The concrete was transferred from the agitator truck to a bucket ( $1\text{-m}^3$  capacity) at the placing site. Then the bucket was lifted by a crawler crane up to the location where the concrete was cast and placed into the formwork through a drop chute. When the SCC was cast, only two operators were needed, compared with eight operators for ordinary concrete cast with vibrators; thus the use of SCC with precast concrete forms helps to reduce the manpower required to place the concrete and to remove the forms. Also, the time needed for casting concrete was reduced by half with the use of SCC.

Hayakawa et al. (1993) reported that SCC was produced in a ready mixed concrete plant and transported to the site with agitating trucks. Average time for transporting SCC from the plant to construction site was one hour, and SCC maintained its large flow after transportation. More than  $3000\text{ m}^3$  of SCC was conveyed with a concrete pump and placed into the formworks without any vibrators.

Hayakawa et al. (1995) have measured concrete pressure in a pipeline when pumping. A pressure gauge was set adjacent to the column. The pressure exhibited pulsatory motion and increased linearly with the rise of the concrete. An example of the pressure and the relationship between the height and the pressure of the concrete are shown in Fig. 2.22 and Fig. 2.23, respectively. The authors calculated the pressure for pumping according to Eq. 2.7. and they stated that, in actual concrete filling work, concrete pressure was almost equal to the product of unit weight of the concrete and the height. This means that  $\alpha$  in Eq. 2.7. is 1.0 regardless of the existence of diaphragms. This may have

happened because distance between diaphragms in the actual columns was relatively large. However, in some cases, the value of  $\alpha$  was as high as 1.4.

$$P = P_l + \alpha UH/98$$

(Eq. 2.7)

- where  $P$  and  $P_l$ :
- Pressure for pumping and pipeline, respectively, (MPa)
- $\alpha$ :
- Factor from diaphragms
- $U$ :
- Unit weight of concrete (tonne/m<sup>3</sup>)
- $H$ :
- Height (m)

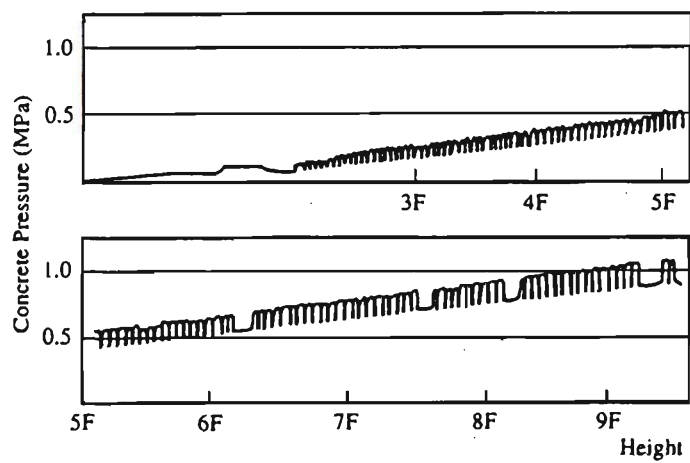


Fig. 2.22: An example of pressure during filling (after Hayakawa et al., 1995)

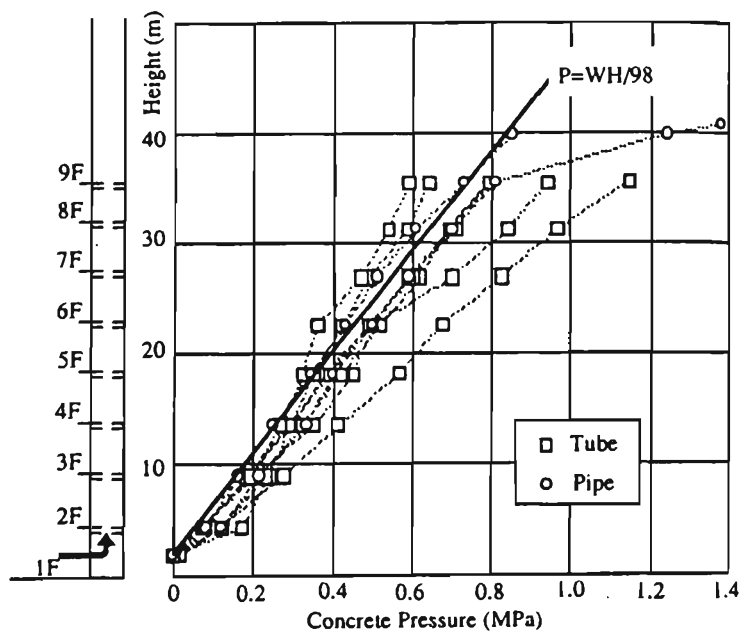


Fig. 2.23: Relationship between pressure and height (after Hayakawa et al., 1995)

Dry mixing of cement, limestone powder and fine aggregate and standard mixing without dry mixing were carried out for the same mixing time by Furuya et al. (1994) who stated that no difference was observed, and dry mixing in advance is considered unnecessary for highly flowing concrete containing large content of limestone powder. The authors also investigated the effect of different mixing time, and found that the bleeding ratio was similar, but compressive strength at mixing time of 90 seconds was slightly lower compared with that of 110 seconds. Time-dependent change of slump flow particularly was observed when mixing time was 90 seconds. Therefore, the authors considered that mixing time of 110 seconds is suitable for production of highly flowing concrete.

Furuya et al. (1994) also studied characteristics of pumpability which was investigated by the measurement of pumping pressure at 350m distance along the conveying pipe. Pressure loss of highly flowing concrete was approximately 70% of normal concrete. After pumping, the increase of slump flow, air content and temperature was about 5 cm, 1-5% and 2°C, respectively, in comparison with those before pumping. Time during which liquid pressure acted as lateral pressure against the forms was two hours. After six hours elapsed time, the pressure was stabilised.

Kuroiwa et al. (1993) reported that mixing time of super-workable concrete should be longer than that for ordinary concrete. Super-workable concrete is not so sticky, but a small amount of the concrete will remain in the mixer or the truck agitator. It can be discharged from a mixer or truck agitator easily.

### 2.3. THE USE OF SELF-COMPACTING CONCRETE IN REAL STRUCTURES

The use of SCC in actual structures was reviewed by Domone et al. (1996), and Bui and Montgomery (1998). The majority of applications of self-compacting concrete have been in Japan, however limited use of self-compacting concrete in structures in Sweden and France has also occurred. Table 1 lists some of the structural applications of self-compacting concrete in Japan.

As can be seen from Table 2.1, self-compacting concrete has been used in a wide range of structures, such as high rise buildings, bridges, walls, panels, storage tanks, stadiums, port structures, tunnel culverts etc. At age of 28-days, compressive strength of self-compacting concrete used in those structures ranged from 35 MPa to 65 MPa. Self-compacting concrete has been used particularly in structures having difficult construction conditions such as those containing heavily reinforced sections of complicated shape, tall and thin elements, etc. Domone and Chai (1996) have summarised the advantages claimed for self-compacting concrete as follows:

- reduced need for skilled labour during construction;
- shorter concrete placing times;
- improved compaction in areas of high reinforcement density;
- improved compaction and enhanced durability of the critical cover zone of structural members;
- the possibility of altering construction procedures to advantage eg. by higher single lift in narrow columns, or by the use of alternative composite construction.

Table 2.1: Typical structural applications of self-compacting concrete in Japan (after Domone and Chai, 1996; and Bui and Montgomery, 1998)

Structure	Details	Concrete volume (m <sup>3</sup> )	28-day strength (MPa)	Date
High rise building	Heavily reinforced structural concrete	3000	40	1993
20-storey building	Lower part of central heavily reinforced core	1600	47	1993
70-storey building (296-m high)	Lower 9 floors with 66 steel tubular columns, filling height of 36m	885	44	1993
Cable stayed bridge	Upper part of central column into permanent formwork	650	53	1993
Arch bridge	Heavily reinforced section	1500	-	1994
Bridge pier caps	Pier caps with difficult conditions	1000	65	1996
Thin and tall wall	Heavily reinforced wall, 6-8m high, 200mm thick	80	35	1993
LNG storage tank	Heavily reinforced wall base junction, flowing distance of 10m	800	35	1993
Stadium	Reinforced concrete guide track for retractable roof	10000	45	1993
Precast panels	Lightweight concrete in thin section (75-mm thickness)	-	65	1994
Port Structures	Breakwater, caisson floor with 14 reinforcement layers and 1.1-m thickness	760	40	1995
Jetty Structure	Joints of T-box and tubular sections	1190	60	1997
Tunnel culvert	Heavily reinforced upper slab	1091	-	1994





The Landmark Tower, Yokohama (Hayakawa et al, 1995) is a 296-metre high building with 70 storeys in which the lowest nine have 66 steel columns placed with self-compacting concrete (Fig. 2.26). The filling height and total volume of self-compacting concrete used were about 36m and 885 m<sup>3</sup>, respectively.

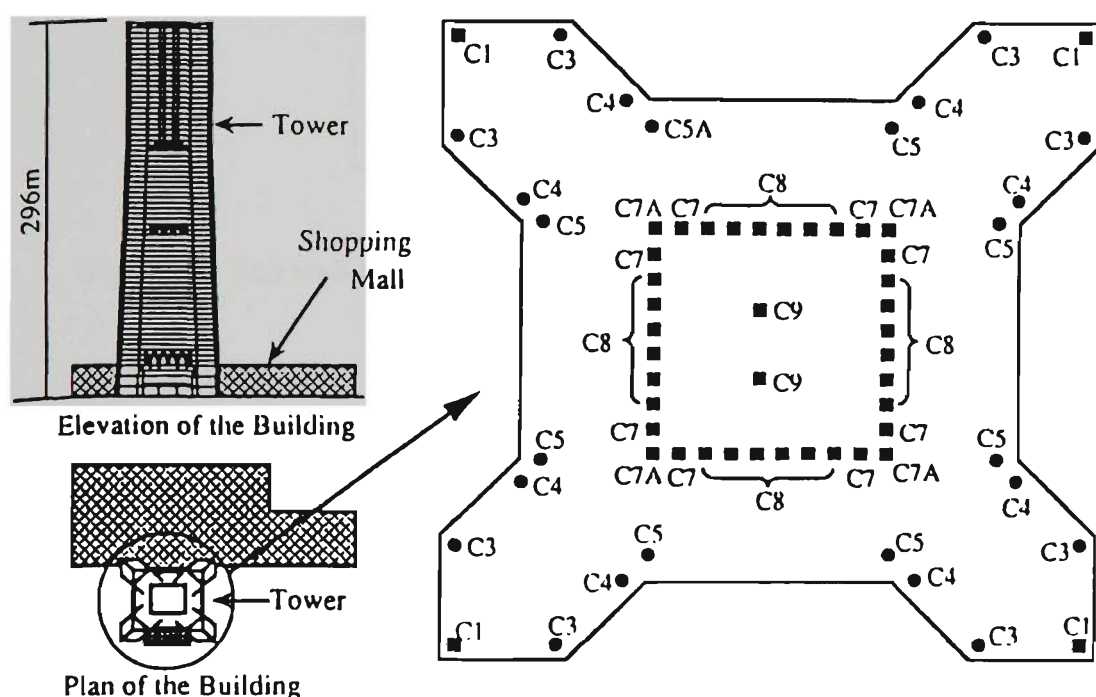


Fig. 2.26: The Landmark Tower (296-m high), Yokohama and floor plan showing locations of the 66 filled steel tubular columns (after Hayakawa et al, 1995)

Self-compacting concrete was also used in the construction of a thin and tall wall (Miura et al, 1993). The wall, which was 200-mm thick and 6 to 8m high, was cast by dropping concrete from the height of 8m (Fig. 2.27). Published results indicate that the wall was of good quality, and the concrete could flow and fill areas around windows even after free falling from the top of the wall. The total volume of self-compacting concrete used was 80m<sup>3</sup>.

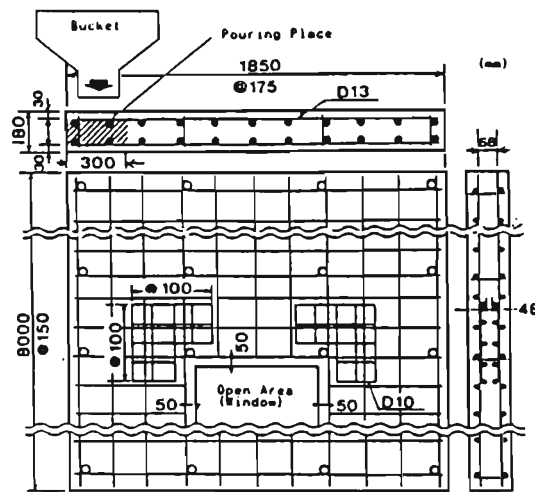


Fig. 2.27: Tall wall model and reinforcement (after Miura et al, 1993)

Izumi et al. (1995) reported the use of SCC in two retractable roofs, with one roof panel weighing approx. 4000 tons. The roofs were of complicated shape and inclined at 45 degrees. The total volume of SCC used was more than 10,000 m<sup>3</sup>. The concrete surface was free of serious defects such as honeycombing, and all corners of the formwork were completely filled. Further, the required formwork stripping strength was obtained at an age of 3 days.

Kato et al. (1993) have carried out a comparative study on the construction process using SCC and conventional concrete. The authors concluded that the use of self-compacting concrete indicates the following benefits:

- SCC reduces the manpower requirement and frees the workers from unpleasant jobs.
- It is possible to simplify pouring plans.
- When SCC is used with conventional placing methods, the construction is unchanged and the manpower requirement falls about 10%; when precast forms are used with

composite structure, the construction period drops by about 5% and the manpower requirement is reduced by about 20%; and when a steel-concrete sandwich composite structure is used, the construction period drops by about 20% and the manpower requirement is reduced by about 50%.

This comparative study has shown that the use of SCC can improve concrete construction practice and reduce both the construction period and manpower requirements on construction sites.

Application of self-compacting concrete in actual structures has been developed in other countries such as Sweden and France. In Sweden, self-compacting concrete (SCC) has been used for the construction of three bridges (Skarendahl, 1998). One of the bridges is part of a motorway, with a deck span of 12 m, width of 11.25m and concrete volume of 270 cubic metres. Results are very encouraging and the use of SCC in several other bridges is being considered. One predominant consideration is the overall economy which contractors find can be achieved with this material. The use of SCC for house building has also been developed, and some parts of structures have been cast, in an effort to increase both the productivity and the degree of industrialisation of the building process. Self-compacting concrete has also been utilised in conjunction with fibre reinforcement. In France, self-compacting concrete of 80MPa compressive strength has been considered for use in a bridge project (Larrard et al, 1996).

## CHAPTER 3

### METHODOLOGY, EXPERIMENTAL PROGRAMS AND MATERIAL PROPERTIES

#### 3.1. METHODOLOGY

##### 3.1.1. Limestone Modified Cements for High Performance Concretes

Bache (1973) suggested that the quality of superplasticized concrete could be improved by adjusting the particle size (part of cement being extremely fine) and the particle size distribution of the cement. However, the use of very fine cement can cause problems of too rapid hardening and high heat of hydration. Bache (1981) proposed a theory for densified cement/ultra-fine particle-based materials. The densified cement/ultra-fine particle-based materials are defined as materials with a matrix comprising, or formed from, 1) densely packed particles of a size ranging from 0.5 to 100  $\mu\text{m}$ ; and 2) homogeneously arranged, ultra-fine particles ranging in size from about 50  $\text{\AA}$  to 0.5  $\mu\text{m}$ , arranged in the spaces between the larger particles. The densified cement/ultra-fine particle-based materials were based on portland cement, ultra-fine silica fume and superplasticizer (the structure of the fresh paste is shown in Fig. 3.1). Also, the materials have an extremely low water content (0.13 - 0.18 by weight of cement + ultra-fine particles). However, ultra-fine silica fume is quite expensive and not always locally available. Therefore, the questions raised here are:

- a) is it possible to use a cheaper and more widely available powder to produce high performance concrete ?
- b) is it possible to use powders that are coarser than silica fume, and what degree of fineness should the powders have?

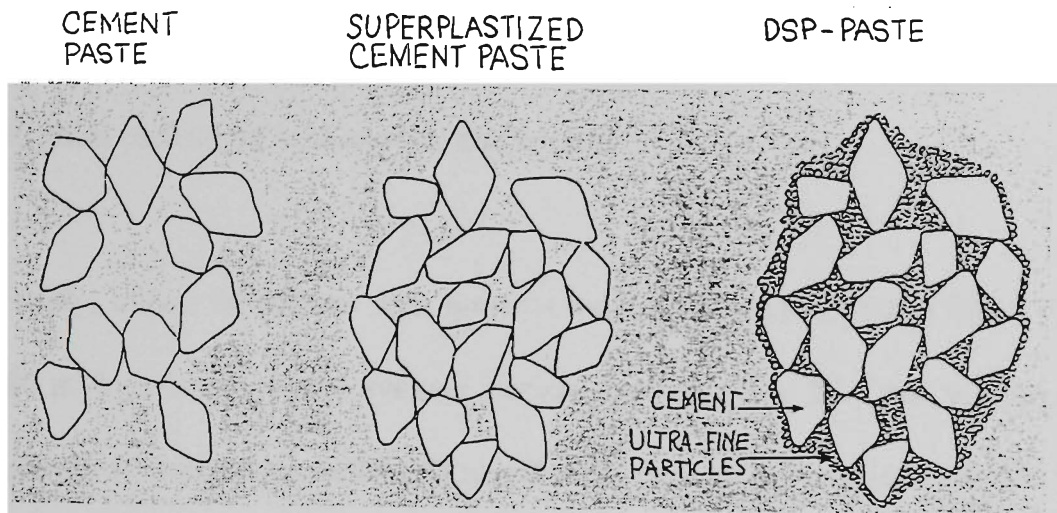


Fig. 3.1: Structure of the paste in fresh concrete based on 1) portland cement, 2) portland cement + superplasticizer and 3) portland cement + silica fume + superplasticizer (after Bache, 1981)

Milled limestone is of relatively uniform quality, low cost and widely available. Therefore, as indicated in Chapter 2, various studies on the use of milled limestone in normal vibrated concrete and self-compacting concrete have been carried out. In this current study, milled limestone was blended together with portland cement to develop limestone modified cements to be used for self-compacting and vibrated high performance concretes, that have not only high performance in their fresh state, but also in their hardened state (high strength, low drying shrinkage and low heat of hydration).

It is well known that milled limestone is chemically less reactive than cement and pozzolanic materials. Therefore, the use of milled limestone to replace a part of cement can eliminate the problem of too rapid hardening and high heat of hydration for very fine cement, and the fineness and content of milled limestone are the factors that can

contribute to improve the quality of high performance concrete. Milled limestone should play a role as a filler that can fill the pores and voids in cement paste and concrete. In order to play this role, the milled limestone should have fineness and content that promote good packing of binder paste and concrete.

In this study, milled limestones with fineness indices (Blaine) of 380 m<sup>2</sup>/kg, 870 m<sup>2</sup>/kg and 1680 m<sup>2</sup>/kg (the respective average particle size was about 27.4 µm, 6.3 µm and 3.8 µm) were used. Also, the content of the milled limestones were varied from 5% to 40% of total binder (portland cement + milled limestone) in order to develop self-compacting and vibrated high performance concrete with water to binder ratios ranging from 0.28 to 0.35 and compressive strength between 50 MPa and 90 MPa.

### **3.1.2. Rapid Testing Methods for Deformability, Blocking Behaviour and Segregation Resistance of Self-Compacting Concrete**

Self-compacting concrete (SCC) is a relatively new type of concrete and quite sensitive to quality control; it is therefore required to have appropriate testing methods. In this study, rapid testing methods for deformability, blocking behaviour and segregation resistance of SCC have been developed. The testing procedures should be as simple as possible and able to be carried out in the laboratory and on-site with less time and less extent of testing. The number of individual pieces of apparatus should be kept to a minimum, and they should be light and easy to carry.

In this study, a penetration apparatus (Fig. 7.3 and 7.6 in Chapter 7) was developed in order to rapidly test segregation resistance of SCC. The penetration apparatus utilises a penetration head which is assumed to be an imaginary coarse aggregate; therefore, the

penetration head should have appropriate weight and be able to penetrate into the mortar fraction of the concrete, without causing side effects and high resistance of concrete. Therefore, the penetration head was made from a plastic cylinder that has a mass about twice that of the average mass of maximum size coarse aggregate particles, and a thin wall in order to penetrate into concrete easily if the concrete segregates.

The L-shape apparatus (Fig. 7.2 and 7.5 in Chapter 7) was also modified to test deformability and blocking behaviour. The apparatus should be manufactured so that it is easy to change diameter of the reinforcement bars, adjust clear spacing between the bars or replace the set of bars. The testing methods developed require only the L-shape apparatus and the simple penetration apparatus. The rapid testing methods and developed apparatus are described in detail in Chapter 7.

### **3.1.3. Mix Design Method for Self-Compacting High Performance Concrete**

A mix design method has been proposed in which the fresh self-compacting concrete is considered as a two-phase material consisting of solid and liquid phases. The solid phase includes fine and coarse aggregates. The liquid phase consists of water, cement, mineral powder, admixtures and air in the concrete. A flow chart for the mix design method is given in Fig. 3.2.

As stated in Chapter 2, the author and co-worker (Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al., 1996) previously focused mainly on the solid phase, e.g. the aggregate phase, when considering blocking behaviour; and the published blocking criteria for aggregate phase was proposed. In this study, a major emphasis has been placed on considering the liquid phase, e.g. the paste phase; and the criteria for liquid



phase has been developed. Also, a comprehensive mix design method has been developed. The development of the liquid-phase criteria and the mix design method are described in Chapter 8.

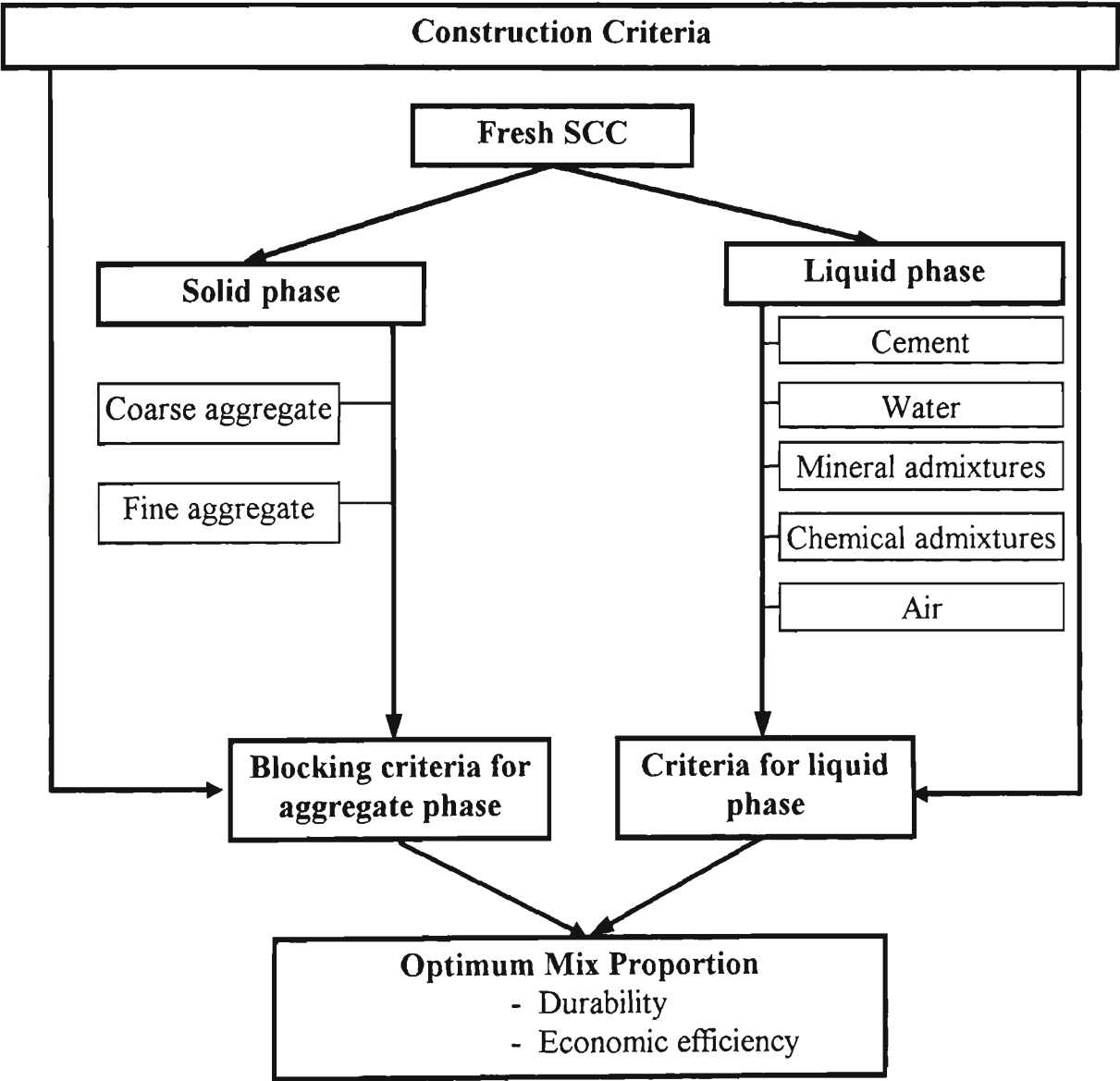


Fig. 3.2: Flow chart for mix design method for self-compacting high performance concrete

3.2. EXPERIMENTAL PROGRAMS AND MATERIALS USED

3.2.1. Experimental Programs

The following experimental programs were carried out to:

- test the properties of cement pastes and mortars containing milled limestone;
- investigate the effect of milled limestone on properties of vibrated concretes (including vibrated high performance and normal concretes containing milled limestone);
- study the performance of self-compacting high performance concrete containing milled limestone;
- develop a rapid testing method for determining the quality of self-compacting concrete;
- propose a mix design method;
- study the microstructure of pastes and concretes as well as mineral compositions of cement hydration products (using SEM and XRD).

Specific details of each experimental program are described in Chapter 4, 5, 6, 7 and 8.

### 3.2.2. Materials Used

Five types of cement, comprising two types of shrinkage limited portland cement, one type of ordinary portland cement and two types of blast furnace slag cement, were used. The two types of shrinkage limited portland cement and ordinary portland cement are designated as SPC1, SPC2 and OPC, respectively, while the two types of blast furnace slag cement, which contain 30% and 65% of blast furnace slag, are designated as BFC1 and BFC2, respectively. Five types of mineral admixtures, namely three sources of milled limestone, fly ash and blast furnace slag were also used in laboratory tests. These are specified as LS1, LS2, LS3, FA and BFS, respectively. The specific gravities, fineness and chemical analysis of the cements and mineral admixtures are shown in Appendix 3.1. The particle size distributions of the shrinkage limited portland cement and

milled limestones are presented in Appendix 3.3A, 3.3B 3.4A, 3.4B, 3.5A, 3.5B 3.6A, 3.6B, 3.7A and 3.7B.

Six sources of crushed basalt coarse aggregate and two sources of river sand were used in the concrete testing program. The six sources of the coarse aggregates, which include two with maximum size of 20 mm, two with maximum size of 14 mm and two with maximum size of 10 mm, are specified as A, B, C, D, E and F, respectively. Two sources of river sand are specified as RS1 and RS2. Particle size distributions and specific gravity of the coarse aggregates and river sands are given in Appendix 3.2. Naphthalene sulphonate superplasticizer in dry and liquid forms was used. The standard sand specified in EN196-1 was used in testing mortars.

## **CHAPTER 4**

### **PASTES AND MORTARS**

### **CONTAINING LIMESTONE MODIFIED CEMENTS**

#### **4.1. MATERIALS**

Three sources of limestone were utilised together with two types of shrinkage limited portland cement, named as SPC1 and SPC2. The specific gravity, fineness and chemical analysis of the cements and limestones, nominated as LS1, LS2 and LS3 are shown in Appendix 3.1. Particle size distributions of the cements and limestones are shown in Appendix 3.3 to Appendix 3.7, inclusive. Standard sand specified in EN196-1 and naphthalene based superplasticizers in liquid form were used in testing mortars.

#### **4.2. NORMAL CONSISTENCE AND SETTING TIMES OF PASTES**

##### **4.2.1. Experimental Program**

Cements and all three types of milled limestone, comprising 5, 10, 15 and 20% of total binder by mass, were blended in a plastic bag. Normal consistence and setting times of binder pastes were investigated in accordance to Australian Standards AS 2350.3 and AS 2350.4 (1988).

##### **4.2.2. Normal Consistence**

The test results for normal consistence and setting times of pastes containing different types and contents of limestones are indicated in Appendix 4.1. The normal consistence tests for pastes containing LS1 indicated higher values of required mixing water than those for pure cements, while the required quantities of mixing water for normal consistence of paste containing LS2 and LS3 were lower than those for pure cements,

with the exception for blends containing 20% of limestones LS2 and LS3 with cements SPC1 and SPC2, respectively.

The higher the content of limestone LS1, which has average particle size higher than that of both cements, then the higher the mixing water required in order to achieve normal consistence. For limestone LS2, which had average particle size approximately three times smaller than that of the cements, the minimum required mixing water was obtained when the limestone content was 5% and 10%, respectively, of total binder containing cement types SPC1 and SPC2. For limestone LS3, which had average particle size approximately six times and two times smaller, respectively, than that of the cements and limestone LS2, the minimum required mixing water was obtained when the limestone content was 10% and 15%, respectively, of total binder containing cement types SPC1 and SPC2. Therefore, when using cement SPC1, minimum required mixing water was achieved with the content of limestones LS1 (coarse), LS2 (fine) and LS3 (very fine) being 0%, 5% and 10%, respectively. Similarly, for cement SPC2, the minimum required mixing water was achieved when content of limestones LS1 (coarse), LS2 (fine) and LS3 (very fine) was 0%, 10% and 15%, respectively. This behaviour contradicts the normal observation that fine cements demand higher quantities of mixing water than coarse cements. However, the test results may indicate that blends containing suitable contents of limestones LS2 and LS3 result in better particle packing than that with limestone LS1, because the smaller particles of limestone LS2 and LS3 can fill the pores between cement particles, but coarse particles of limestone LS1 can not; and that smaller pores in the cement paste result in less mixing water being to achieve normal consistence. This finding is similar to that of Bache (1981) who studied densified cement/ultra-fine materials based on the use of superplasticizer and ultra-fine particles (silica fume). The

study on microstructure of pastes containing limestone modified cements (section 4.4 in this chapter) supports this hypothesis.

In summary, it is concluded that the combination between cement and milled limestone with suitable fineness and content can reduce the mixing water required to obtain normal consistence.

#### **4.2.3. Setting Times**

As can be seen from Appendix 4.1, in general, the setting times of pastes containing all limestones were shorter than those of pure cement pastes, however, all setting times satisfied the requirements of the Australian Standard AS3972-1991. This can be indirectly explained by the fact that a filler's primary effect is to accelerate cement hydration (Soroka and Setter, 1977).

### **4.3. MORTARS CONTAINING LIMESTONE MODIFIED CEMENTS**

#### **4.3.1. Experimental Program**

Cements and all three types of milled limestone comprising 5, 10, 15 and 20% of total binder by mass were blended in a plastic bag. For mortars, testing parameters were drying shrinkage, compressive strength and flexural strength. Mortar specimens were prepared using one of three procedures. In the first procedure (mode AS), water to binder ratio was held constant at 0.5 in accordance with Australian Standard AS 2350.12-1995. In the second procedure (mode F1), the water content was adjusted to produce similar flow values for the mortars without superplasticizer. In the third procedure (mode F2), the water content was adjusted to produce similar flow values for mortars containing constant dosage of superplasticizer in order to investigate the effect

of combining milled limestone and superplasticizer. The test results are indicated in Appendices 4.2, 4.3 and 4.4.

Heat of hydration of mortars in which milled limestones comprised 10%, 20%, 35% and 40% of total binder by mass was tested in accordance with Australian Standard AS2350.7 (1997) . Test results are indicated in Appendix 4.5. A model predicting reduction in heat of hydration for mortars containing milled limestone is developed (section 4.3.4 in this chapter).

#### **4.3.2. Tests with Constant Water to Binder Ratio**

##### Compressive Strength

As can be seen from Fig. 4.1 to Fig. 4.6, inclusive, at ages of 28 days, 362 days and 724 days, all mortars containing the three types of limestone LS1, LS2 and LS3 exhibited compressive strength values lower than those with pure cements, with the greatest reduction in strength occurring at 362 days. After 362 days, the compressive strength reduction of mortars containing the limestones were unchanged or lowered in comparison with mortars containing pure cements. Higher contents of limestone resulted in higher reduction of compressive strength of mortars.

Mortars containing limestone LS1 exhibited compressive strength lower than that with pure cements at all ages except for the mortar containing cement SPC1 and 5% of limestone LS1 at age of 3 days. (Fig. 4.1 and 4.2).

At 3 and 7 days, compressive strengths of mortars containing 5% and 10% of limestone LS2 and LS3 were higher than those of mortars containing pure cement SPC1 (Fig. 4.3

and Fig. 4.4). At 28 days, compressive strength of mortar containing 5% of limestone LS3 was similar to that of pure cement SPC1. Mortars containing 10% and 20% of LS2 and LS3 produced compressive strength data between 5 and 28% lower than those of pure cements (Fig. 4.3, 4.4 and 4.6). The compressive strengths of mortars containing limestone LS2 and LS3 were generally higher than those for mortars containing limestone LS1 at all ages (Fig. 4.5 and 4.6).

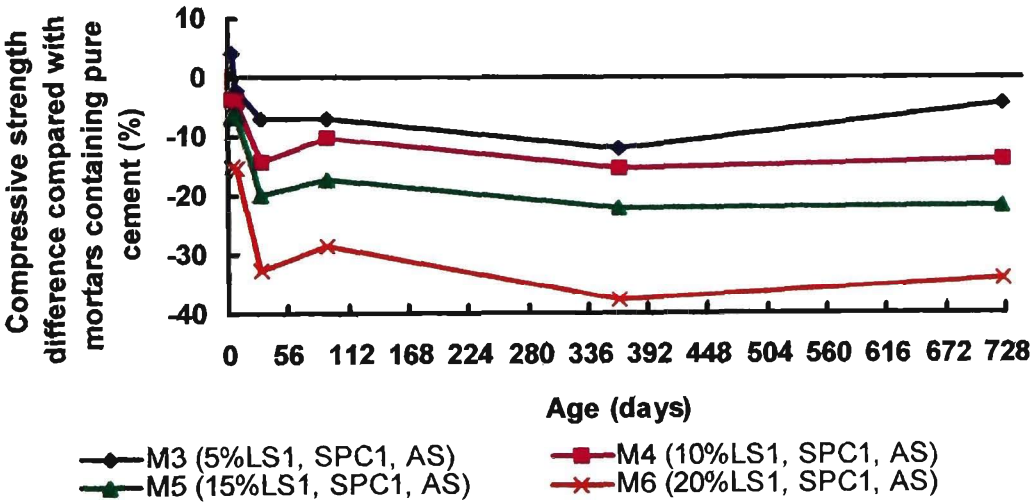


Fig. 4.1: Compressive strength difference of mortars containing limestone LS1, compared with that containing pure cement SPC1

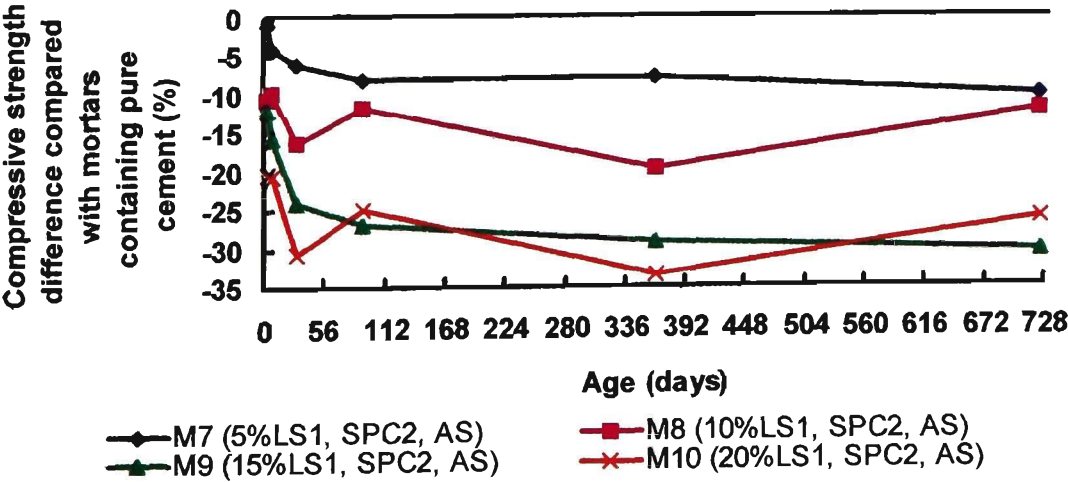


Fig. 4.2: Compressive strength difference of mortars containing limestone LS1, compared with that containing pure cement SPC2



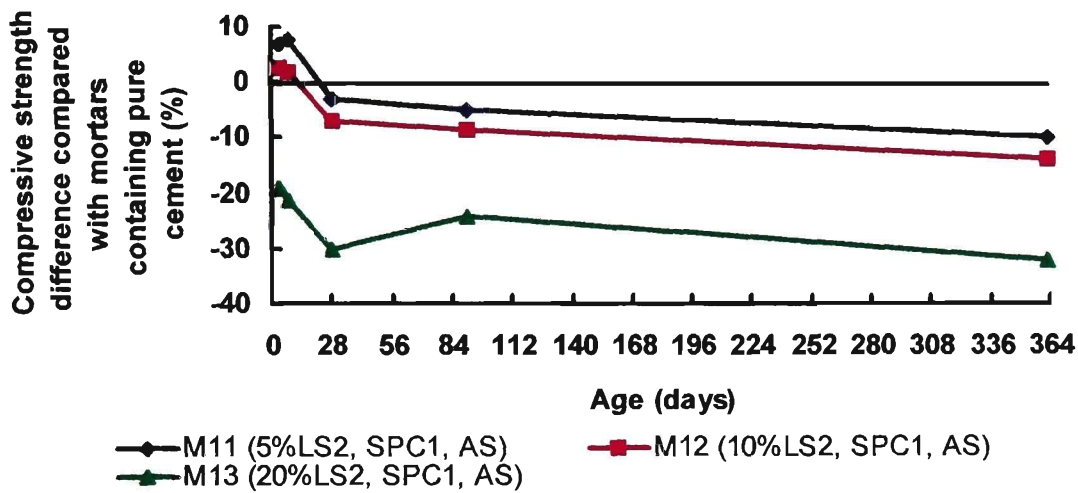


Fig. 4.3: Compressive strength difference of mortars containing limestone LS2, compared with that containing pure cement SPC1

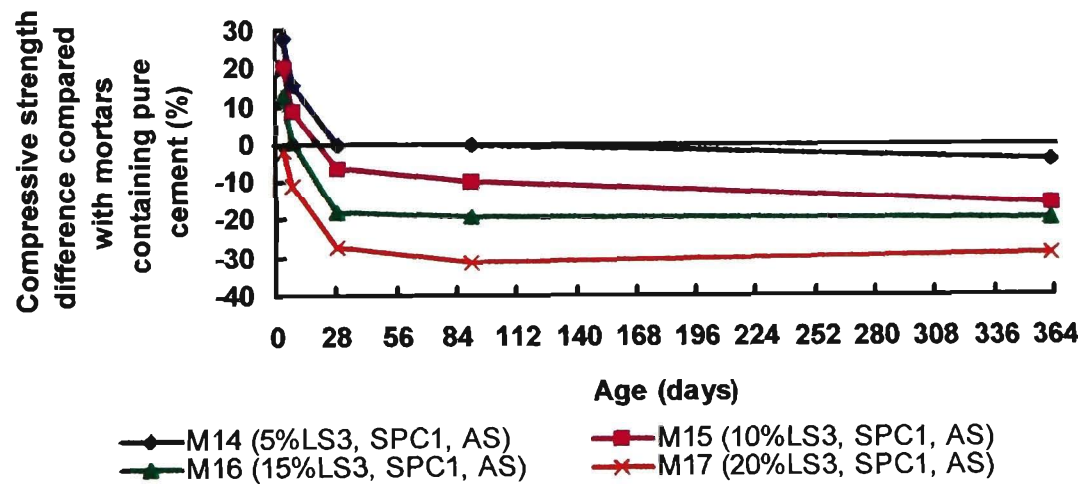


Fig. 4.4: Compressive strength difference of mortars containing limestone LS3, compared with that containing pure cement SPC1

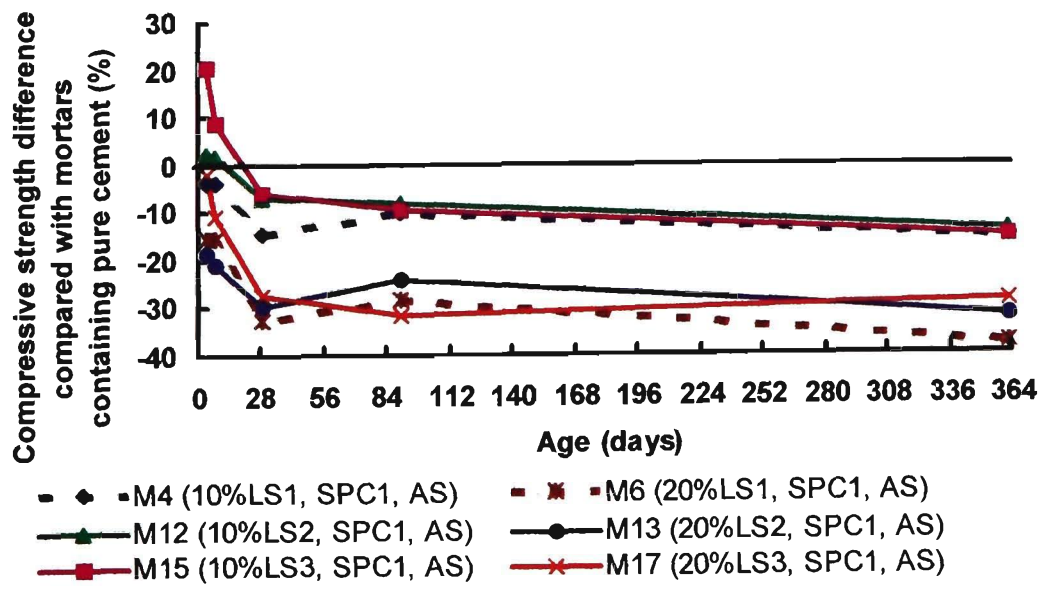


Fig. 4.5: Compressive strength difference of mortars containing different limestones (LS1, LS2 and LS3) compared with that containing pure cement SPC1

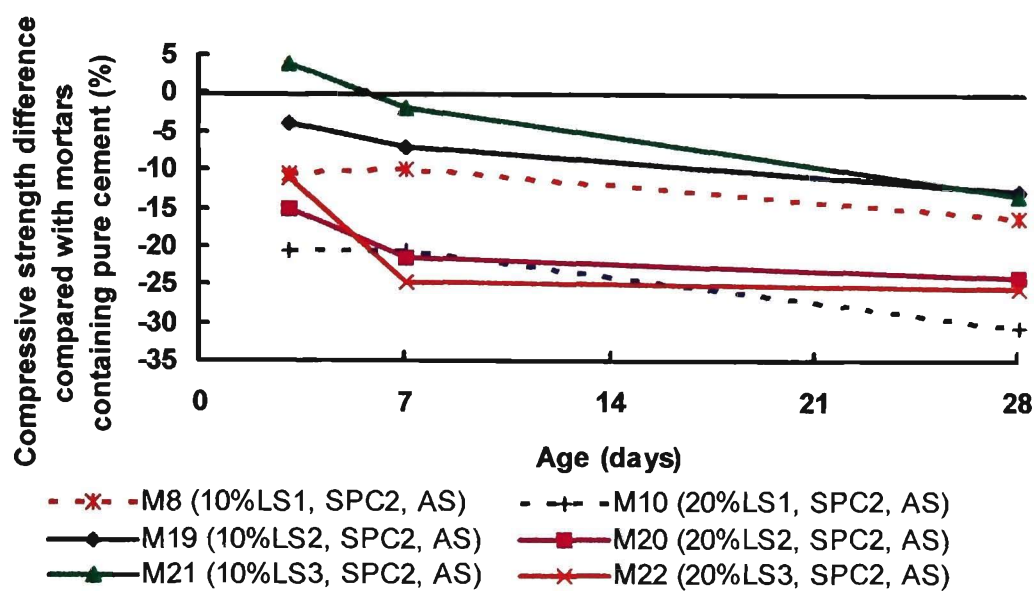


Fig. 4.6: Compressive strength difference of mortars containing different limestones (LS1, LS2 and LS3) compared with that containing pure cement SPC2

Mortars containing 10% of limestone LS2 and LS3 exhibited an increase in early age strengths (3 and 7 days) and reduced strength at ages of 28 days and later. The results are similar to those published previously (Soroka and Setter, 1977). This phenomena can be explained by the fact that limestones LS2 and LS3, which were fine and very fine, respectively, can form chemical reactions with the minerals in portland clinker and thereby accelerate the hydration of binders. SEM and XRD analysis support this explanation (section 4.4 in this Chapter).

Flexural Strength

As can be seen from Fig. 4.7 to Fig. 4.12, inclusive, the flexural strengths of mortars containing the three limestones were lower than those of mortars with pure cements, except for mortars containing 5% of limestones. Higher addition of limestone resulted in lower flexural strength of mortars.

For the use of cement SPC1, at age of 362 days, flexural strength reductions of all mortars containing 10% and 20% addition of the three limestones were lower than those at age of 90 days (Fig. 4.12).

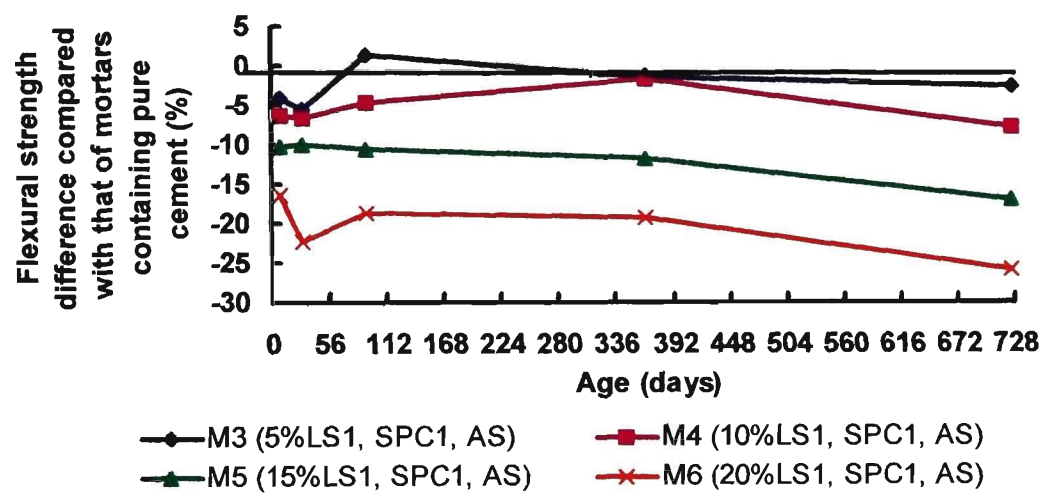


Fig. 4.7: Flexural strength difference of mortars containing limestone LS1, compared with that containing pure cement SPC1

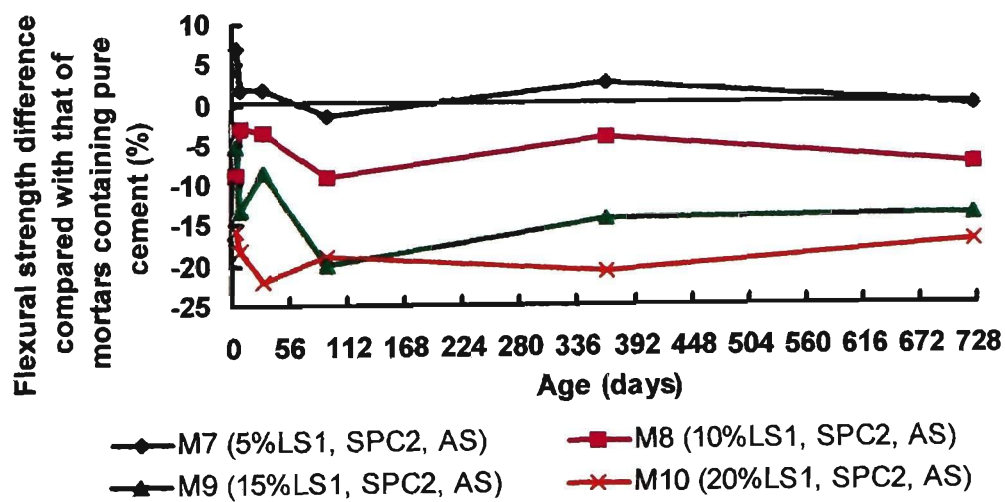


Fig. 4.8: Flexural strength difference of mortars containing limestone LS1, compared with that containing pure cement SPC2

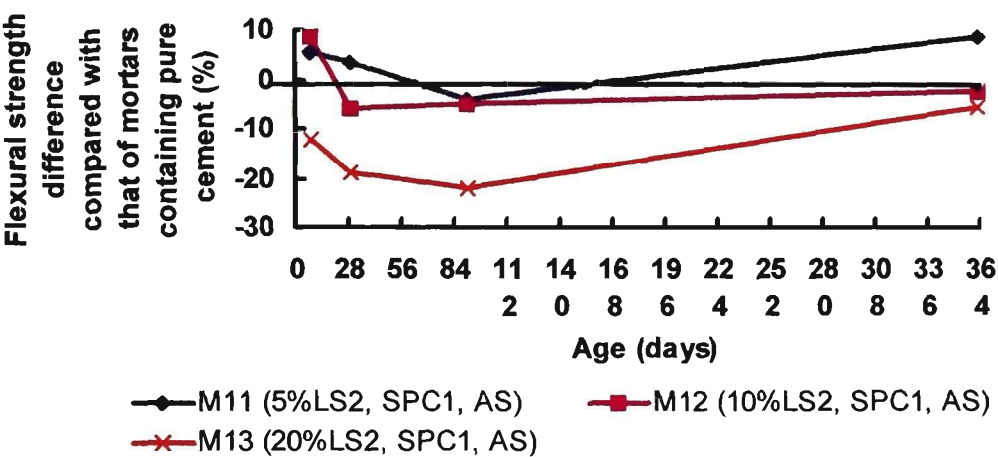


Fig. 4.9: Flexural strength difference of mortars containing limestone LS2, compared with that containing pure cement SPC1

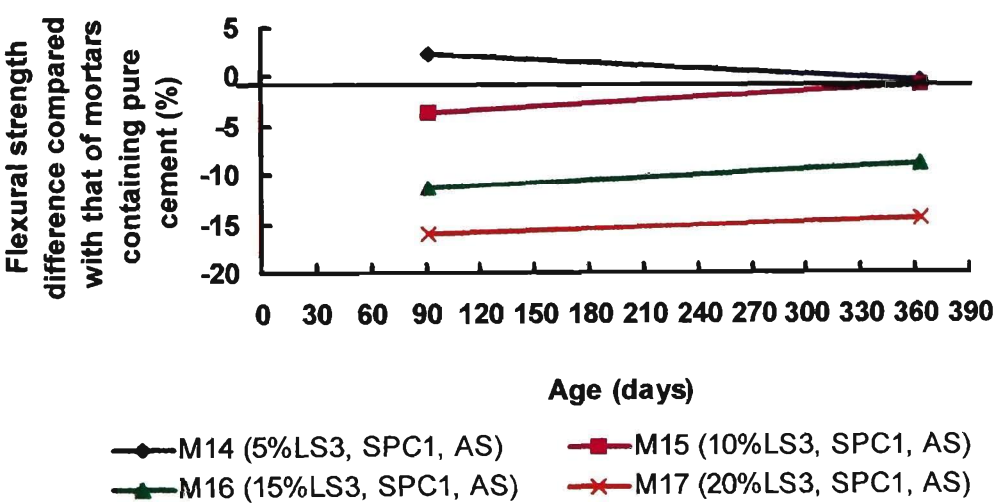


Fig. 4.10: Flexural strength difference of mortars containing limestone LS3, compared with that containing pure cement SPC1

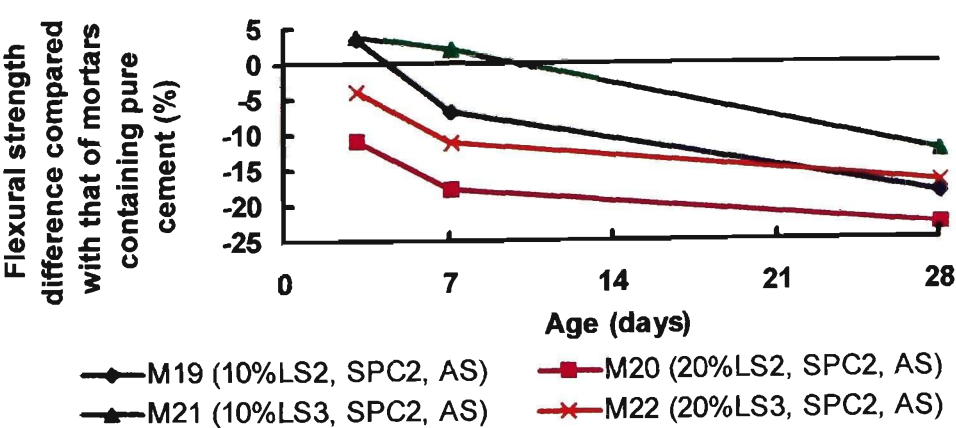


Fig. 4.11: Flexural strength difference of mortars containing limestones LS2 and LS3, compared with that containing pure cement SPC2

For the use of cement SPC1, mortars containing 10% of limestone LS1, LS2 and LS3 had similar flexural strengths at ages of 90 days and 362 days, while mortars containing 20% of limestone LS2 and LS3 exhibited flexural strengths higher than that with 20% of limestone LS1 at age of 362 days (Fig. 4.12). This indicates that the use of higher content of fine and very fine limestones produced higher flexural strength of mortars at long-term age when compared with the use of coarse limestone.

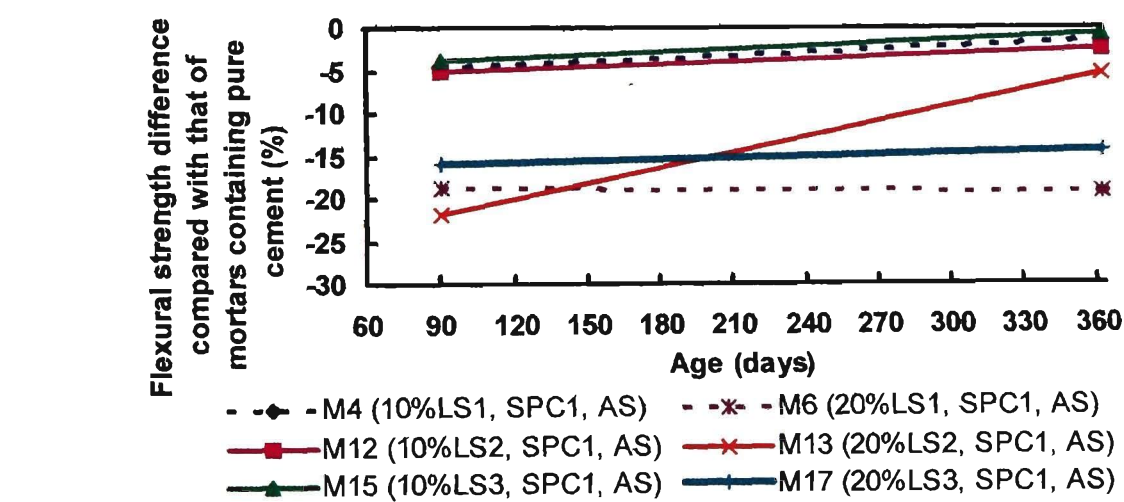


Fig. 4.12: Flexural strength difference of mortars containing different types of limestone, compared with that containing pure cement SPC1

Drying Shrinkage

As can be seen from Fig. 4.13, for the use of cement SPC1, drying shrinkage of mortars containing limestone LS1 was generally higher than that with pure cement at all ages except for that of mortar containing cement SPC1 and 20% of limestone LS1, which was slightly lower than that with pure cement SPC1 at age of 365 days.

For the use of cement SPC2, drying shrinkage of mortars containing 5% and 20% of limestone LS1 was higher than that with pure cement at all ages except 365 days; while

mortars containing 10% and 15% of limestone LS1 exhibited drying shrinkage lower than that with pure cement at ages greater than 28 days and 112 days, respectively. At age of 365 days, mortar containing 10% of limestone LS1 exhibited the lowest drying shrinkage. (Fig. 4.14).

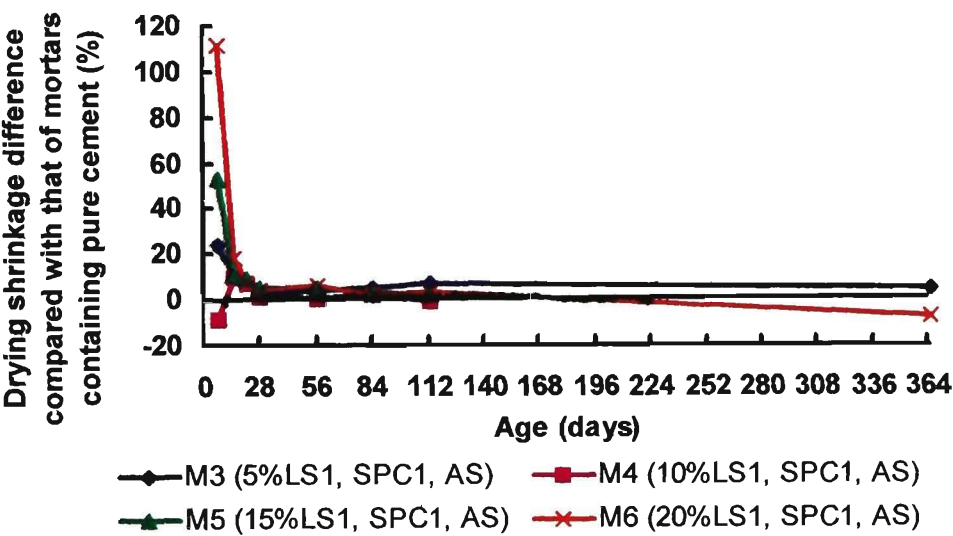


Fig. 4.13: Drying shrinkage difference of mortars containing limestone LS1, compared with that containing pure cement SPC1

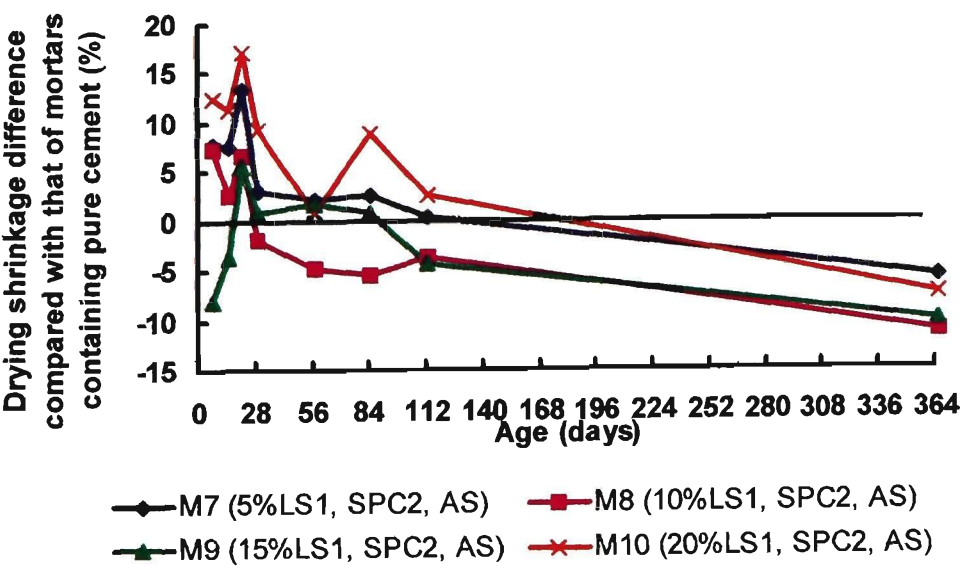


Fig. 4.14: Drying shrinkage difference of mortars containing limestone LS1, compared with that containing pure cement SPC2

For specimens containing cement SPC1 and limestones LS2 and LS3, drying shrinkage of all mortars was lower than for pure cement at ages greater than 28 days (Fig. 4.15 and 4.16). In the case of cement SPC2, the drying shrinkage of mortars containing limestone LS2 and LS3 were always lower than that of the pure cement, except at the age of 7 days (Fig. 4.17).

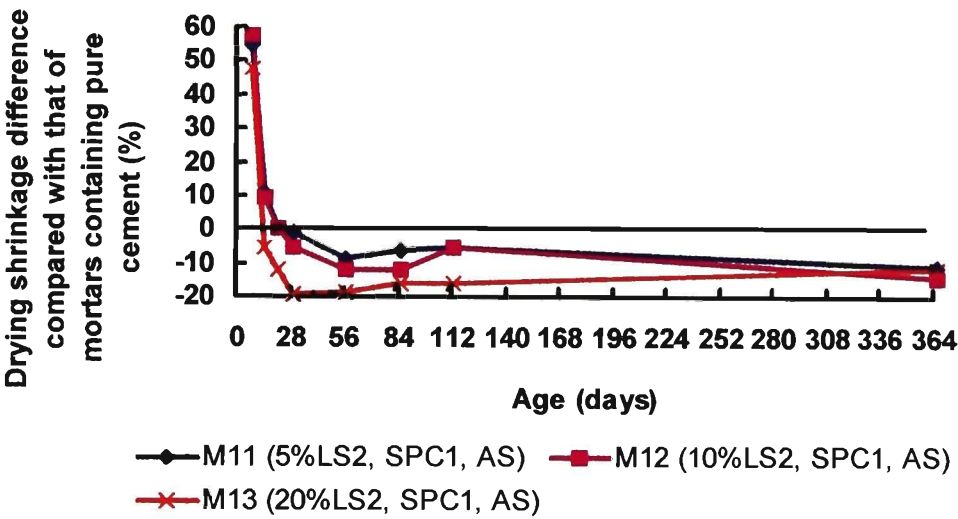


Fig. 4.15: Drying shrinkage difference of mortars containing limestone LS2, compared with that containing pure cement SPC1

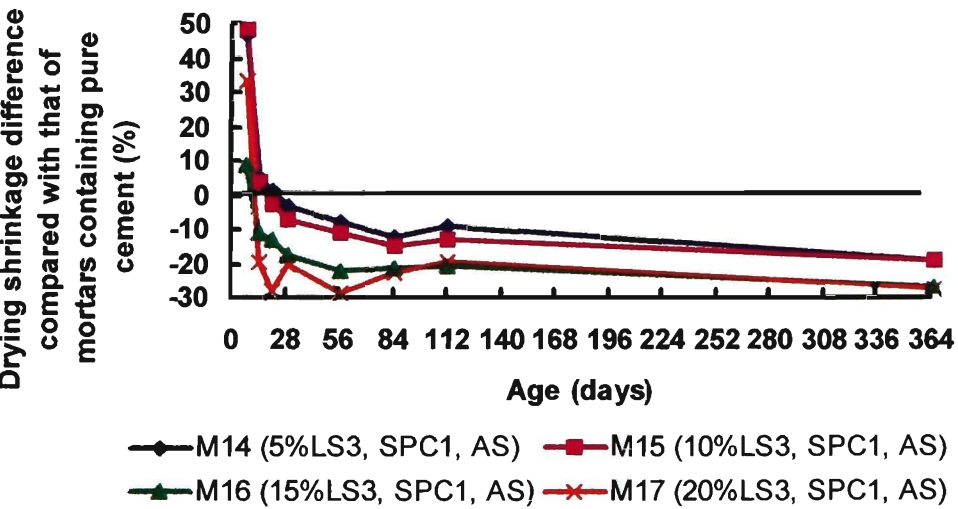


Fig. 4.16: Drying shrinkage difference of mortars containing limestone LS3, compared with that containing pure cement SPC1



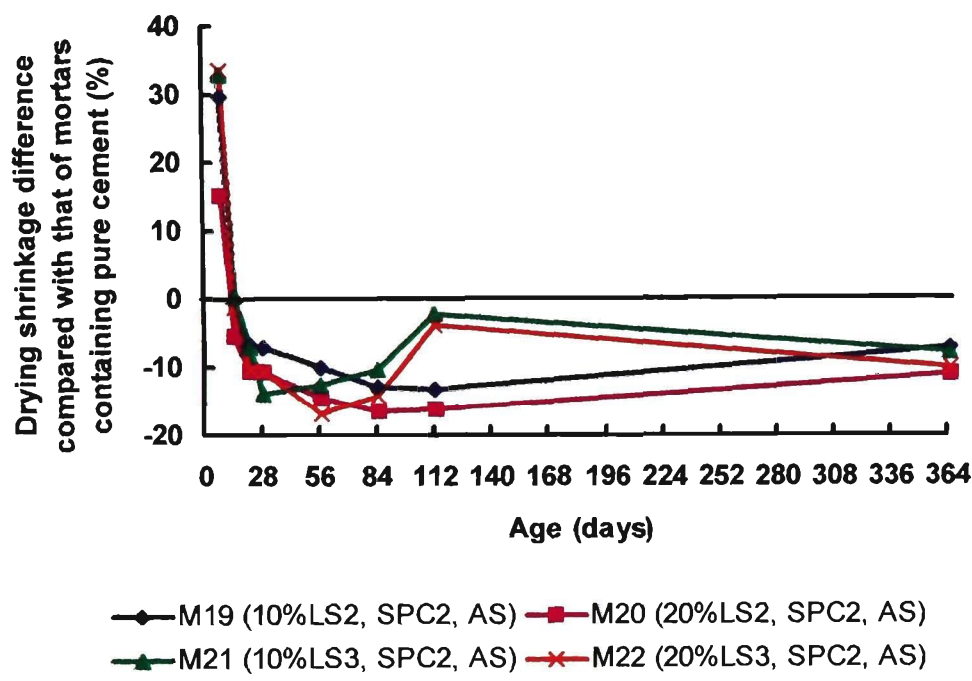


Fig. 4.17: Drying shrinkage difference of mortars containing limestones LS2 and LS3, compared with that containing pure cement SPC2

In general, at ages greater than 14 days, drying shrinkage of mortars containing 20% of limestones LS2 and LS3 was lowest in comparison with mortars containing pure cements and 5%, 10% and 15% of limestones LS2 and LS3 (Fig. 4.15, 4.16 and 4.17). This indicates that there is an optimum content of limestone which can improve drying shrinkage of mortars.

Mortars containing limestones LS2 and LS3 exhibited drying shrinkage lower than those with pure cements and limestone LS1 at ages greater than 14 days (Fig. 4.18 and 4.19). This indicates that the fineness of milled limestone also has an effect on drying shrinkage characteristics of mortars.



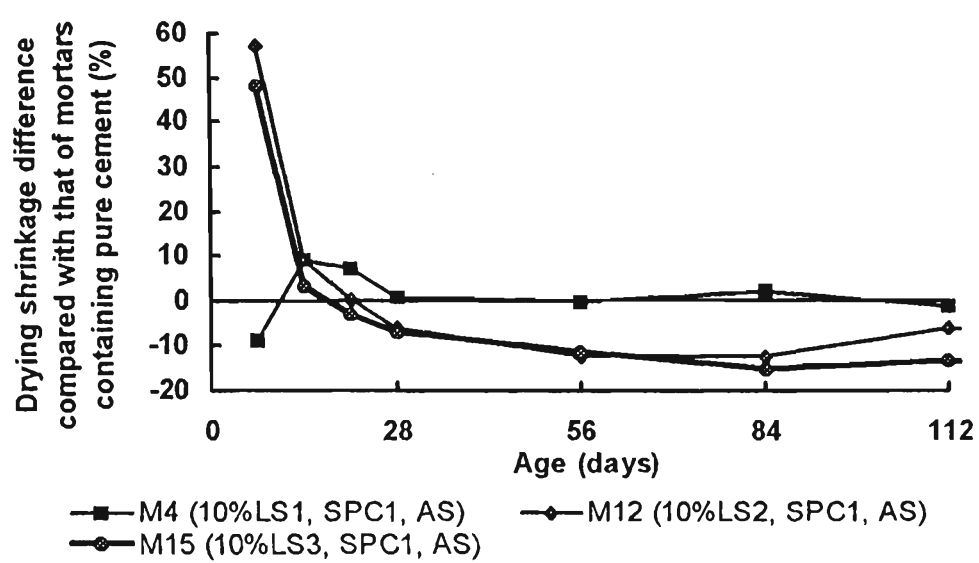


Fig. 4.18: Drying shrinkage difference of mortars containing 10% of different limestone types, compared with that containing pure cement SPC1

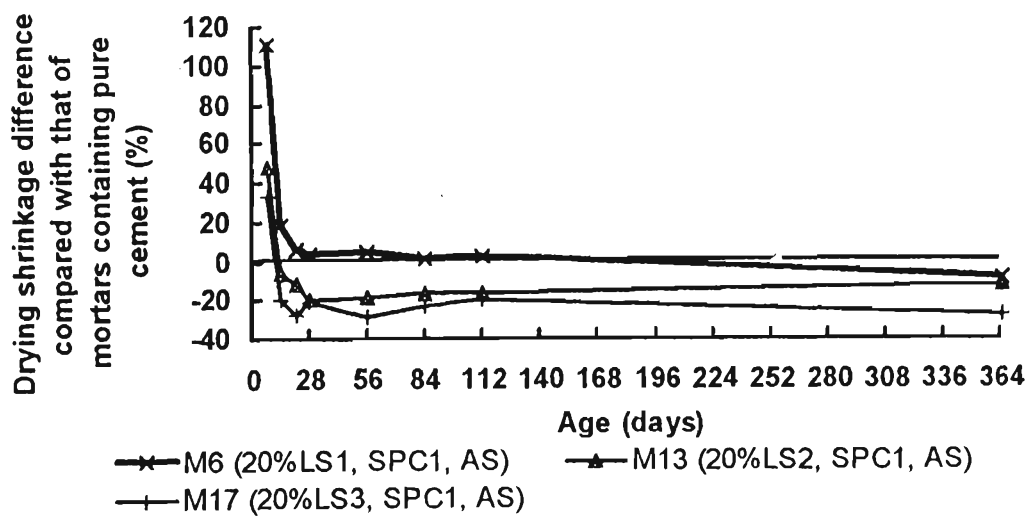


Fig. 4.19: Drying shrinkage difference of mortars containing 20% of different limestone types, compared with that containing pure cement SPC1

As can be seen from Fig. 4.13 to Fig. 4.19, inclusive, early age (7 days) drying shrinkages of all mortars containing milled limestone were generally higher than those of mortars containing pure cements. This behaviour can be explained by the fact that the mixing water content was maintained constant for all mixes, and the free water content in mortars containing limestone was higher than that in mortars with pure cements (it was well known that milled limestone, which is chemically less reactive, led to less water content bound in chemical status; therefore, the free water content in mortars containing

limestone was higher than that in mortars with pure cements). This can lead to higher water content being evaporated from mortars during the first seven days. It seems that, for high water to binder ratio, drying shrinkage of mortars at early age is mainly affected by free water content; however, microstructural characteristics of the mortars, such as porosity and the type of capillary system, play a more important role for drying shrinkage in later ages.

#### 4.3.3. Tests with Similar Flow Values

The compressive strengths of mortars containing 10% of limestones LS2 and LS3 were improved in comparison with those containing limestone LS1, due to the fact that mortars prepared with limestones LS2 and LS3 required less water content than those with pure cements and limestone LS1 (Fig. 4.20). Mortars containing 10% of limestones LS1, LS2, LS3 and pure cement SPC2 required water to binder ratios of 0.50, 0.46, 0.47 and 0.48, respectively, in order to achieve similar flows of  $110 \pm 5\%$ .

At constant superplasticizer dosage and also at 28 days, compressive strengths of mortars with 10% of limestones LS2 and LS3 were slightly lower, and similar to, respectively, that of pure cement SPC2; and strengths of mortars with 20% of limestones LS2 and LS3 were about 12% lower than that of pure cement containing the same superplasticizer dosage (Fig.4.21). Mortars with superplasticizer and 10% of limestones LS2 and LS3 exhibited 28-day compressive strength similar to and higher than, respectively, those without superplasticizer (Fig. 4.22). This indicated that superplasticizer has a more effect with limestone of high fineness, and which may be due to the superplasticizer enhancing more uniform distribution of limestone particles in the mortars.

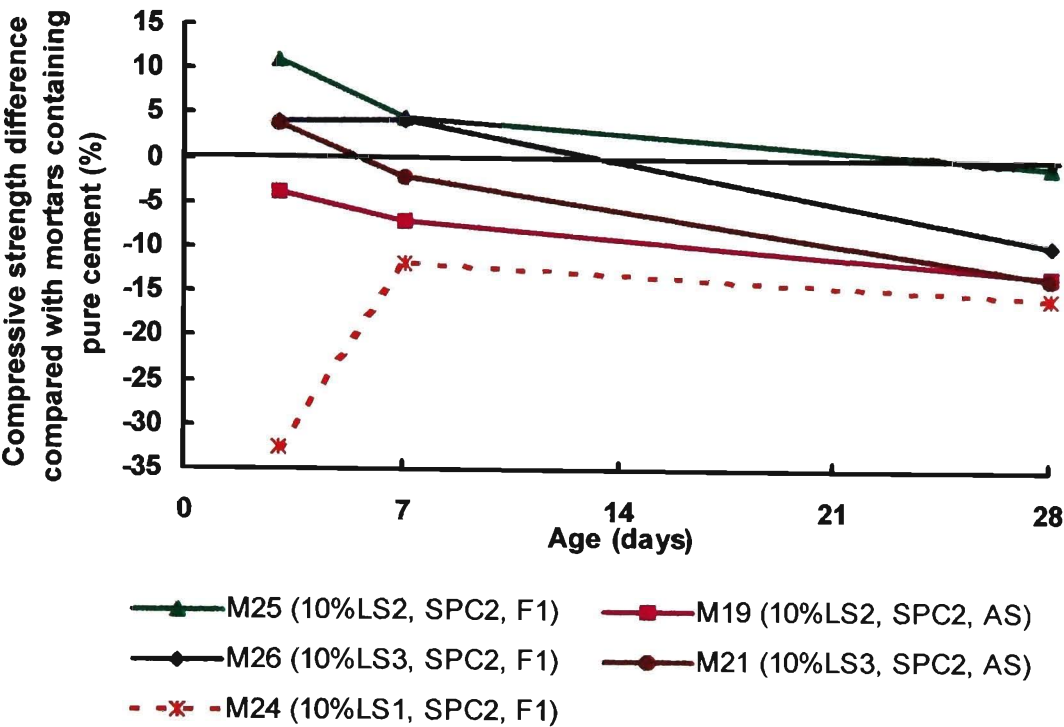


Fig. 4.20: Compressive strength of mortars containing 10% of limestones LS1, LS2 and LS3 (with similar flow values and without superplasticizer) (mode F1)

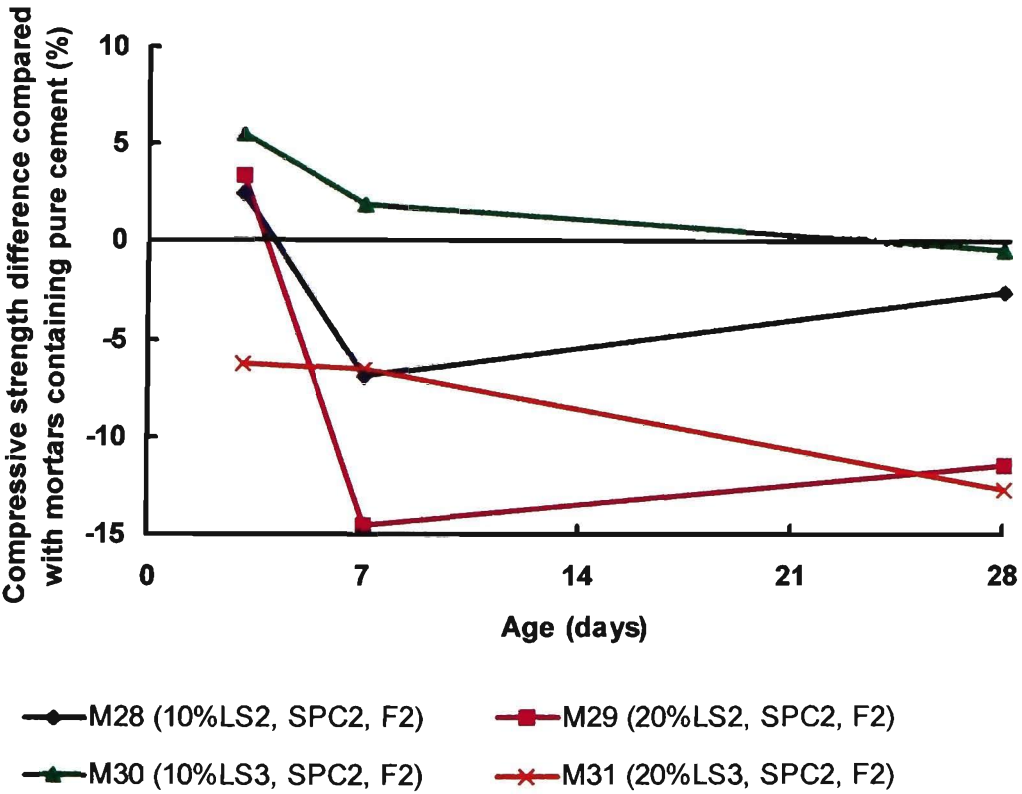


Fig. 4.21: Compressive strength of mortars containing limestones LS2 and LS3, prepared with similar flow values and superplasticizer (mode F2)

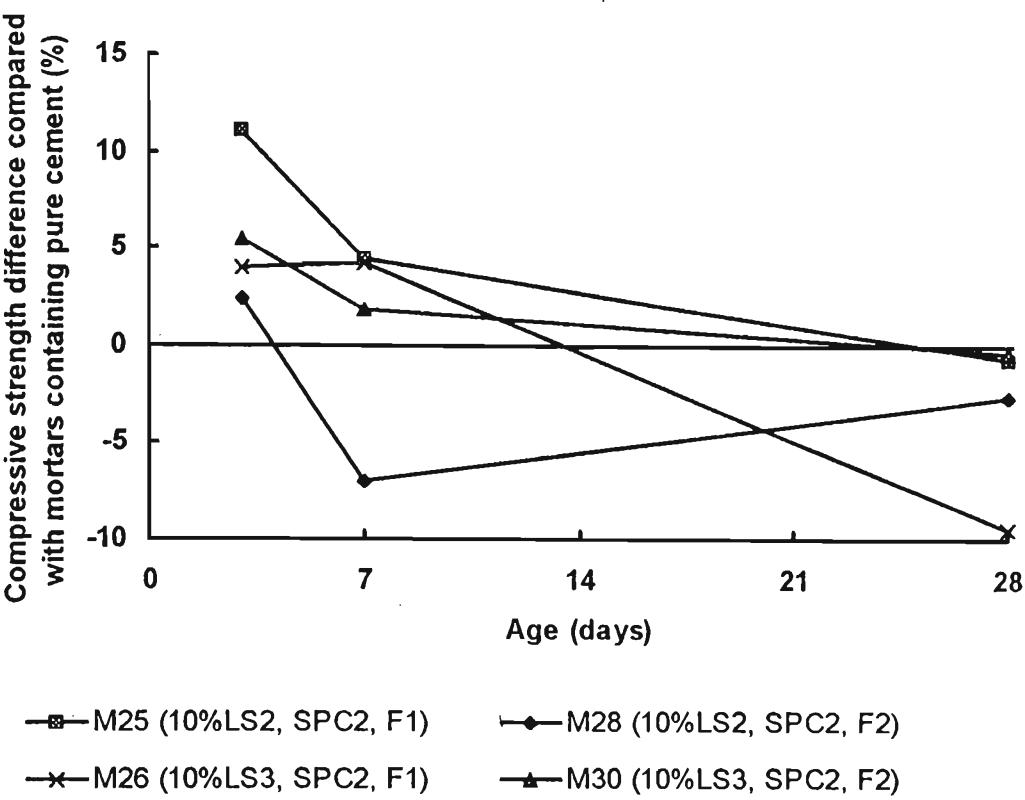


Fig. 4.22: Compressive strength of mortars containing 10% of limestones LS2 and LS3, prepared with and without superplasticizer (modes F2 and F1, respectively)

Mortars containing limestones LS2 and LS3 required less water content than those with pure cement and limestone LS1, although limestones LS2 and LS3 were finer than limestone LS1 and the cements. The results are similar to those of prior research (Krstulovic et al., 1994) which also found that workability of mortar and concrete containing very fine filler was better than for pure cement and coarse fillers.

4.3.4. Heat of Hydration of Mortars Containing Limestone Modified Cements

4.3.4.1. Test Results on Heat of Hydration

As can be seen from Appendix 4.5 and Fig. 4.23 to Fig. 4.26, inclusive, heat of hydration of mortars containing the three limestones were always lower than those containing pure cements after hydration for 6 hours; and mortars containing higher contents of limestone had lower heat of hydration.

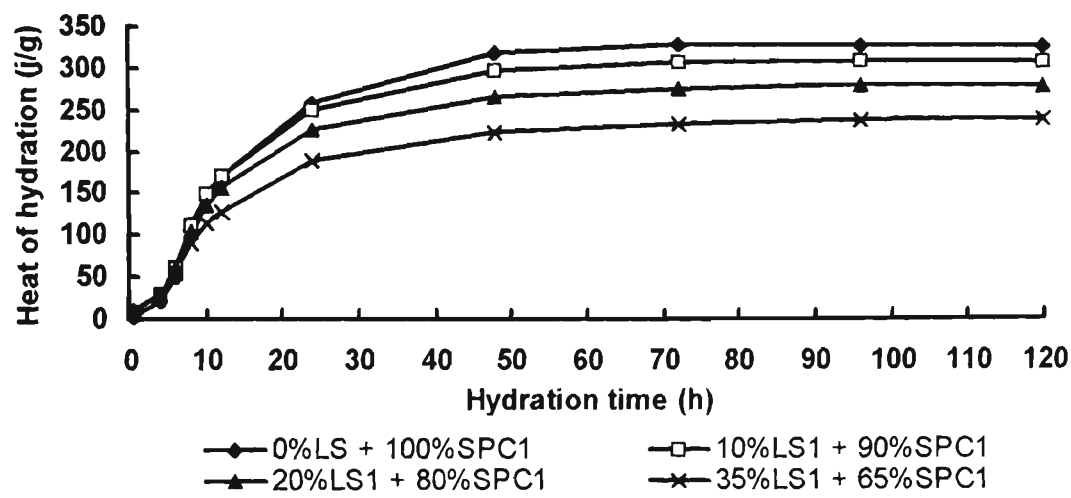


Fig. 4.23: Heat of hydration of mortars containing limestone LS1 and cement SPC1

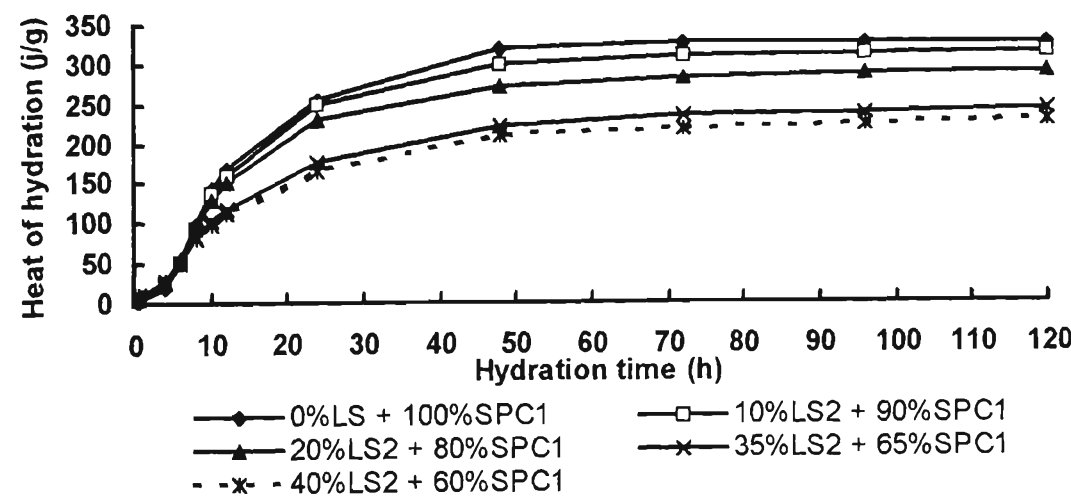


Fig. 4.24: Heat of hydration of mortars containing limestone LS2 and cement SPC1

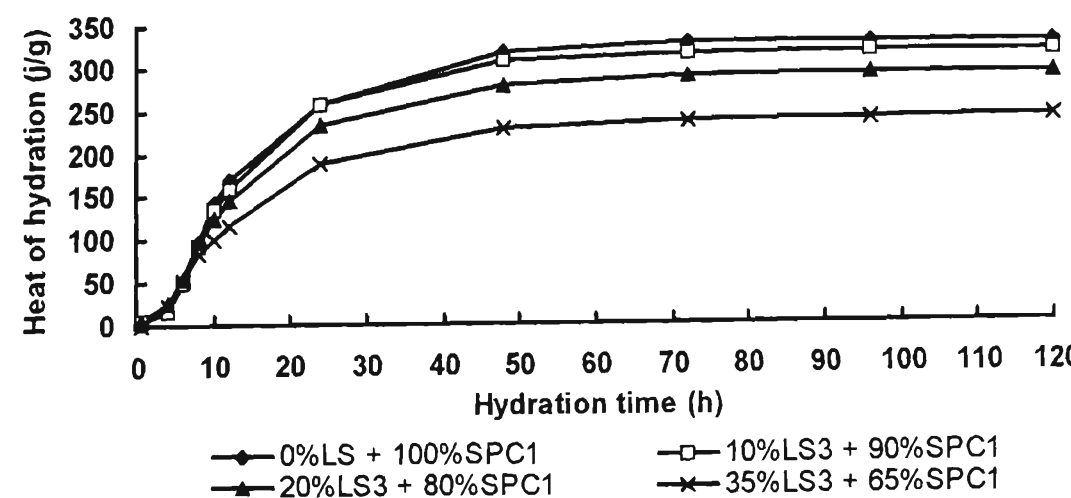


Fig. 4.25: Heat of hydration of mortars containing limestone LS3 and cement SPC1

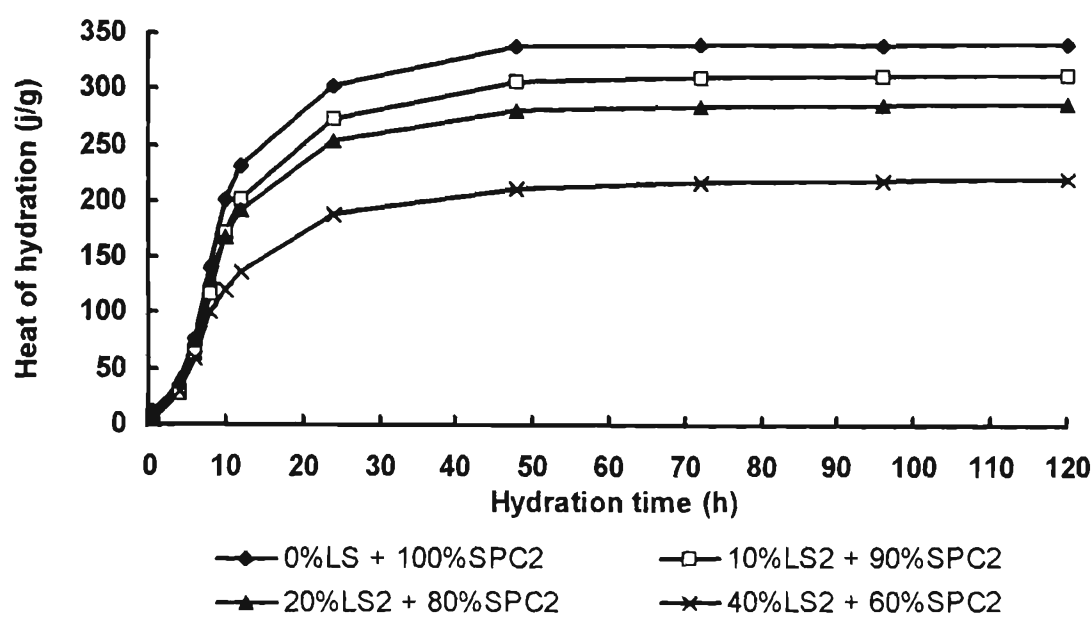


Fig. 4.26: Heat of hydration of mortars containing limestone LS2 and cement SPC2

For the use of cement SPC1 and at age of 120 h, the mortars containing 10% of limestones LS1, LS2 and LS3 had similar heat of hydration, being about 5.5%, 3.6% and 3.0%, respectively, lower than that with pure cement; while the mortars containing 20% of limestones LS1, LS2 and LS3 also had similar heat of hydration, being about 14.6%, 11.2% and 11.2%, respectively, lower than that with pure cement. Also, mortars containing 35% of limestones LS1, LS2 and LS3 had similar 120-hour heat of hydration being about 26.4% lower than that with pure cement SPC1. Heat of hydration of mortar containing 40% of limestone LS2 was about 30.4% lower than that of mortar with pure cement SPC1.

At the age of 120 h, mortars containing 10%, 20% and 40% of limestone LS2 had heat of hydration about 8.2%, 15.8% and 35.1%, respectively, lower than that with pure cement SPC2.

4.3.4.2. Formula for Calculating Reduction of Heat of Hydration in Binder Containing Milled Limestone

The above data shows that the fineness of limestone does not have much effect on the heat of hydration of mortars, however the content of limestone does have considerable effect. From the experimental data, the following formula (Eq. 4.1) that was developed (by using least square method), can be used to predict the percentage reduction of heat(of hydration of mortars containing different limestone contents.

$$R_{LS} = 0.932 X_L - 4.04$$

(Eq. 4.1)

where  $R_{LS}$  is the percentage reduction of heat of hydration of mortar containing limestone, compared with that containing pure cement at ages of 48 h, 72 h, 96 h and 120 h, and  $X_L$  is percentage of limestone (by mass) in the binder.

Fig. 4.27 presents experimental results and computed values for the percentage reduction of heat of hydration, at ages of 48 h, 72 h, 96 h and 120 h, for mortars containing limestone, compared with that containing pure cement. The experimental results and computed values are very similar, therefore, Eq. 4.1 can be useful in predicting heat of hydration for limestone modified cement mortar at ages of 48 h, 72 h, 96 h and 120 h.

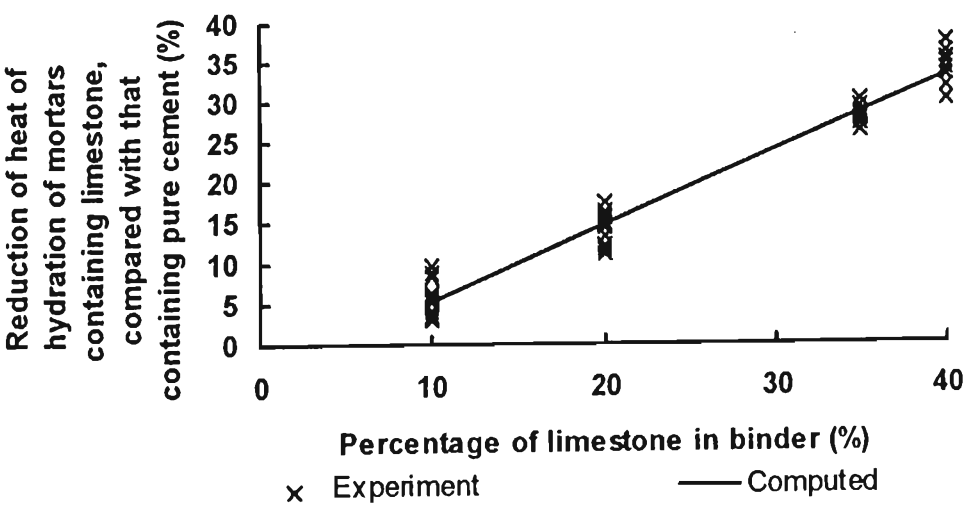


Fig. 4.27: Percentage reduction of heat of hydration for mortars containing limestone, compared with that containing pure cement

#### **4.4. SEM AND XRD ANALYSIS OF PASTES**

All specimens that were used for SEM and XRD analysis were prepared with constant water to binder ratio of 0.50. In the first study, binder pastes containing 10% of limestones LS1, LS2 and LS3 were investigated. In the second study, binder pastes containing 10%, 20% and 40% of limestones LS2 were studied. A control specimen containing pure cement SPC2 was also prepared.

Specimens were moulded in small plastic bottles which were very tightly sealed in order to eliminate any evaporation of water from the specimens. After 28 days, the specimens were demoulded and dried in an oven at 110°C for 24 hours; then the specimens were put into a desiccator prior to investigating the microstructure (using SEM). Similarly, specimens having ages of 28 days, 90 days and 180 days were prepared for investigating minerals formed during hydration of binder pastes (using XRD).

##### **4.4.1. Microstructure of Binder Pastes (Using SEM)**

Typical microstructure of binder pastes containing 0% and 10% of limestones LS1, LS2 and LS3 can be seen in Fig. 4.28, 4.29, 4.30 and 4.31, respectively. Fig. 4.32 and 4.33 show the microstructure of binder pastes containing 20% and 40%, respectively, of limestone LS2. Fig. 4.35, 4.36 and 4.37 indicate binder pastes containing pure cement and 10% of limestones LS1 and LS2, respectively.

As can be seen from Fig. 4.28 to Fig. 4.33, inclusive, the pastes containing 10%, 20% and 40% of limestones LS2 and 10% of limestone LS3 appear to have microstructures which are more uniform and exhibit less porosity (seen as microcracks) than those containing pure cement and 10% of limestone LS1. Pore sizes in pastes containing 10%



of limestones LS1 and LS2 are generally larger and smaller, respectively, than that with pure cement (Fig. 4.35, 4.36 and 4.37). This indicates that pastes containing limestones LS2 and LS3 have more uniform microstructure than those containing pure cement and 10% of limestone LS1.

Fig. 4.35, 4.36 and 4.37 also show that, in comparison with paste containing pure cement, paste containing 10% of limestone LS1 exhibits less fibrous material, with the fibres being shorter; while paste containing 10% of limestone LS2 has the least number of fibres (Fig. 4.37). This may be due to the fact that the pastes containing fine milled limestone exhibited a new hydration product, namely monocalcium carboaluminate ( $C_3A \cdot CaCO_3 \cdot 10-11 H_2O$ ) which has a different shape to the normal long fibre product, i.e. Ettringite ( $C_3A \cdot CaSO_4 \cdot 30-32 H_2O$ ). This may lead to the reduction of fibrous products in the pastes containing fine limestone. Similarly, Soroka and Setter (1977) suggested that the presence of  $CaCO_3$  suppresses the hydration of  $C_3A$  with this effect being attributed primarily to the formation of monocalcium carboaluminate on the surface of the  $C_3A$ . That is, for the conditions in hand, it may be argued that a significant formation of the monocalcium carboaluminate took place only when the fine filler was used and only a small amount, if any, was formed when coarser fillers were involved. The authors also suggested that, as the fillers accelerate the crystallisation of  $Ca(OH)_2$ , their effect on the cement hydration is brought about through accelerated hydration of tri-calcium-silicate ( $C_3S$ ); apparently this effect taking place irrespective of whether or not the monocalcium carboaluminate is formed.

#### 4.4.2. Minerals Formed in Pastes Containing Milled Limestone (XRD Analysis)

Typical X-ray diffraction patterns of pastes containing limestone modified cements are shown in Fig. 4.38 to Fig. 4.47, inclusive, and minerals analysed by using XRD can be seen in Appendix 4.6 to Appendix 4.29, inclusive.

The results shown in Appendix 4.6 to Appendix 4.29, inclusive, show that the minerals in form of calcium aluminium oxide carbonate hydrate ( $C_3A.3CaCO_3.32H_2O$  and  $C_3A.3CaCO_3.11H_2O$ ) as well as calcium aluminium oxide carbonate sulfide hydrate ( $C_3A.0.33CaSO_3.0.67CaCO_3.11H_2O$ ), were found in all pastes containing milled limestones; and calcite ( $CaCO_3$ ) was not found in all pastes containing 10% of limestones LS1, LS2 and LS3. In addition, at ages of 28 and 90 days, paste containing SPC2 and 20% of limestone LS2 contained calcite ( $CaCO_3$ ) (No. 56-0586 in Appendix 4.6 to Appendix 4.29, inclusive) which does not appear in paste containing SPC2 and 10% of limestone LS2. This indicates that the total content of calcite ( $CaCO_3$ ) in paste containing 10% of limestone LS2 may react with  $C_3A$ ; while only a part of the  $CaCO_3$  in paste containing 20% of limestone LS2, which had calcite content larger than that that with 10% of limestone LS2, reacted with  $C_3A$ . However, at ages of 180 days, calcite ( $CaCO_3$ ) is not found in pastes containing cement SPC2 with 10% and 20% of limestone LS2, i.e, after a long period of hydration, the total content of calcite  $CaCO_3$  has reacted with  $C_3A$ . Similarly, this phenomena also occurred for pastes containing cement SPC1 with 10% and 20% of limestone LS2.

Nesquehonite,  $MgCO_3.3H_2O$  (No. 56-0669 in Appendix 4.6 to Appendix 4.29, inclusive) was found in all pastes containing the three sources of milled limestones, at ages of 28, 90 and 180 days. This showed that nesquehonite is chemically less reactive than calcite.

In summary, the microstructure of pastes containing milled limestones LS2 and LS3 was more uniform than those containing pure cement and 10% of milled limestone LS1. Calcite ( $\text{CaCO}_3$ ) in milled limestones reacts mainly with minerals containing  $\text{C}_3\text{A}$  in portland cements to form compounds containing aluminium oxide, such as calcium aluminium oxide carbonate hydrate,  $\text{C}_3\text{A} \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$ ,  $\text{C}_3\text{A} \cdot 3\text{CaCO}_3 \cdot 11\text{H}_2\text{O}$  and calcium aluminium oxide carbonate sulfide hydrate,  $\text{C}_3\text{A} \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3 \cdot 11\text{H}_2\text{O}$ .

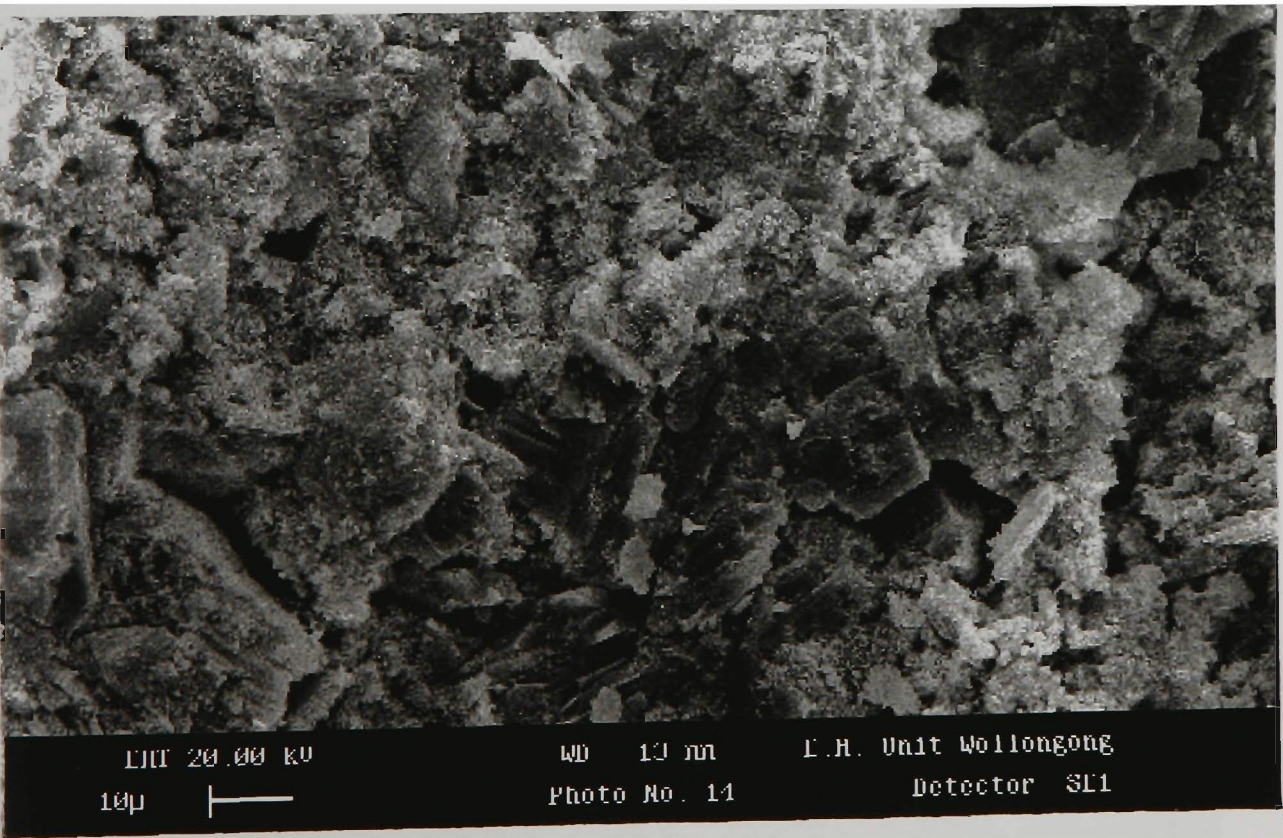


Fig. 4.28: Microstructure of paste containing pure cement SPC2 (low magnification)



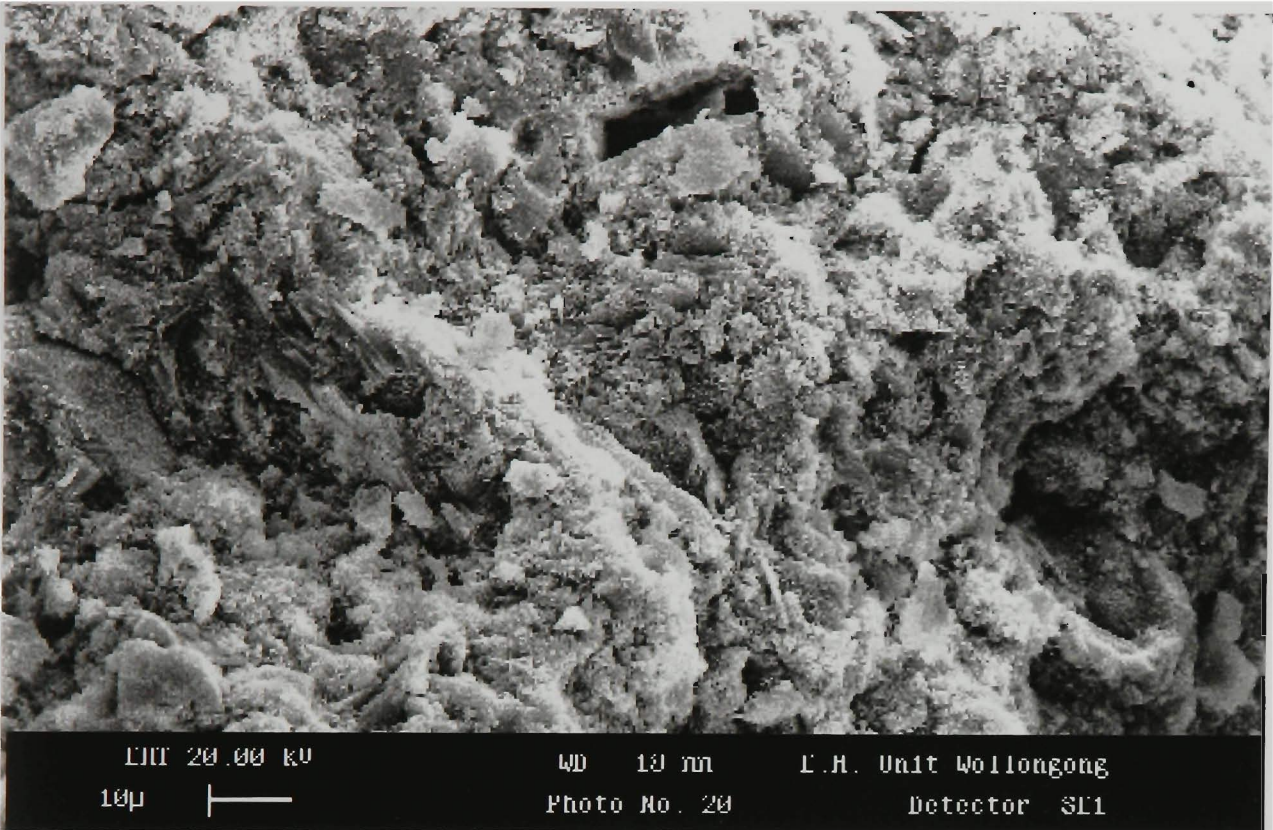


Fig. 4.29: Microstructure of paste containing cement SPC2 and 10% of limestone LS1 (low magnification)

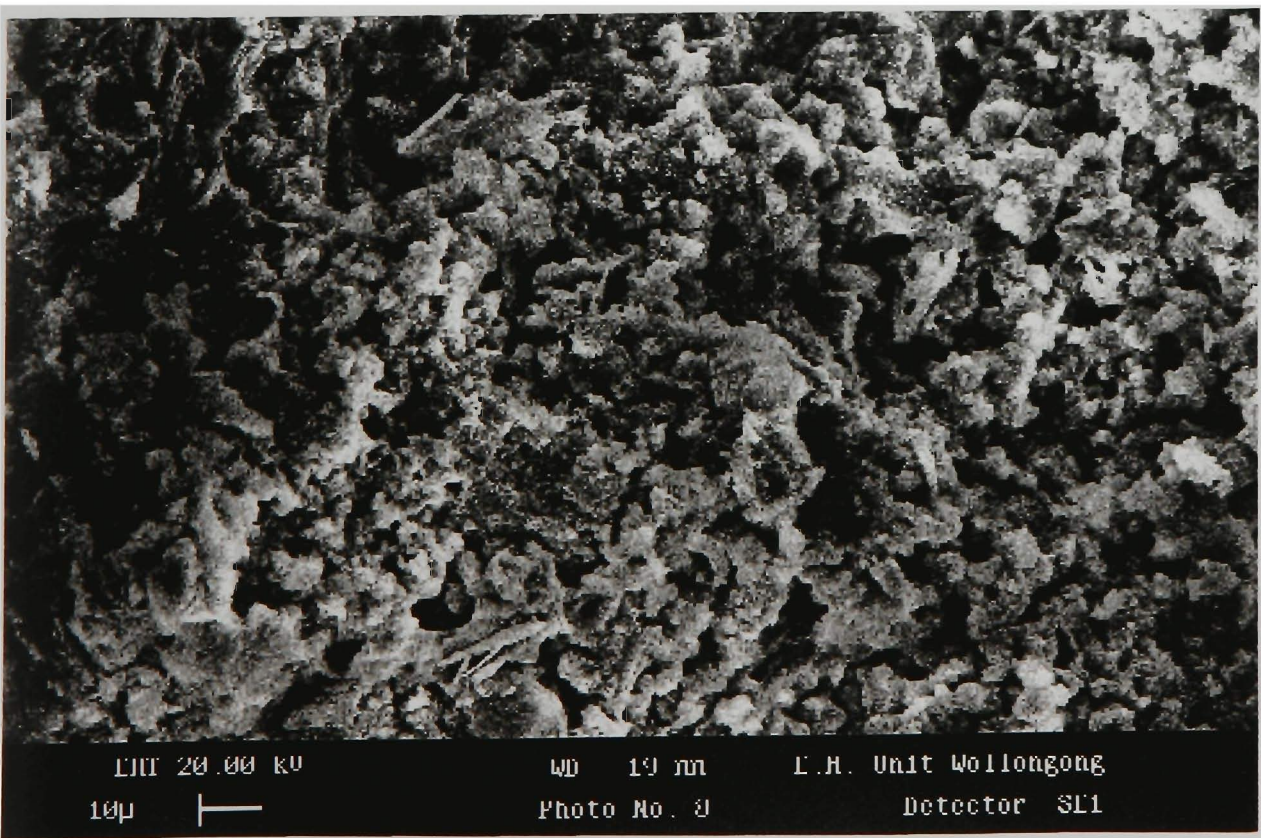


Fig. 4.30: Microstructure of paste containing cement SPC2 and 10% of limestone LS2 (low magnification)



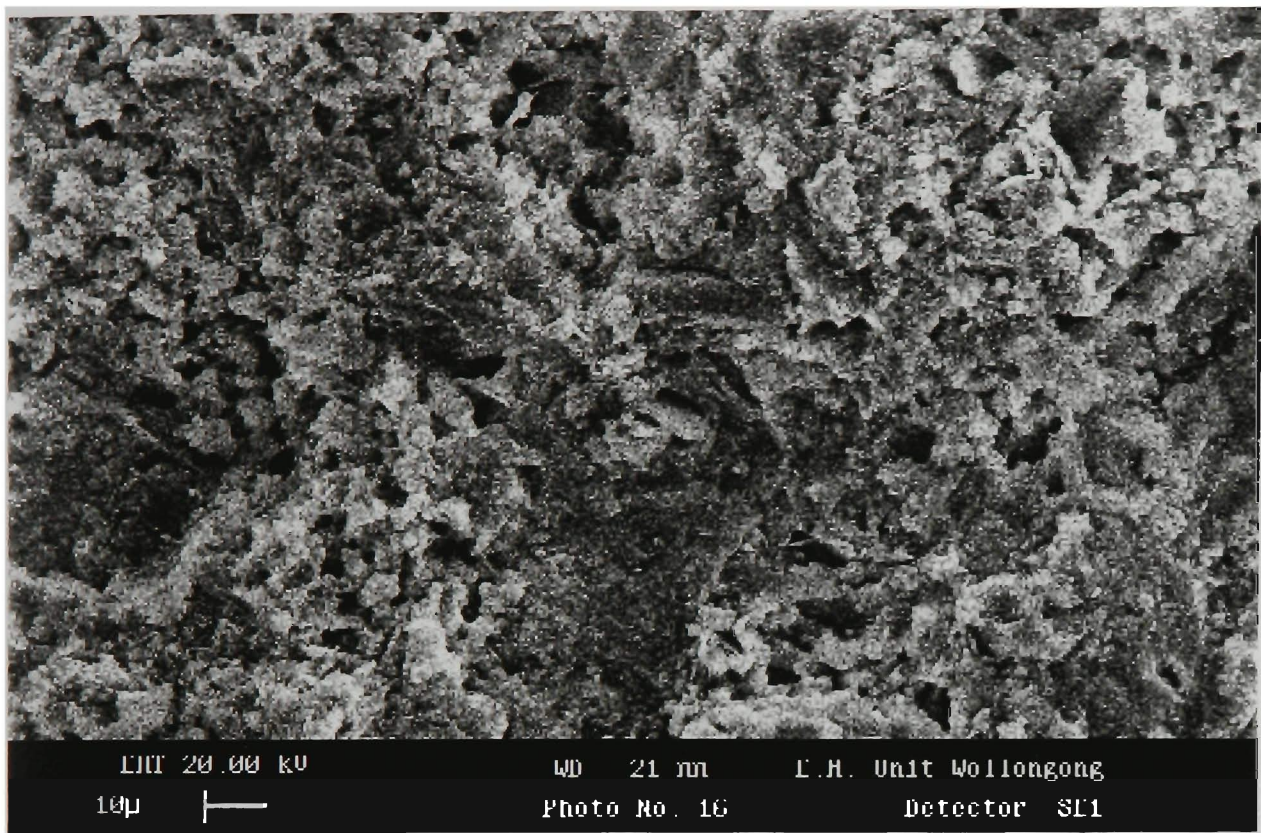


Fig. 4.31: Microstructure of paste containing cement SPC2 and 10% of limestone LS3

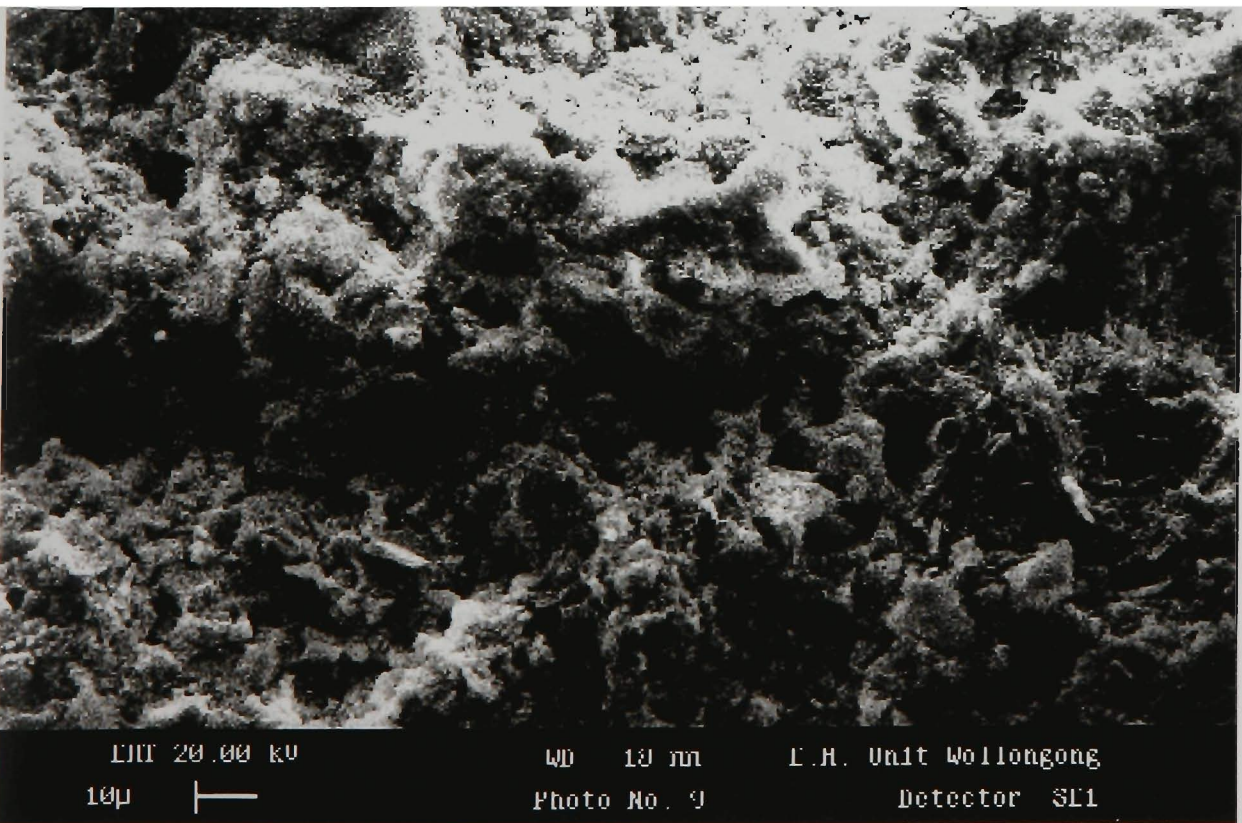


Fig. 4.32: Microstructure of paste containing cement SPC2 and 20% of limestone LS2



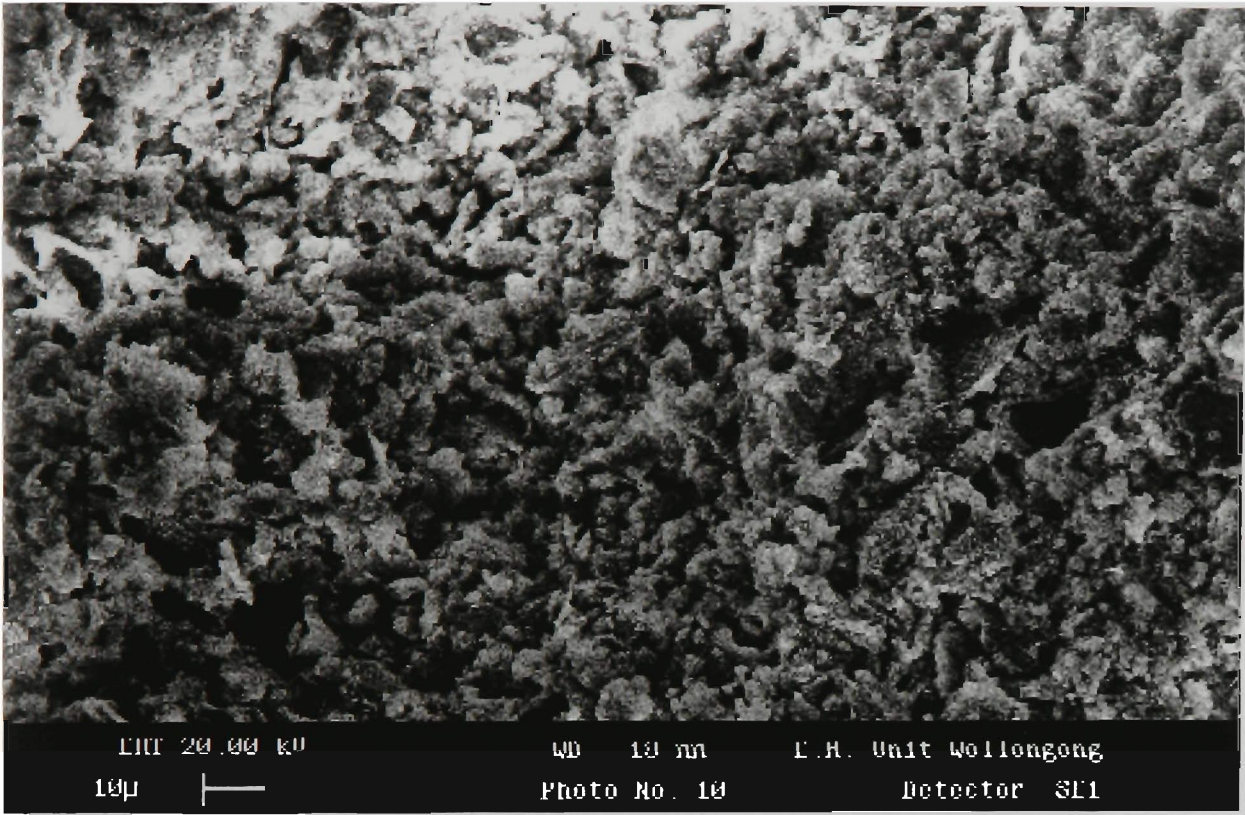


Fig. 4.33: Microstructure of paste containing cement SPC2 and 40% of limestone LS2

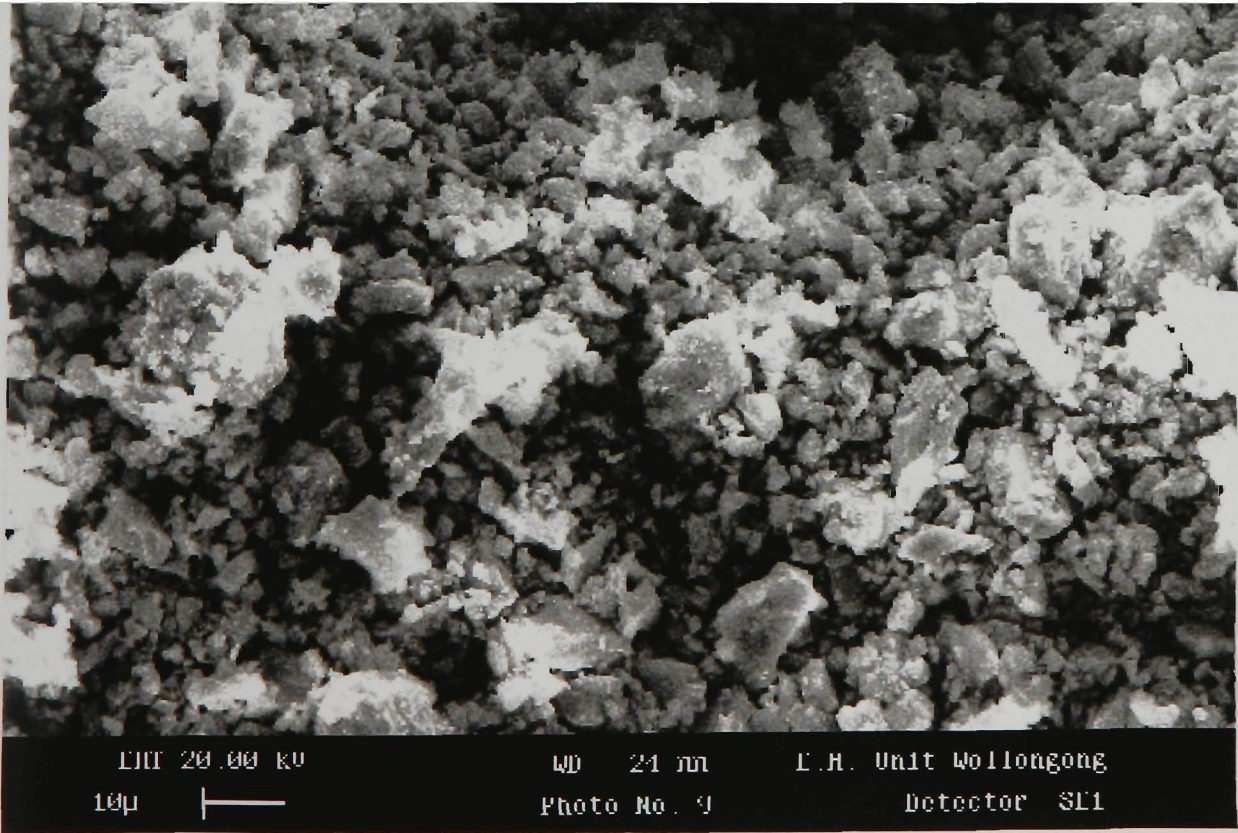


Fig. 4.34: Microstructure of limestone LS2





Fig. 4.35: Microstructure of paste containing pure cement SPC2 (high magnification)



Fig. 4.36: Microstructure of paste containing cement SPC2 and 10% of limestone LS1 (high magnification)



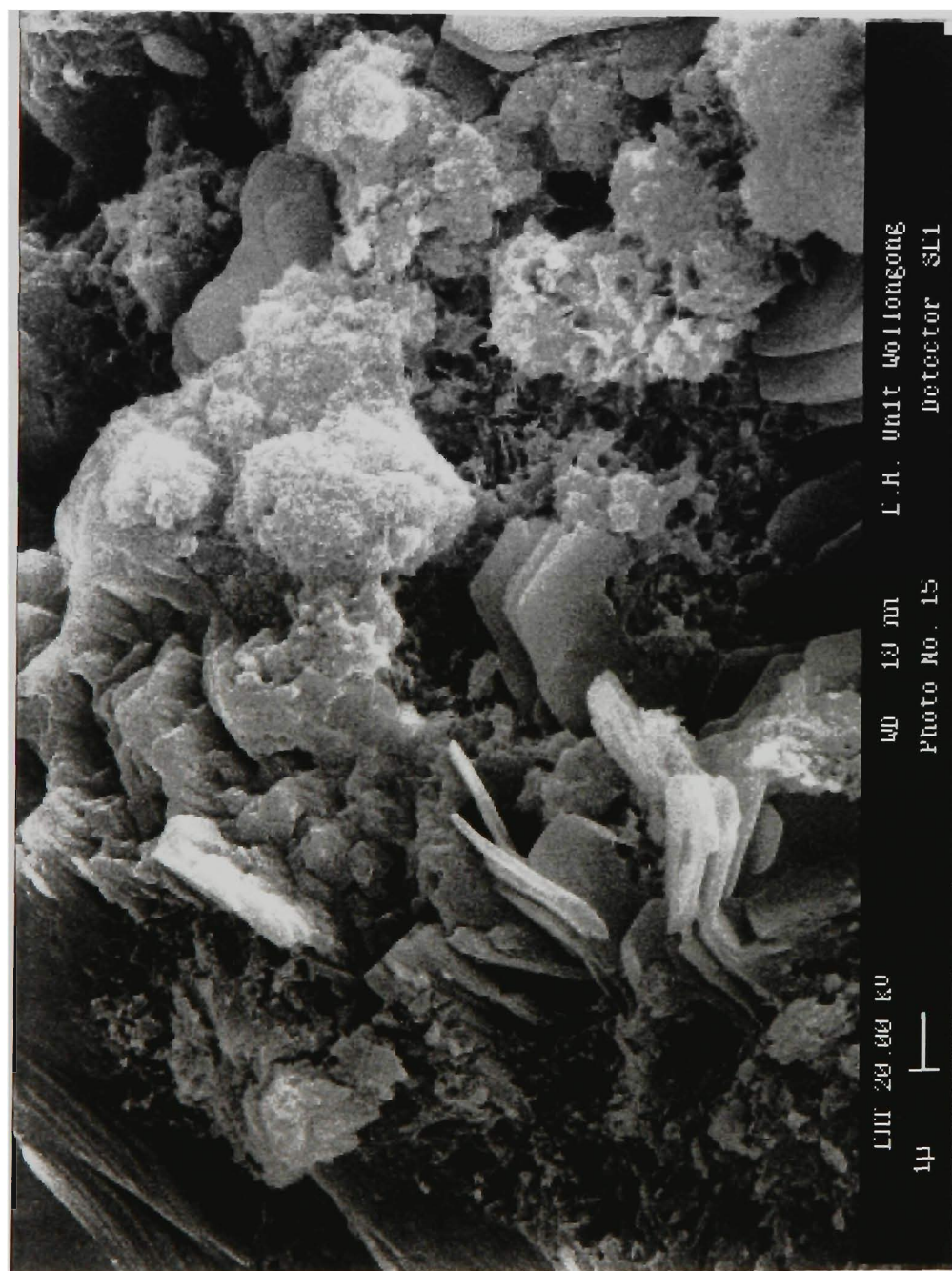


Fig. 4.37: Microstructure of paste containing cement SPC2 and 10% of limestone LS2 (high magnification)

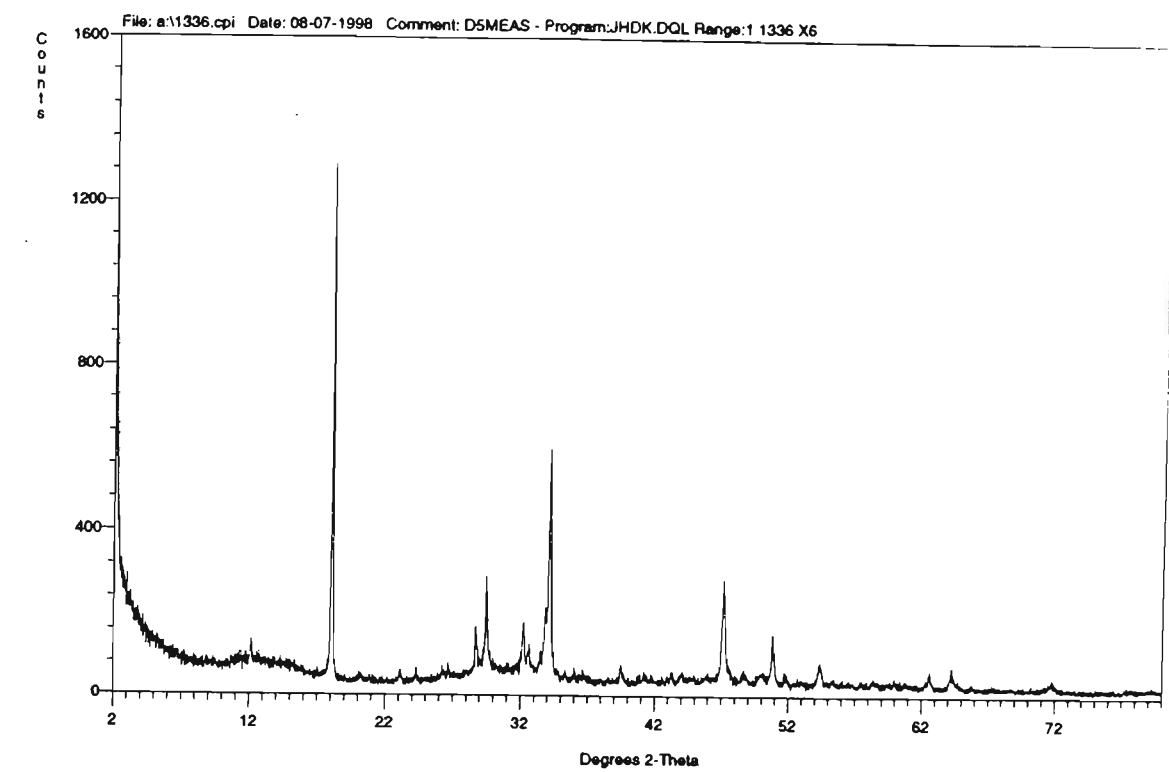


Fig. 4.38: XRD-patterns of pastes containing SPC1 and 10% of limestone LS1 (age of 28 days)

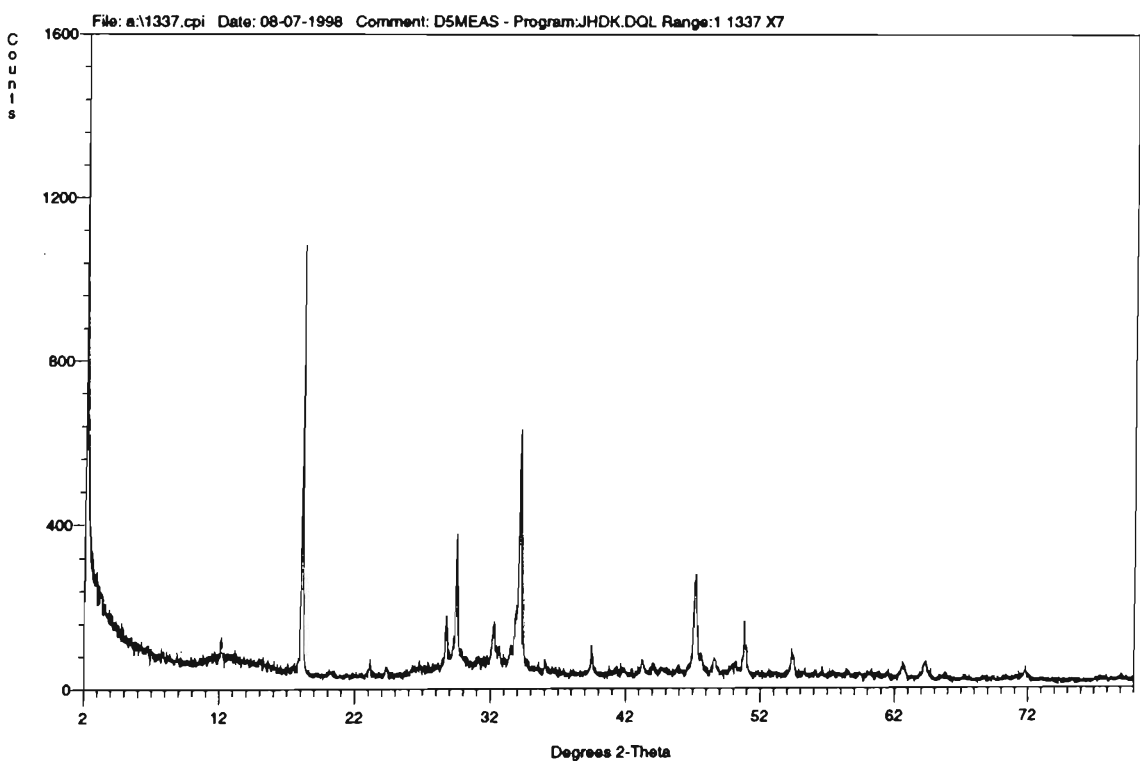


Fig. 4.39: XRD-patterns of pastes containing SPC1 and 10% of limestone LS2 (age of 28 days)

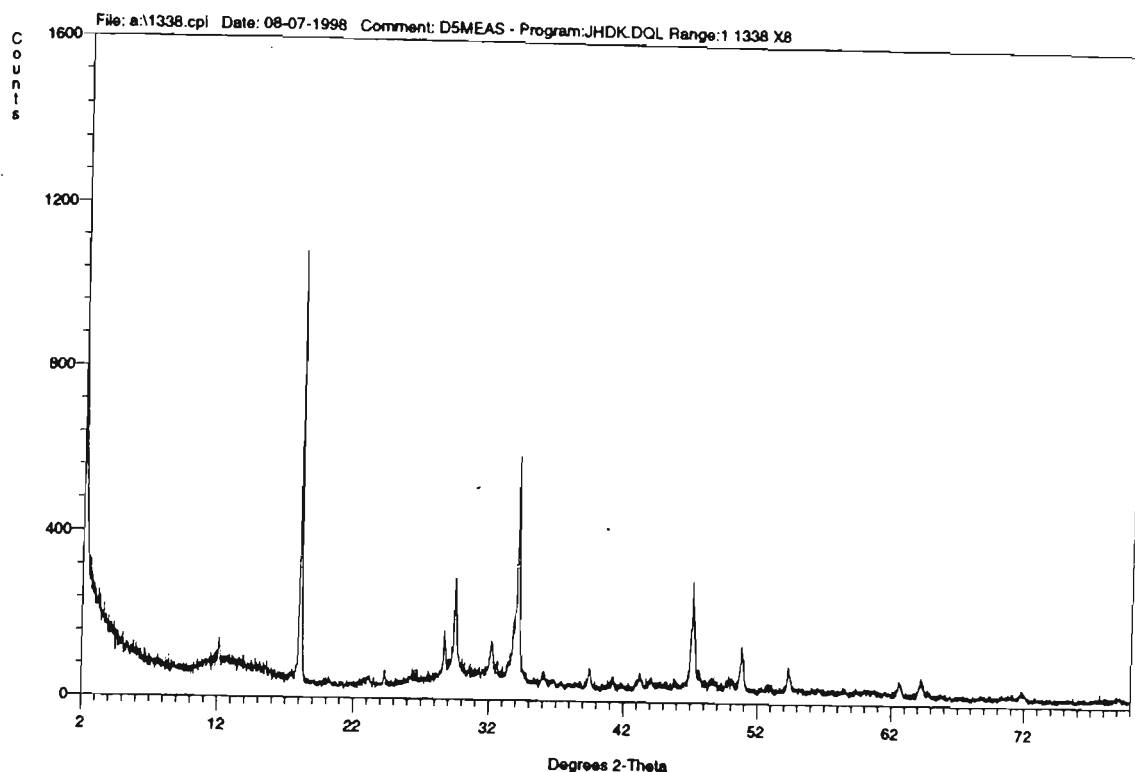


Fig. 4.40: XRD-patterns of pastes containing cement SPC1 and 10% of limestone LS3 (age of 28 days)

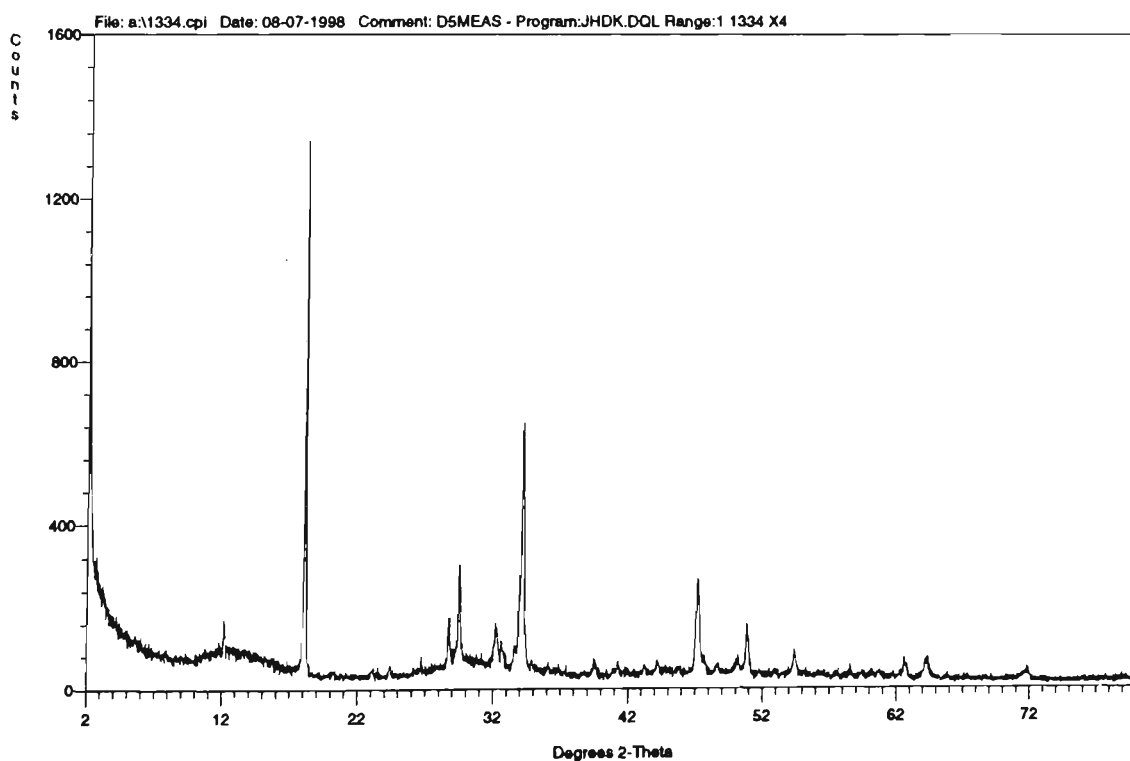


Fig. 4.41: XRD-patterns of pastes containing SPC2 and 10% of limestone LS1 (age of 28 days)

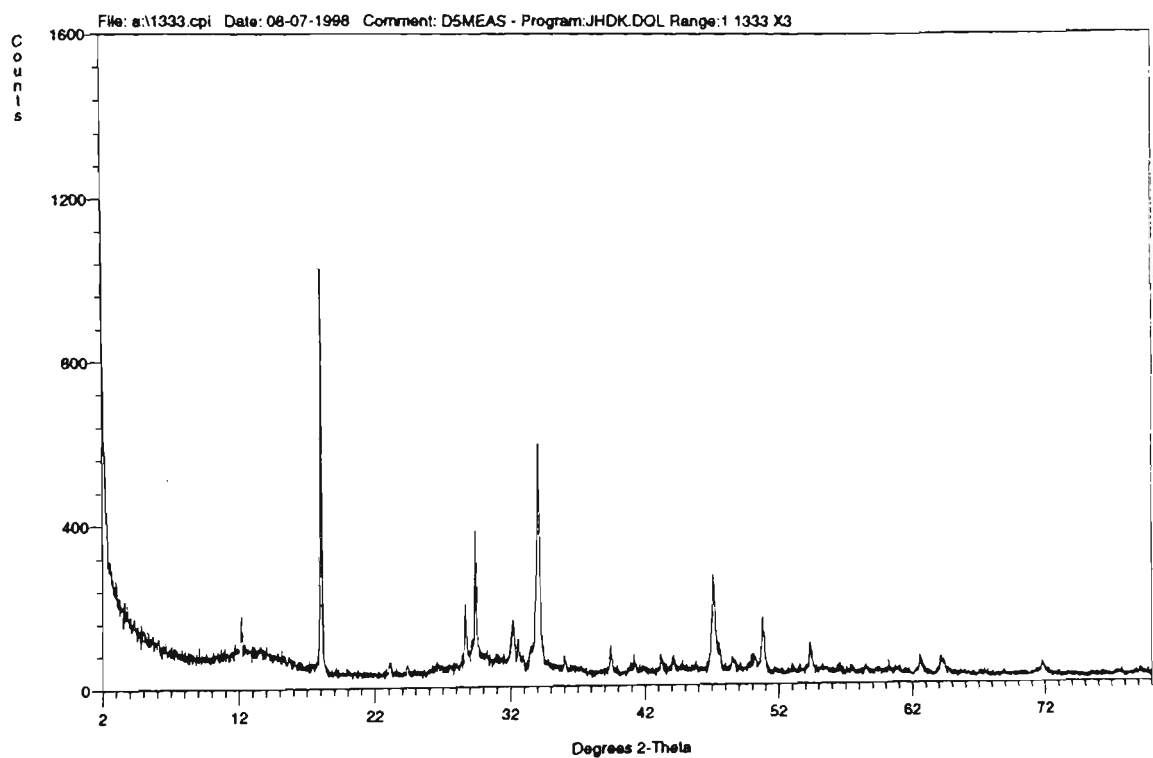


Fig. 4.42: XRD-patterns of pastes containing SPC2 and 10% of limestone LS2 (age of 28 days)

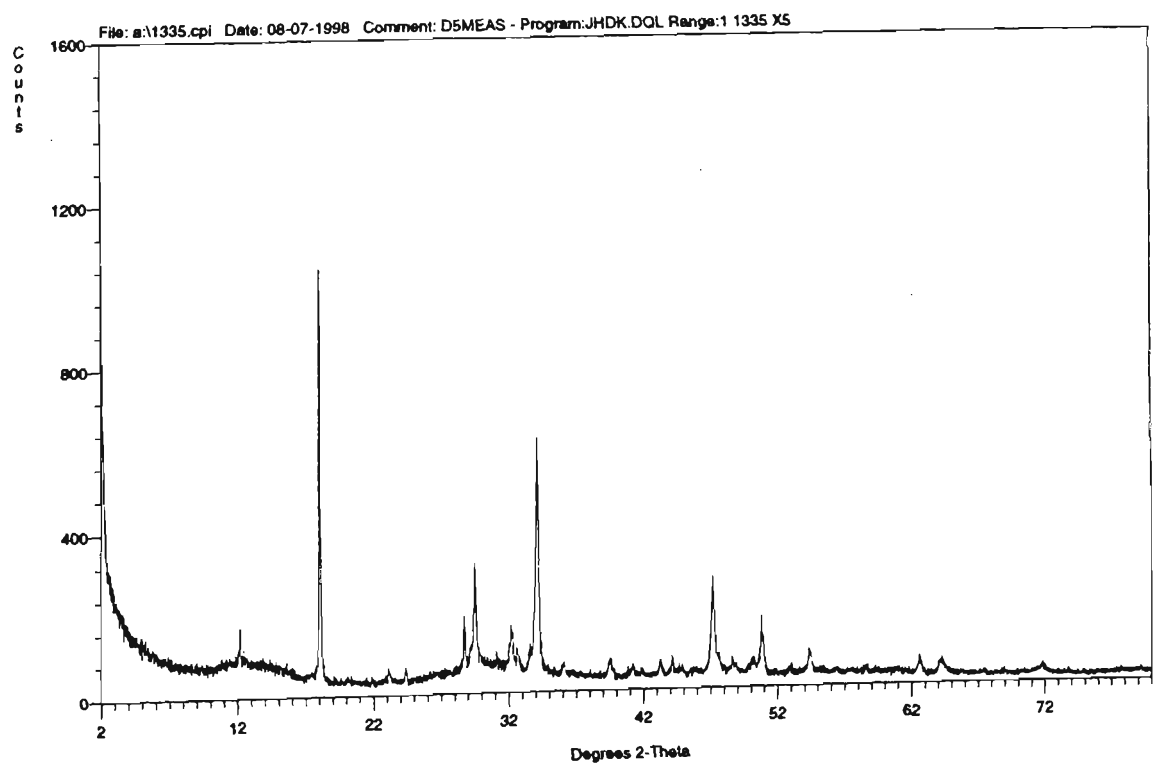


Fig. 4.43: XRD-patterns of pastes containing cement SPC2 and 10% of limestone LS3 (age of 28 days)

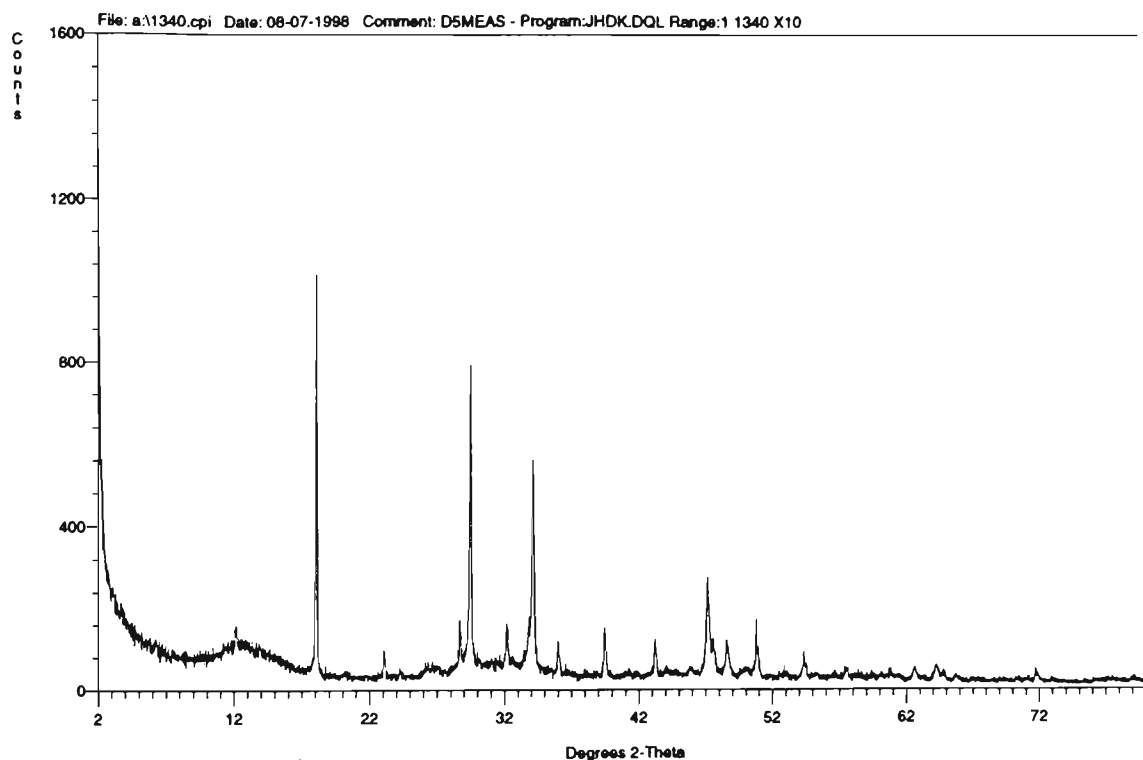


Fig. 4.44: XRD-patterns of pastes containing SPC1 and 20% of limestone LS2 (age of 28 days)

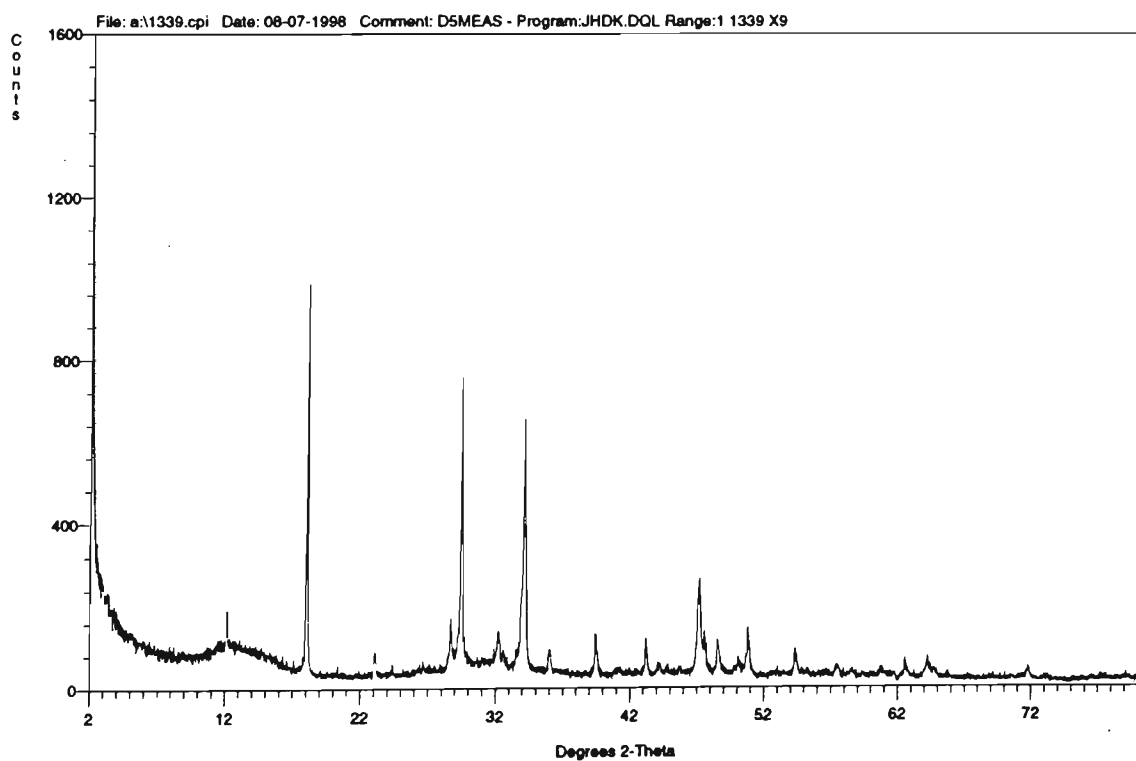


Fig. 4.45: XRD-patterns of pastes containing cement SPC2 and 20% of limestone LS2 (age of 28 days)

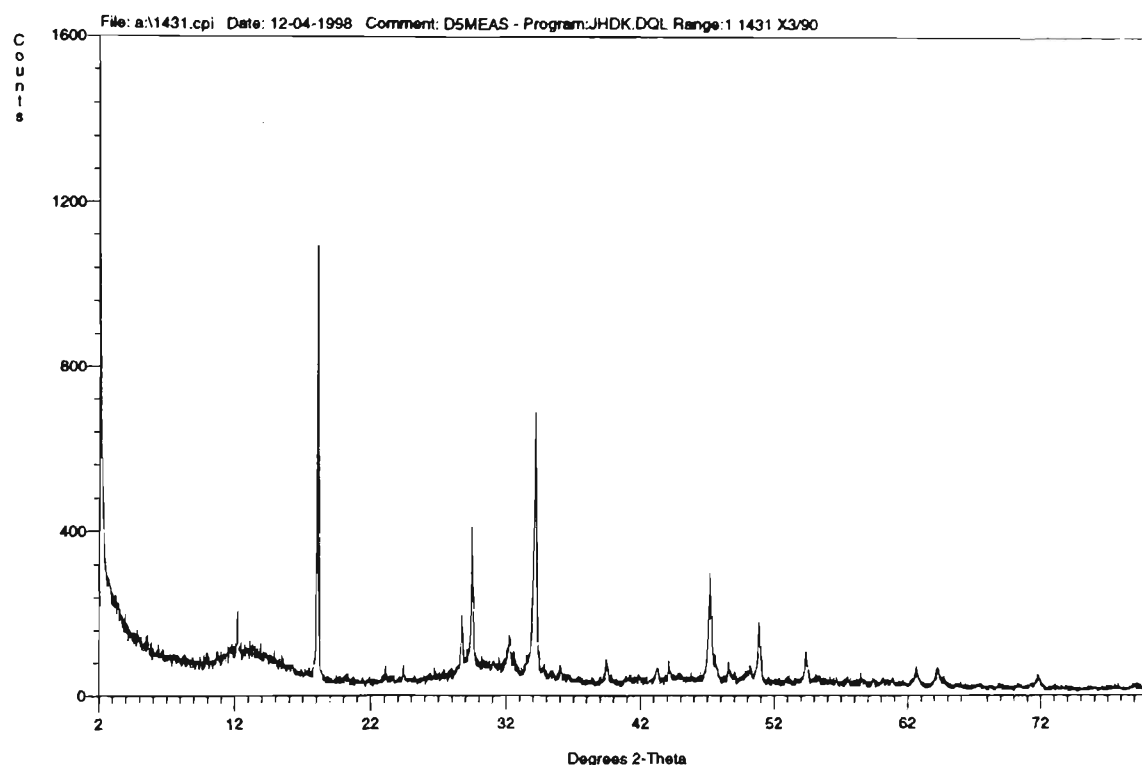


Fig. 4.46: XRD-patterns of pastes containing SPC2 and 10% of limestone LS2 (age of 90 days)

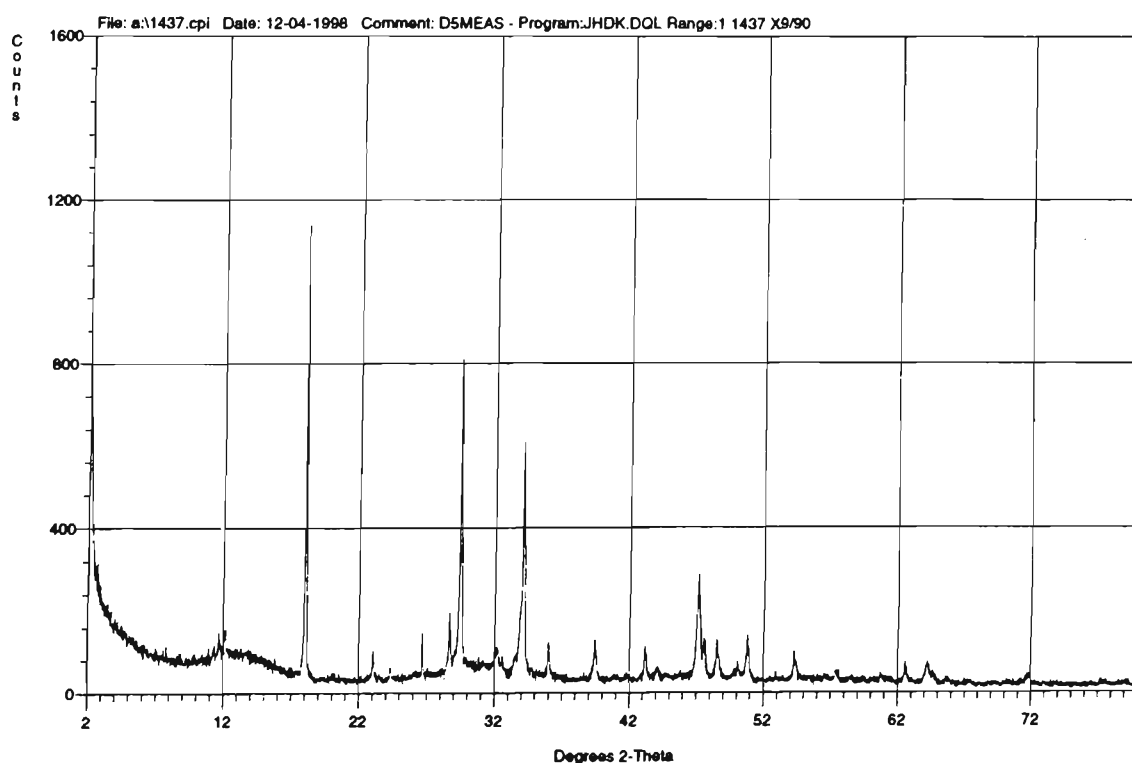


Fig. 4.47: XRD-patterns of pastes containing cement SPC2 and 20% of limestone LS2 (age of 90 days)

#### 4.5. SUMMARY

Pastes containing milled limestones of different fineness and replacement contents required different amounts of mixing water in order to achieve normal consistence of the binder pastes. Suitable content of milled limestone with average particle size about three to six times smaller than mean particle size of cement can reduce the required amount of mixing water for normal consistence. There is an optimum content of limestone of each fineness which can enhance the lowest amount of mixing water for normal consistence. Setting times of binders containing milled limestone were shorter than those of pure cement, however they all meet the requirement of Australian Standard AS2350.4 (1988).

For constant water content, mortars containing milled limestones exhibited 28-day compressive strength lower than those with pure cement. The use of fine and very fine limestones improved compressive strength of mortars in comparison with that containing coarse limestone. For similar flow values, mortars containing fine and very fine limestone required less water content than those with coarse limestone and pure cements. This led to the improvement of compressive strength of the mortars containing fine and very fine milled limestone. Superplasticizer had the greatest effect when combined with very fine limestone.

The use of fine and very fine milled limestones significantly reduced the drying shrinkage of mortars at ages greater than 7 days in comparison with those of mortars containing coarse limestone or pure cements. However, at age of 7 days, drying shrinkages of mortars containing milled limestones were generally higher than those of mortars containing pure cements. This can be explained by the fact that the high content of free

water in mortars with milled limestones resulted in high evaporation of water during the first seven days and thus led to high drying shrinkage at this age.

The use of milled limestones with suitable fineness and replacement content can improve workability and drying shrinkage of binder paste and mortar. Microstructure of pastes containing fine and very fine milled limestones was more uniform than those containing pure cement and coarse milled limestone.  $\text{CaCO}_3$  in milled limestones reacts mainly with minerals containing  $\text{C}_3\text{A}$  in portland cements to form compounds containing aluminium oxides, such as calcium aluminium oxide carbonate hydrate  $\text{C}_3\text{A}.3\text{CaCO}_3.32\text{H}_2\text{O}$ ,  $\text{C}_3\text{A}.3\text{CaCO}_3.11\text{H}_2\text{O}$  and calcium aluminium oxide carbonate sulfide hydrate,  $\text{C}_3\text{A}.0.33\text{CaSO}_3.0.67\text{CaCO}_3.11\text{H}_2\text{O}$ .

The use of milled limestones can significantly reduce the heat of hydration of the binder. Higher content of limestone resulted in larger reduction of heat of hydration. The proposed model can be used to predict the reduction of the heat of hydration for mortars containing milled limestone, at ages of 48 h, 72 h, 96 h and 120 h, in comparison with those containing pure cements.



## CHAPTER 5

### VIBRATED HIGH PERFORMANCE CONCRETE CONTAINING LIMESTONE MODIFIED CEMENTS

#### 5.1. MATERIALS AND EXPERIMENTAL PROGRAM

##### 5.1.1. Materials

Three sources of limestone were utilised together with shrinkage limited portland cements (SPC1 and SPC2). The specific gravity, fineness and chemical analysis of the cements and limestones, nominated as LS1, LS2 and LS3, are shown in Appendix 3.1. River sand and crushed basalt coarse aggregate with maximum sizes of 20 mm, 14 mm and 10mm (specified as A, C and E, respectively, in Appendix 3.2) were used in concrete testing. Particle size distributions are given in Appendix 3.2. Naphthalene sulphonate-formaldehyde condensate superplasticizer in dry form was used in all tests.

##### 5.1.2. Experimental Program

Mixture proportions and properties of high-performance concrete are given in Appendix 5.1 and 5.2. Fine to total aggregate ratio of 0.45 was maintained in all tests. The testing parameters studied were superplasticizer requirement, compressive strength and drying shrinkage. The tests of compressive strength and drying shrinkage of concrete were carried out according to Australian Standards AS 1012.9 and AS 1012.13, respectively. In a preliminary program, concretes containing pure cement, 10% of limestone LS1, LS2 and LS3 with water to binder ratio of 0.35 and 0.32 were tested in order to determine the most suitable limestone. In a secondary program, concretes containing 10%, 20%, 30% and 40% of limestone LS2 with water to binder ratios of 0.28, 0.30, 0.32 and 0.35 were investigated. The preliminary and secondary programs were carried

out in order to study the effects of fineness and content of milled limestone on properties of vibrated high performance concrete (V-HPC). Subsequently, the effect of coarse aggregate with different maximum sizes on properties of the concrete was also investigated by the use of limestone LS2 and coarse aggregate with maximum sizes of 20 mm and 14 mm. Finally, normal vibrated concrete containing limestone LS2 with less binder content and high water to cement ratios was investigated in order to check if limestone modified cements are beneficial for use in normal vibrated concrete which is defined as vibrated concrete having 28-day compressive strength of less than 50 MPa.

## **5.2. EFFECT OF FINENESS AND CONTENTS OF MILLED LIMESTONE ON PROPERTIES OF VIBRATED HIGH PERFORMANCE CONCRETE**

### **5.2.1. Preliminary Program with Different Types of Limestone**

In this program, concretes containing constant binder content of  $488 \text{ kg/m}^3$  and 10% of limestones LS1, LS2 and LS3 were tested. The cement SPC2 was used in all tests. Water to binder ratios of 0.35 and 0.32 were used, and superplasticizer dosages were adjusted to achieve slump of about 200mm.

#### *Superplasticizer Requirement:*

For constant binder content of  $488 \text{ kg/m}^3$  and water to binder ratio of 0.35, concretes containing 10% of limestones LS1 and LS2 required superplasticizer dosage similar to, and considerably lower than, respectively, that with pure cement (Fig. 5.1). For constant binder content of 488 kg, concretes containing 10% of limestone LS2 and LS3 with water to binder ratio of 0.32 demanded superplasticizer dosage of 4.4% and 14.1%, respectively, lower than that with pure cement and water to cement ratio of 0.35 (Fig.5.2). This indicated that for similar superplasticizer dosages, concretes containing

limestones LS2 and LS3 require less water content in order to achieve slumps similar to that of concrete containing pure cement. This can be explained by the fact that limestones LS2 and LS3, which had average particle sizes of about 3 and 6 times, respectively, smaller than that of pure cement SPC2, resulted in better particle packing of the concrete. The use of limestone LS1 which had an average particle size larger than that of the pure cement could not improve the workability of V-HPC, although the concrete containing limestone LS1 had a unit paste volume higher than that of the pure cement (for the same binder content and water to binder ratio, concrete containing limestone LS1 with lower specific gravity results in higher unit paste volume of concrete). (The unit paste volume is defined as a paste volume in 1 m<sup>3</sup> concrete, which includes binder, water, superplasticizer and air).

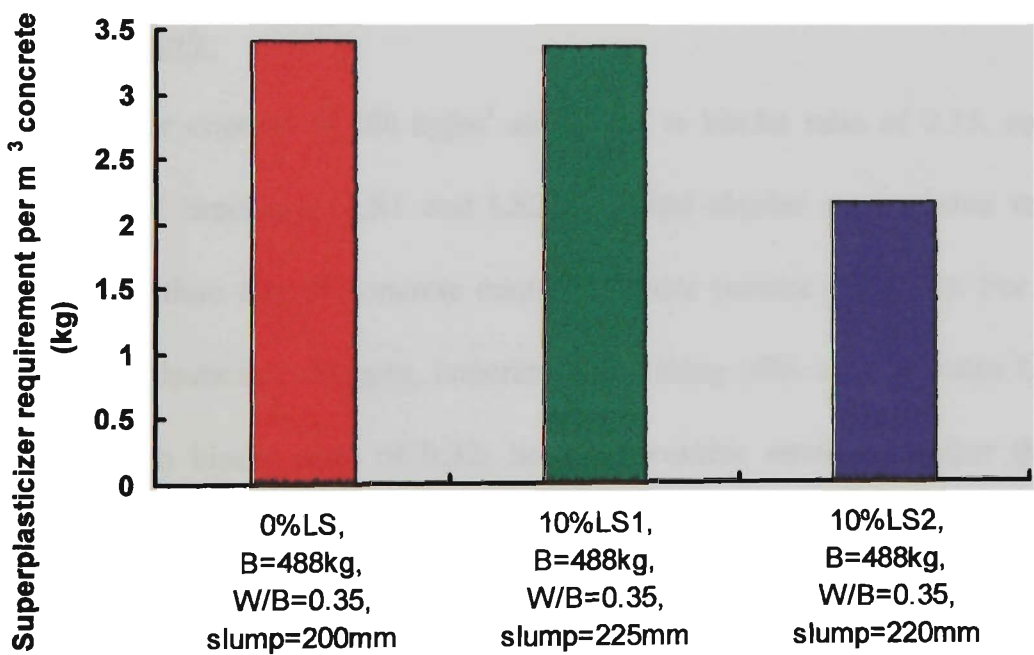


Fig. 5.1: Superplasticizer requirement of V-HPC containing limestones LS1 and LS2 and pure cement SPC2 (W/B = 0.35)

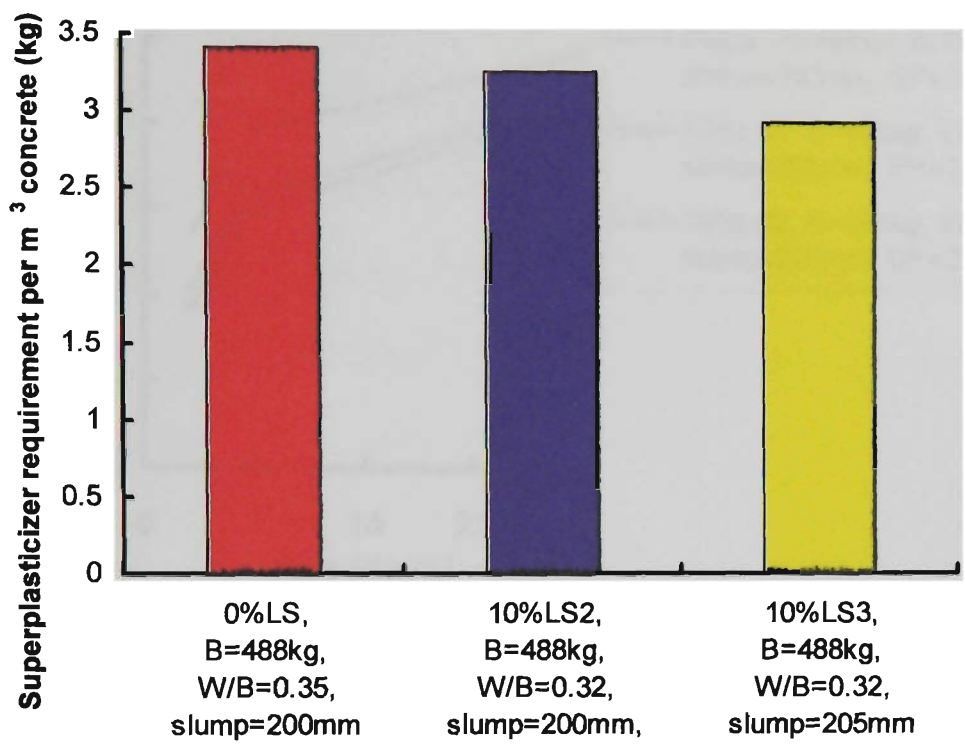


Fig. 5.2: Superplasticizer requirement of V-HPC containing limestones LS2 and LS3 (W/B = 0.32) and pure cement SPC2 (W/B = 0.35)

Compressive Strength:

For constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.35, concretes containing 10% of limestones LS1 and LS2 exhibited similar compressive strengths which were lower than that of concrete containing pure cement (Fig. 5.3). For similar slumps and superplasticizer dosages, concretes containing 10% of limestones LS2 and LS3, with water to binder ratio of 0.32, had compressive strengths higher than and similar to, respectively, that of concrete containing pure cement with water to binder ratio of 0.35 (Fig. 5.4). The results indicate that fineness of limestone plays an important role in improving workability of V-HPC, and compressive strength is improved only if there is reduced water demand for V-HPC.

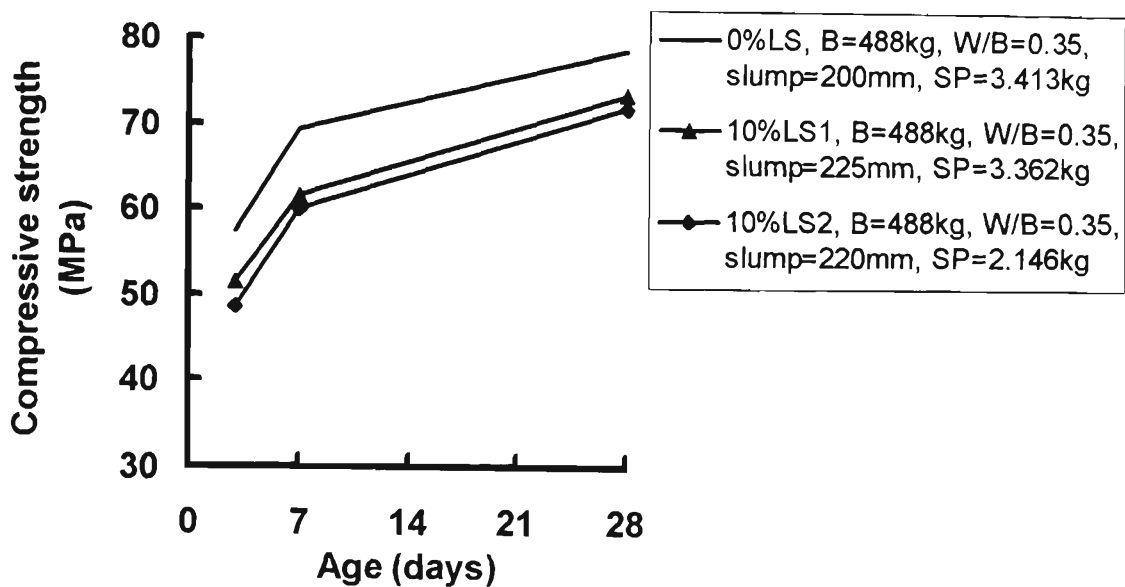


Fig. 5.3: Compressive strength of V-HPC containing limestones LS1 and LS2 and pure cement SPC2 (W/B = 0.35)

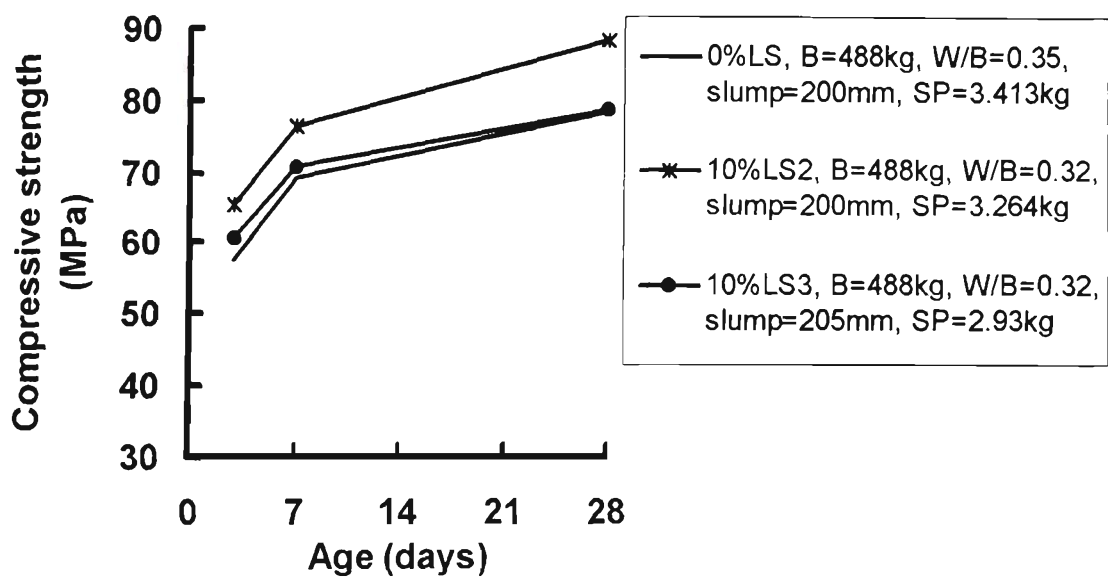


Fig. 5.4: Compressive strength of V-HPC containing limestones LS2 and LS3 (W/B = 0.32) and pure cement SPC2 (W/B = 0.35)

Drying Shrinkage:

Fig. 5.5 shows that, for constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.35, concrete containing 10% of limestone LS1 and LS2 exhibited drying shrinkage higher and lower, respectively, than that containing pure cement. Fig. 5.5 also indicates

that for constant binder content of 488 kg/m<sup>3</sup>, concretes containing 10% of limestones LS2 and LS3, with water to binder ratio of 0.32, had similar drying shrinkages which were considerably lower than that of concrete containing pure cement with water to binder ratio of 0.35. The test results indicate that the use of limestone LS2 and LS3 in high-performance concrete can reduce drying shrinkage, while the use of limestone LS1 had a negative impact on this property.

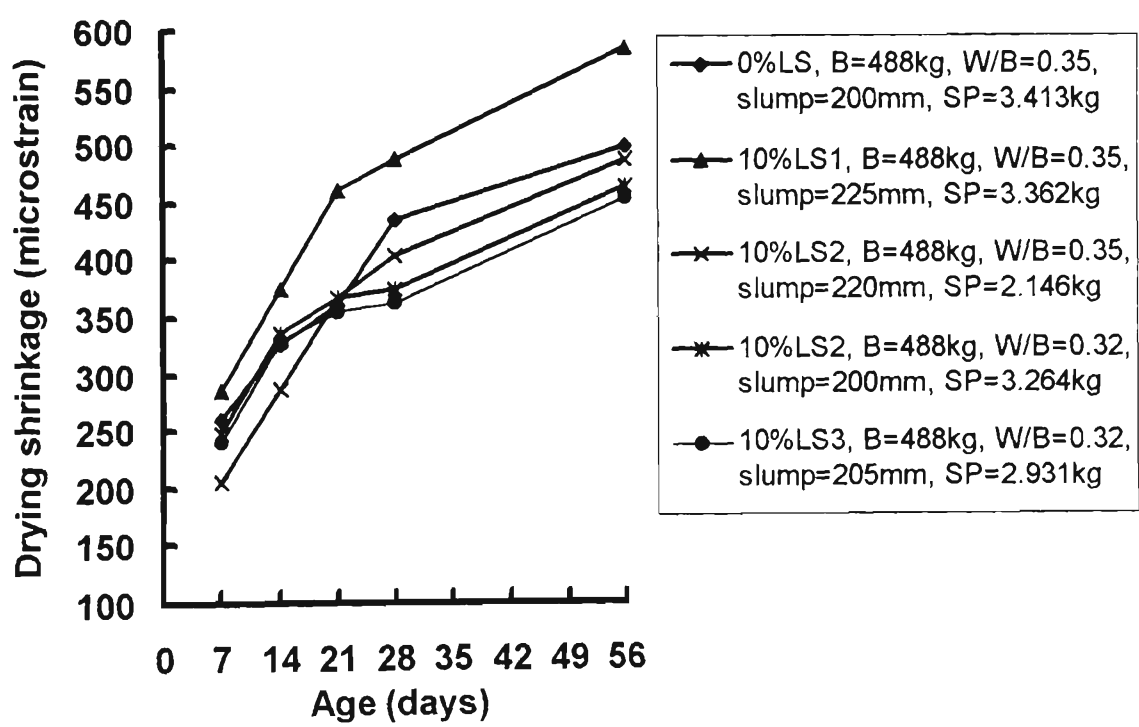


Fig. 5.5: Drying shrinkage of V-HPC containing different limestone types

As discussed previously, the fineness (as measured by fineness index, i.e. Blaine) of milled limestone had an effect on water demand and drying shrinkage of V-HPC. Limestones LS2 and LS3, which had mean particle sizes about 3 and 6 times, respectively, smaller than pure cement SPC2, reduced drying shrinkage and water demand of V-HPC in comparison to V-HPC with limestone LS1 and pure cement. When considering superplasticizer requirement, compressive strength and drying shrinkage of

concrete of V-HPC, limestone LS2 is the most suitable of the three tested limestones.

### 5.2.2. Secondary Program with Different Contents of Limestone LS2

As the preliminary program indicated that limestone LS2 is the most suitable of the three limestone types, concretes containing 10%, 20%, 30% and 40% of limestone LS2 were investigated in the secondary program. Four test groups were investigated in the secondary program as follows:

Group 1: binder content of  $488 \text{ kg/m}^3$ , water to binder ratio of 0.35 with 0%, 10%, 20%, 30% and 40% of limestone LS2, slump of about 200 mm;

Group 2: binder content of  $488 \text{ kg/m}^3$ , water to binder ratio of 0.32 with 10%, 20% and 30% of limestone LS2, slump of about 200 mm;

Group 3: binder content of  $500 \text{ kg/m}^3$ , water to binder ratio of 0.30 with 10%, 20% and 30% of limestone LS2, slump of about 200 mm; and

Group 4: 40% of limestone LS2 with binder contents of  $488 \text{ kg/m}^3$  and  $500 \text{ kg/m}^3$  and water to binder ratios of 0.30 and 0.28, respectively, were used to manufacture concrete specimens having slump of about 200 mm.

#### Superplasticizer Requirement:

For similar slumps, constant binder content of  $488 \text{ kg/m}^3$  and water to binder ratio of 0.35, concretes containing 10%, 20%, 30% and 40% of limestone LS2 required

superplasticizer dosage 37.1%, 32.4%, 32.4% and 41.4% , respectively, lower than that with pure cement (Fig. 5.6).

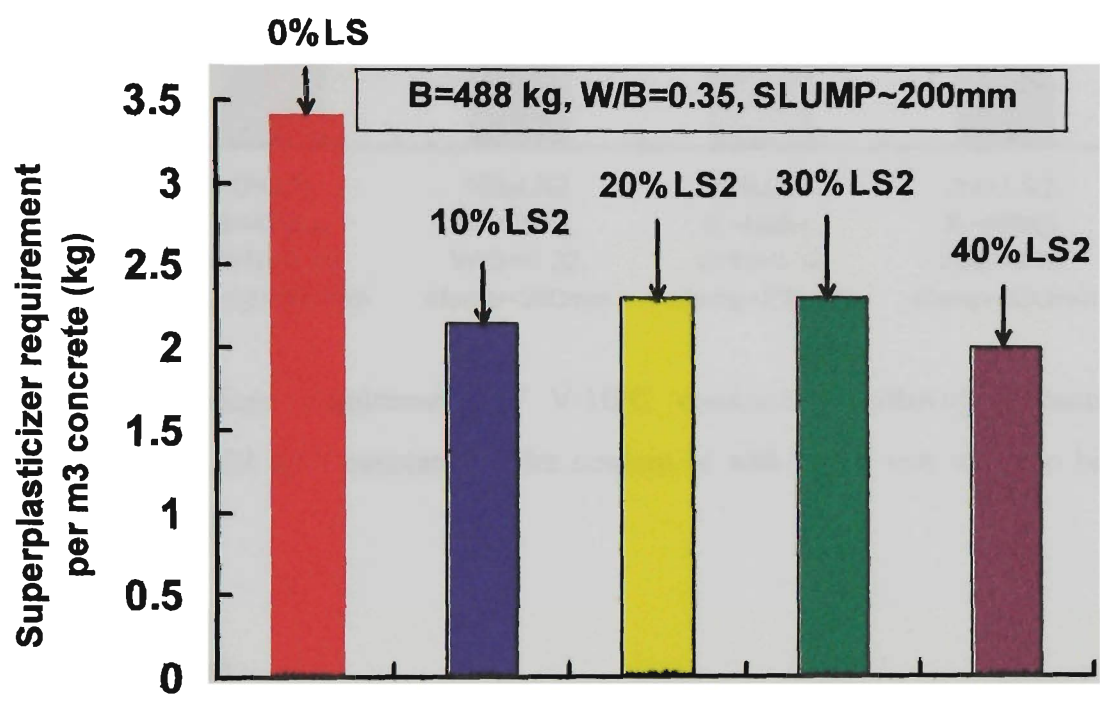


Fig. 5.6: Superplasticizer requirement of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m³ and water to binder ratio of 0.35

For similar slumps and constant binder content of 488 kg/m³, concretes containing 10%, 20% and 30% of limestone LS2 with water to binder ratio of 0.32 required superplasticizer dosage 4.4%, 4.0% and 14.3%, respectively, lower than that of concrete containing pure cement with water to binder ratio of 0.35 (Fig. 5.7). This indicates that, in order to achieve similar slumps, without any increase in superplasticizer dosage, concrete containing limestone LS2 demands less water content than that containing pure cement.



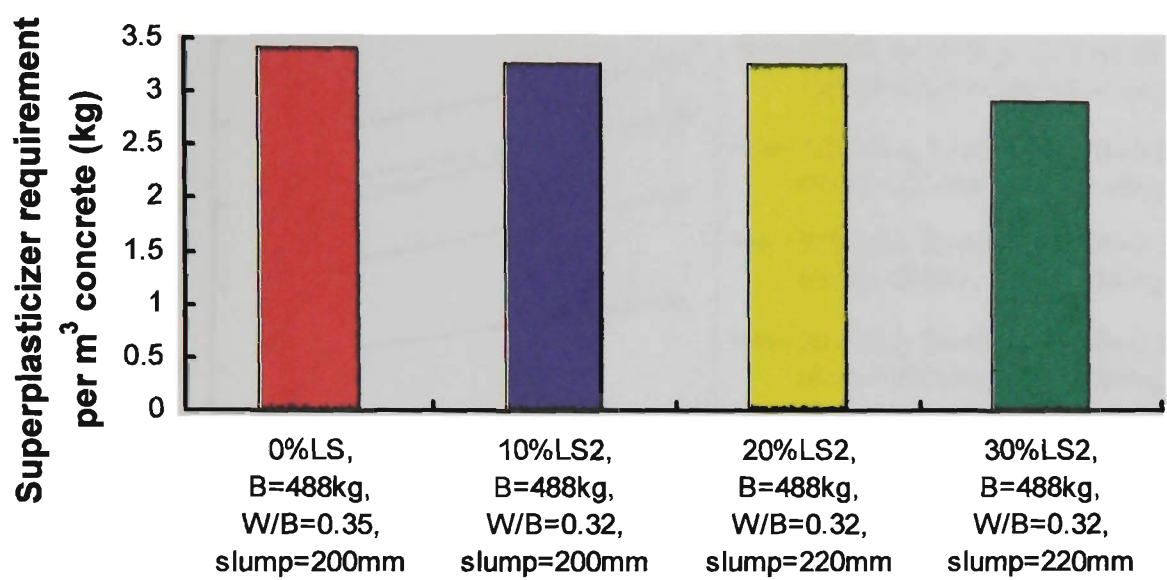


Fig. 5.7: Superplasticizer requirement of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.32

Compressive Strength:

For constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.35, all concretes containing limestone LS2 exhibited compressive strength lower than that with pure cement (Fig. 5.8). However, for constant binder content of 488 kg/m<sup>3</sup> and similar slumps, concretes containing 10%, 20% and 30% of limestone LS2 with water to binder ratio of 0.32 had compressive strength being about 113%, 101% and 86%, respectively, of that with pure cement having water to binder ratio of 0.35 (Fig. 5.9). For both water to binder ratios, the superplasticizer dosages for all concretes containing limestone LS2 were lower than that for concrete with pure cement. Therefore, for similar slumps and superplasticizer dosage, concrete containing 10% and 20% of limestone LS2 with water to binder ratio of 0.32 exhibited 28-day compressive strength higher than, and similar to, that with pure cement and water to binder ratio of 0.35. This is due to the fact that the use of 10% and 20% of limestone LS2 reduced water demand in comparison with the use of pure cement.

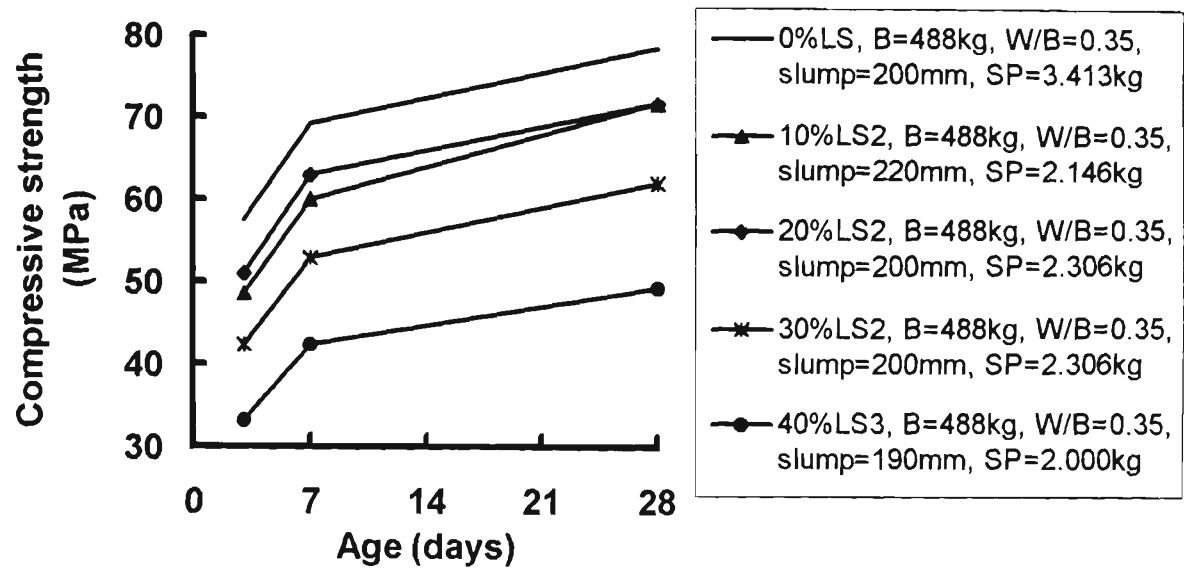


Fig. 5.8: Compressive strength of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.35

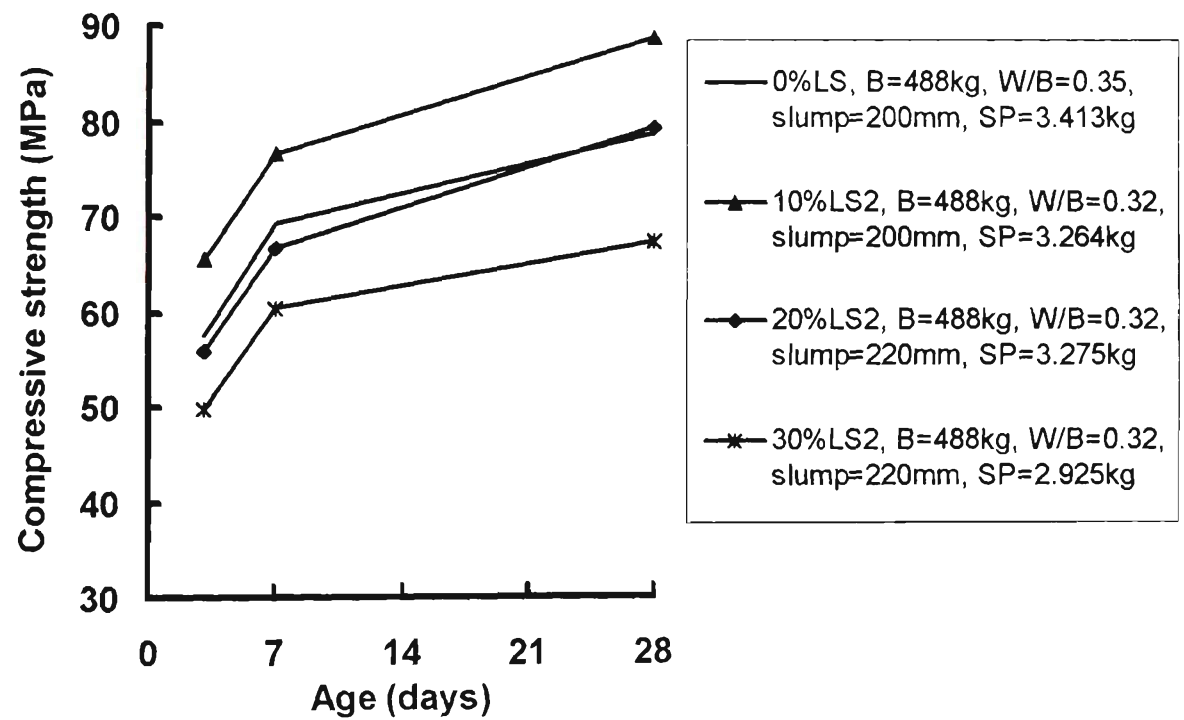


Fig. 5.9: Compressive strength of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.32

For constant binder content of 500 kg/m<sup>3</sup> and water to binder ratio of 0.30, concretes containing 10%, 20% and 30% of limestone LS2 exhibited 28-day compressive strength of 90.1 MPa, 85.8 MPa and 73.5 MPa, respectively (Fig. 5.10).

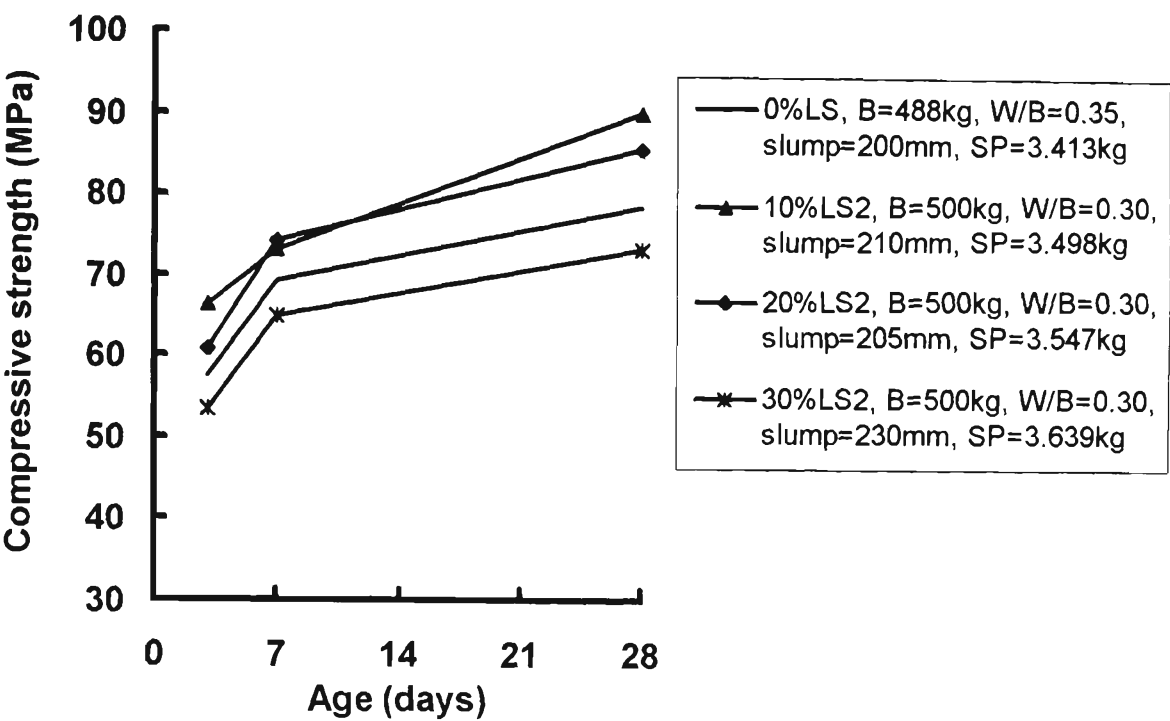


Fig. 5.10: Compressive strength of V-HPC containing different contents of limestone LS2 with constant binder content of 500 kg/m<sup>3</sup> and water to binder ratio of 0.30

For the case of limestone modified cement containing 40% of limestone LS2, concretes having binder contents of 488 kg/m<sup>3</sup> and water to binder ratios of 0.35 and 0.30 exhibited 28-day compressive strength of 49.6 MPa and 62.3 MPa, respectively; and concrete containing binder content of 500 kg/m<sup>3</sup> and water to binder ratio of 0.28 had 28-day compressive strength of 68.0 MPa (Appendix 5.2). Appendix 5.2 also indicates that lower contents of limestone LS2 and lower water to binder ratio resulted in higher compressive strength of V-HPC.

Drying Shrinkage:

As can be seen from Figs. 5.11, 5.12, 5.13, 5.14 and Appendix 5.2, all concretes containing limestone LS2 exhibited 56-day drying shrinkage lower than that of concrete with pure cement, except for mixture No. C7B. For constant water to binder ratio of

0.35, concrete containing 40% of limestone LS2 had 168-day drying shrinkage lower and higher than that containing 30% and 20% of limestone LS2, respectively (Fig. 5.12). Also, for water to binder ratio of 0.35 and at ages of 56 days and 168 days, concrete containing 20% of limestone LS2 exhibited the lowest drying shrinkages in comparison with those with pure cement, 10%, 30% and 40% of limestone LS2 (Fig. 5.11 and 5.12).

For binder content of 500 kg/m<sup>3</sup>, water to binder ratio of 0.30 and at age of 56 days, concrete containing 20% of limestone LS2 had the lowest drying shrinkage in comparison with those containing 10% and 30% of limestone LS2 (Fig. 5.14). Also, for binder content of 500 kg, water to binder ratio of 0.30, concrete containing 20% of limestone LS2 exhibited 168-day drying shrinkage lower than that with 30% of limestone LS2 (Fig. 5.15).

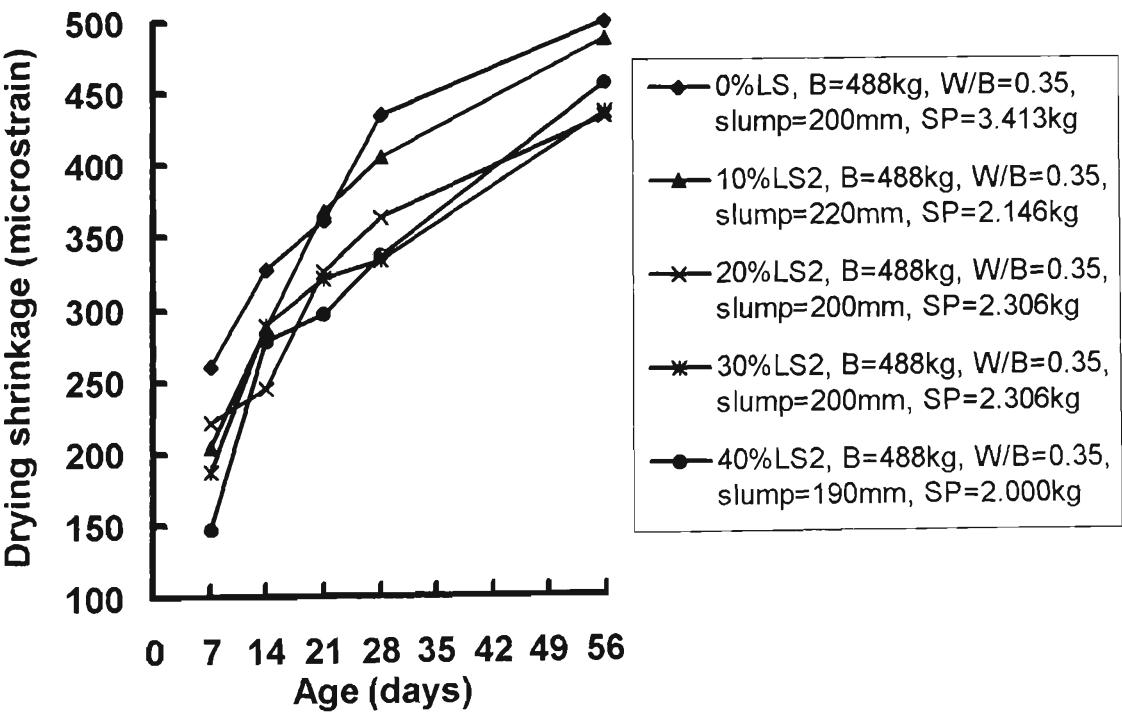


Fig. 5.11: Drying shrinkage of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg and water to binder ratio of 0.35

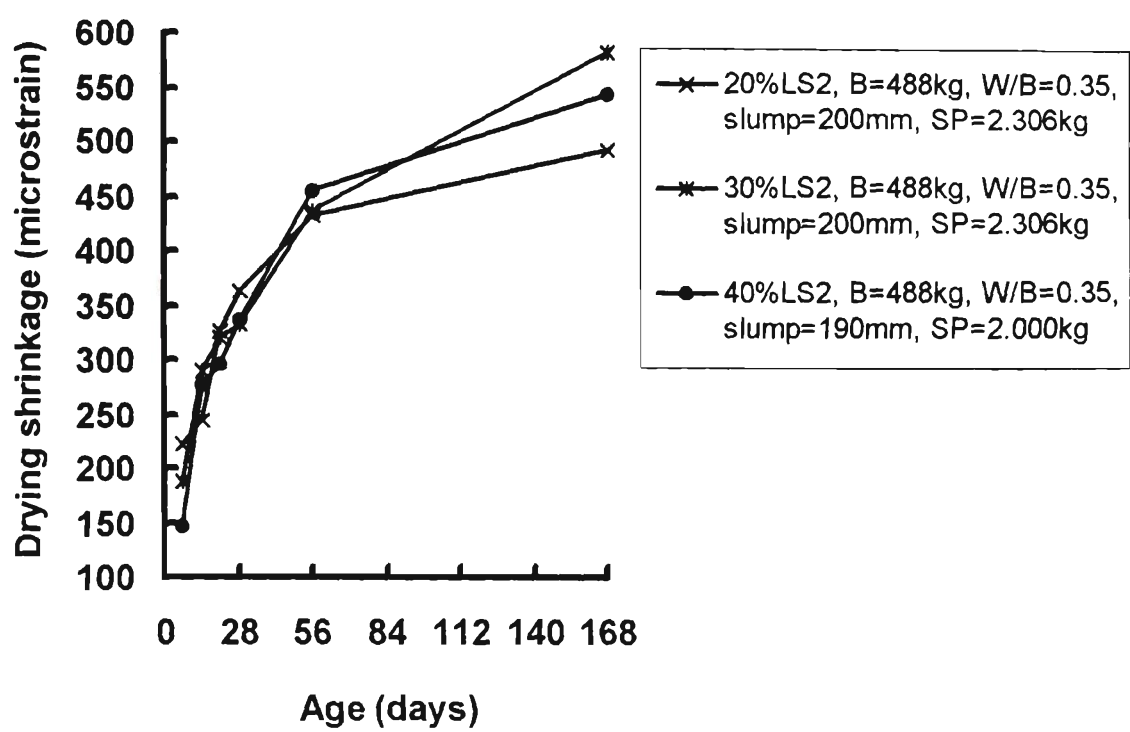


Fig. 5.12: Long-term drying shrinkage of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.35

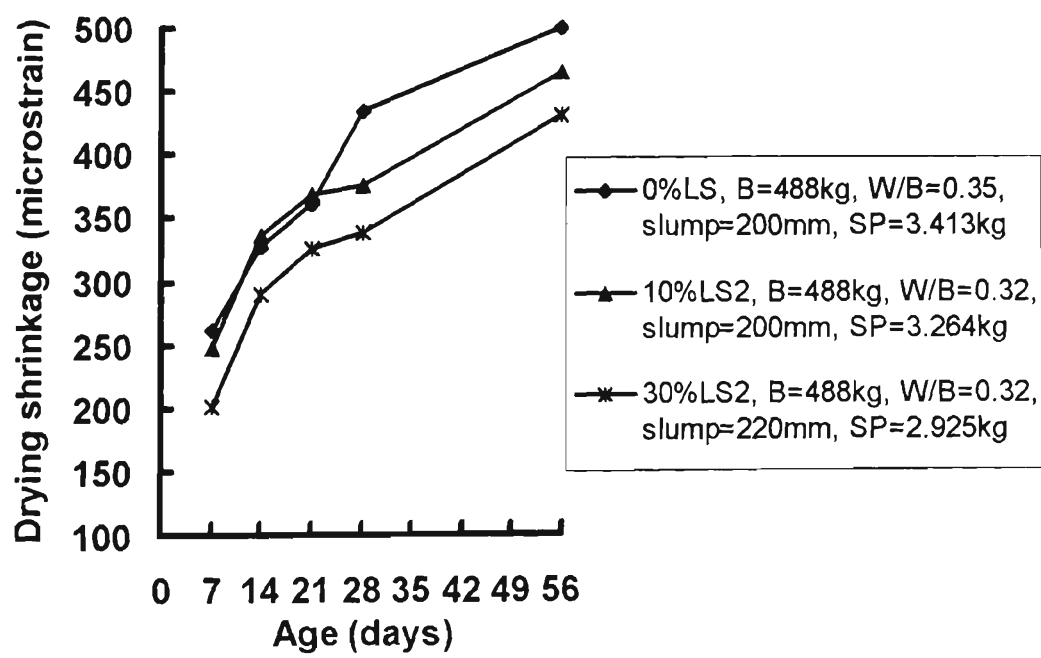


Fig. 5.13: Drying shrinkage of V-HPC containing different contents of limestone LS2 with constant binder content of 488 kg/m<sup>3</sup> and water to binder ratio of 0.32

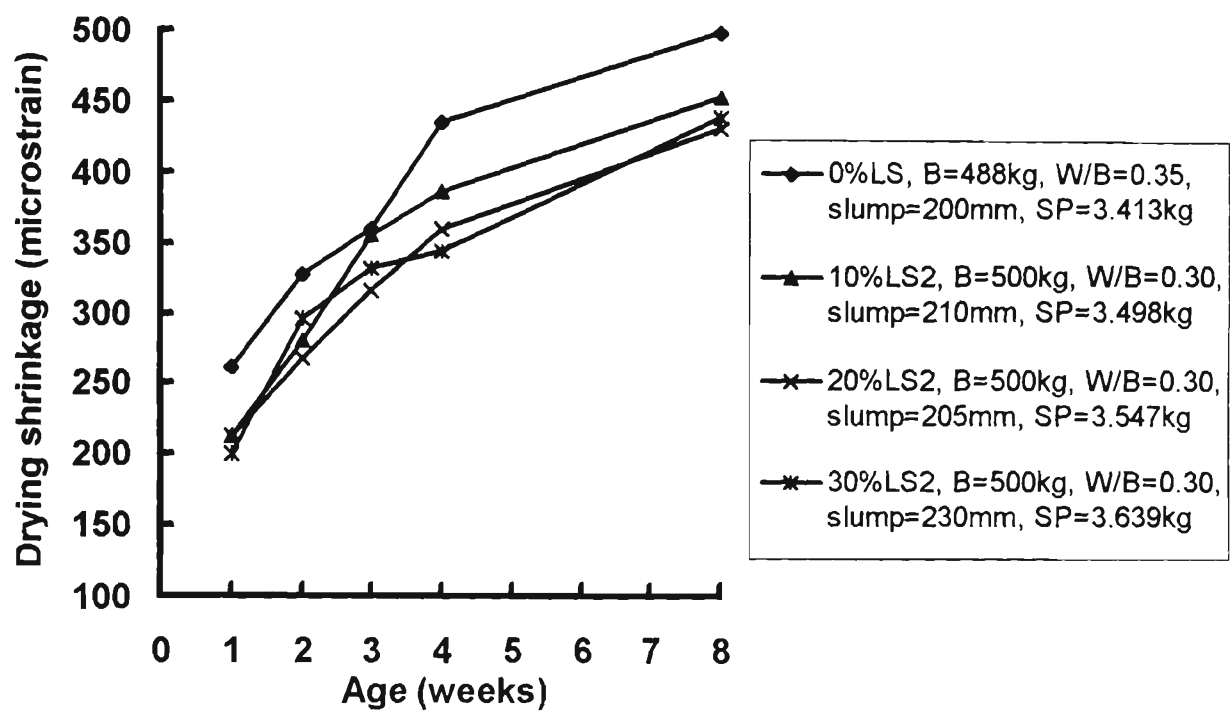


Fig. 5.14: Drying shrinkage of V-HPC containing different of limestone LS2 with constant binder content of 500 kg/m<sup>3</sup> and water to binder ratio of 0.30

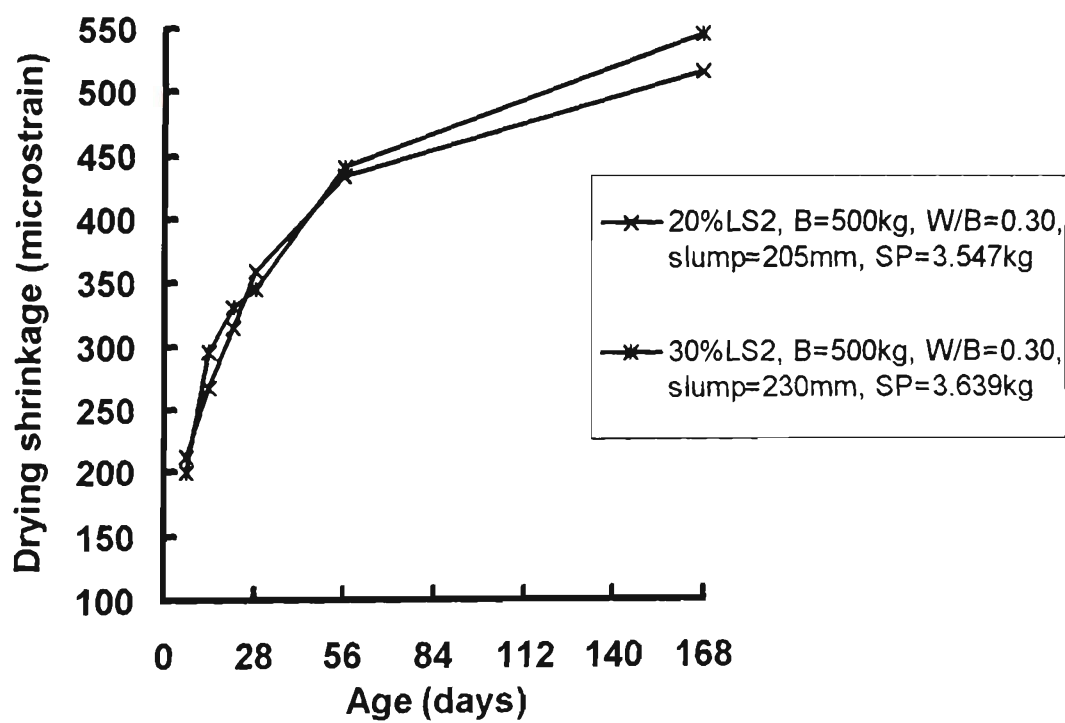


Fig. 5.15: Long-term drying shrinkage of V-HPC containing 20% and 30% of limestone LS2 with constant binder content of 500 kg/m<sup>3</sup> and water to binder ratio of 0.30

For a fixed contents of limestone LS2 and water to binder ratios between 0.30 and 0.35, drying shrinkages of V-HPC were similar (from Fig. 5.16 to Fig. 5.19, inclusive). This indicates that for low water to binder ratio range between 0.30 and 0.35, the higher water to binder ratio did not always result in higher drying shrinkage. This shows that drying shrinkage for V-HPC having water to binder ratio of less than 0.35 depends mainly on microstructure of concrete rather than on water to binder ratio only.

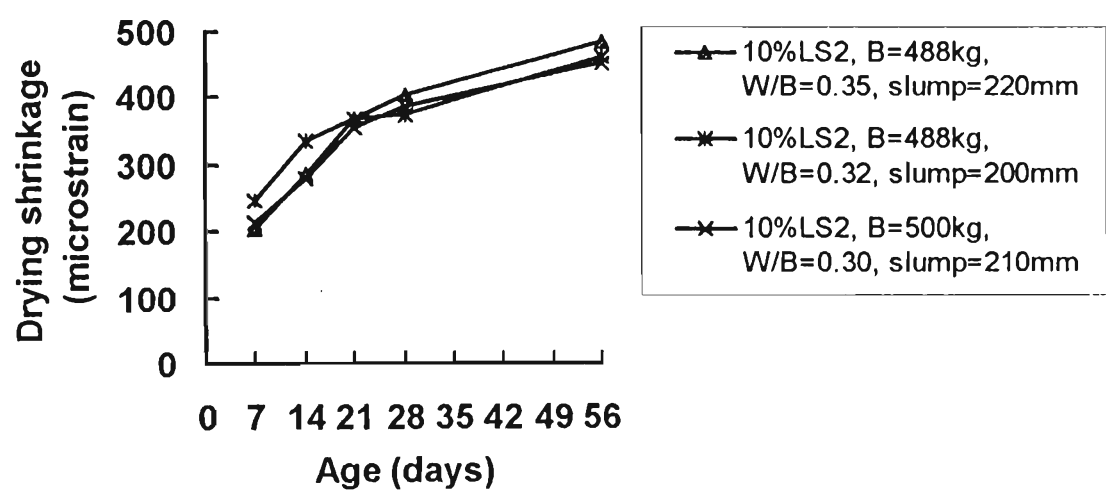


Fig. 5.16: Drying shrinkage of V-HPC containing 10% of limestone LS2 with different water to binder ratios and different binder contents

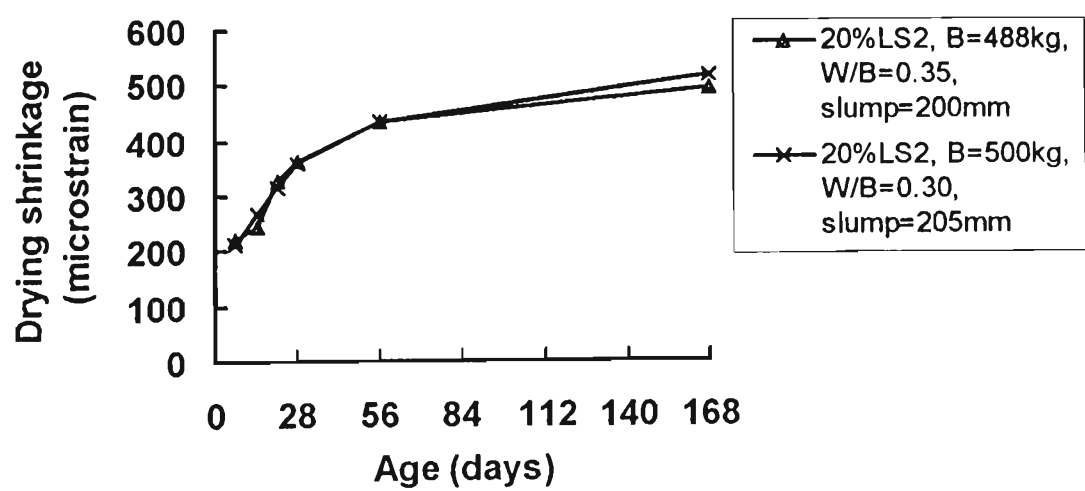


Fig. 5.17: Drying shrinkage of V-HPC containing 20% of limestone LS2 with different water to binder ratios and different binder contents

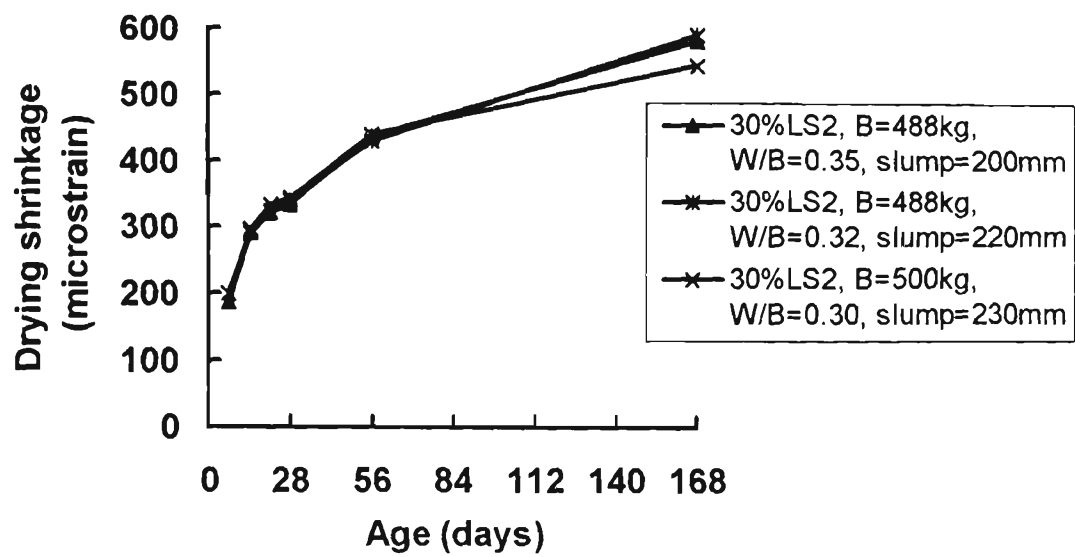


Fig. 5.18: Drying shrinkage of V-HPC containing 30% of limestone LS2 with different water to binder ratios and different binder contents

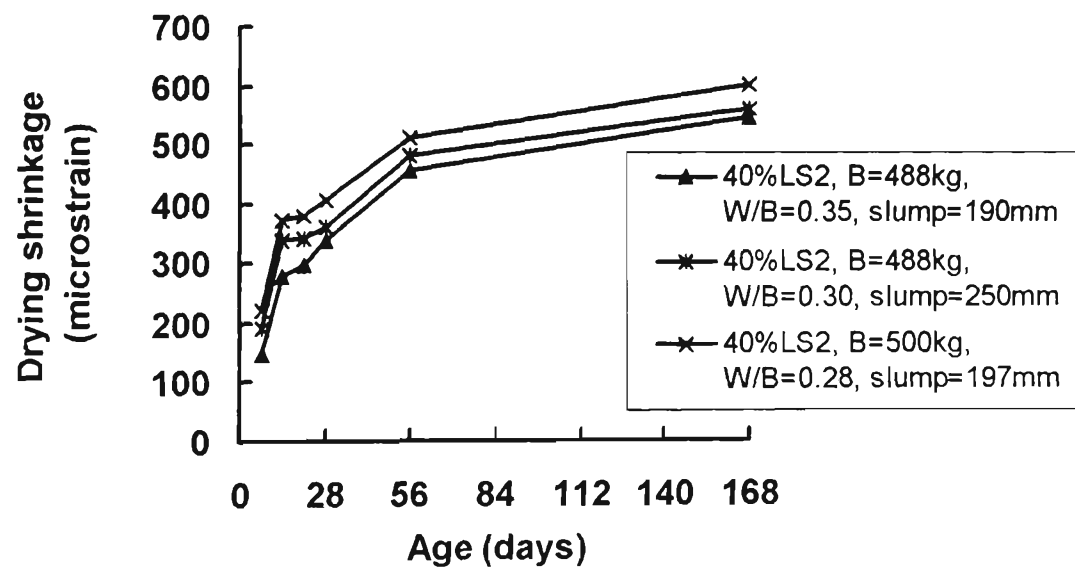


Fig. 5.19: Drying shrinkage of V-HPC containing 40% of limestone LS2 with different water to binder ratios and different binder contents

In summary, consideration of all three parameters indicates that limestone LS2 performed best of all three limestone types; and the use of limestone modified cements consisting of up to 20% of limestone LS2 can produce high performance concretes with low drying shrinkage, high compressive strength and less superplasticizer dosage in



comparison with that containing pure cement. Also, the use of limestone modified cements consisting of 30% and 40% of limestone LS2 can be beneficial for V-HPC with 28-day compressive strength between 50 MPa and 70 MPa, because concretes containing 30% and 40% of limestone LS2 can have reduced superplasticizer requirement (Fig. 5.6), drying shrinkage (Fig. 5.11) and cement content.

### **5.3. EFFECT OF COARSE AGGREGATE MAXIMUM SIZE**

In order to investigate the effect of coarse aggregate maximum size on properties of V-HPC, coarse aggregate with maximum sizes of 20 mm and 14 mm were combined with 10-mm maximum size aggregate types with mass ratios of 62 : 38 and 70 : 30, respectively. These combinations were designed to produce minimum void content. Shrinkage limited portland cement SPC1 and 20% of limestone LS2 were used in both concretes (mixes C9A and C9B). Mixture proportions were generally the same for both concretes, except for the coarse aggregate combination and superplasticizer dosage that was adjusted in order to obtain similar slumps. Test results are given in Appendix 5.2 and Fig. 5.20, 5.21 and 5.22.

For constant content of all components and similar slumps, concrete containing 20-mm coarse aggregate (mix C9A) required superplasticizer dosage some 14 % lower than that with 14-mm coarse aggregate (mix C9B) (Fig. 5.20). Concrete containing 20-mm coarse aggregate exhibited compressive strength slightly lower than that with 14-mm coarse aggregate (Fig. 5.21); while 56-day drying shrinkage of the first concrete (mix C9A) was about 14% lower than that of the second concrete (mix C9B) (Fig. 5.22). The test results indicate that coarse aggregate maximum size affects mainly the superplasticizer requirement and drying shrinkage of V-HPC, and higher maximum size

coarse aggregate results in lower superplasticizer requirement and drying shrinkage of V-HPC due to the fact that, for the same aggregate volume, the higher maximum size coarse aggregate has the lower surface area.

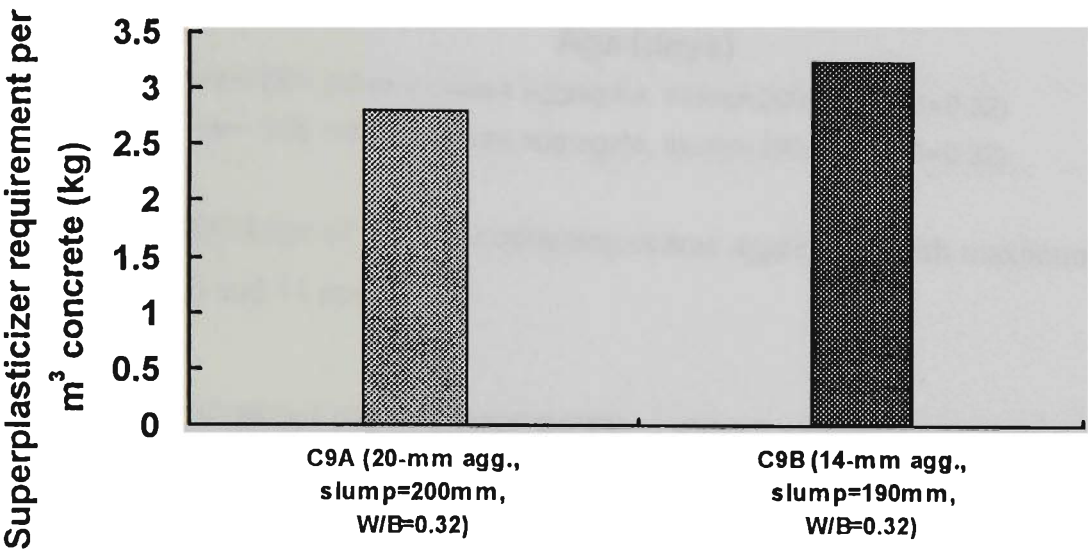


Fig. 5.20: Superplasticizer requirement of V-HPC containing coarse aggregate types with maximum sizes of 20 mm and 14 mm

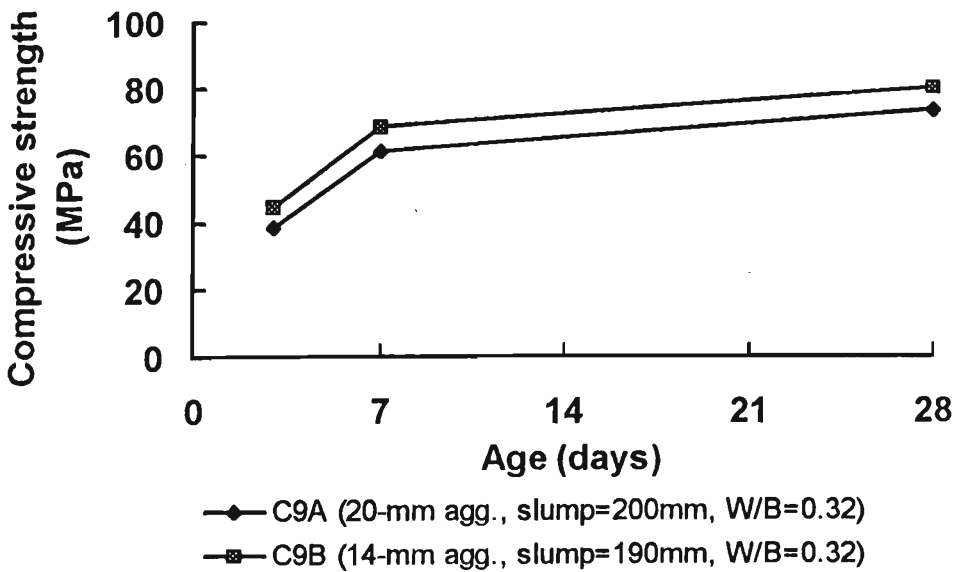


Fig. 5.21: Compressive strength of V-HPC containing coarse aggregate types with maximum sizes of 20 mm and 14 mm

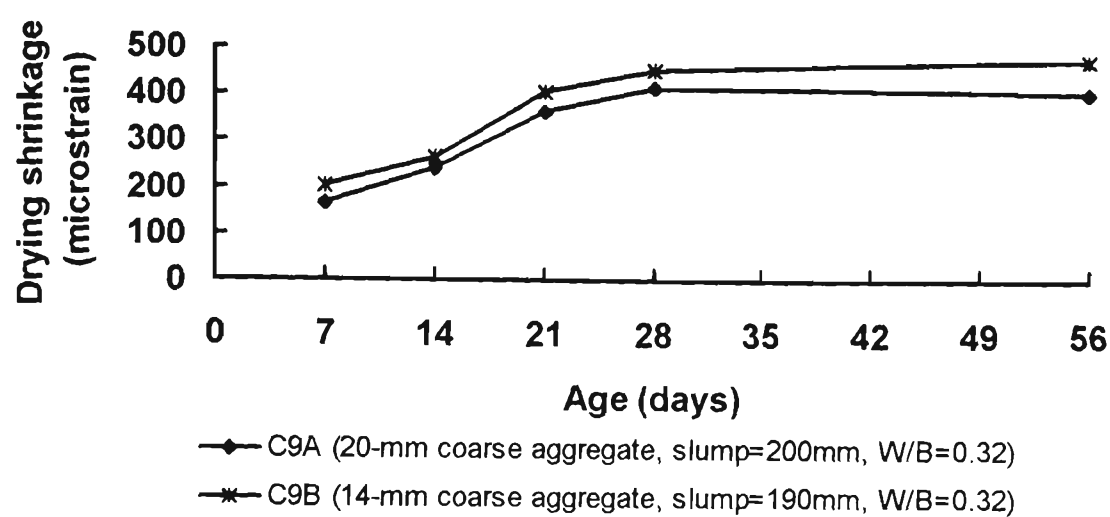


Fig. 5.22: Drying shrinkage of V-HPC containing coarse aggregates with maximum sizes of 20 mm and 14 mm

5.4. NORMAL VIBRATED CONCRETE CONTAINING LIMESTONE MODIFIED CEMENTS (LMC)

Normal (not high performance) vibrated concretes with less binder content and high water to binder ratios were tested in order to investigate the effect of milled limestone on their compressive strength and drying shrinkage. A binder content of 350 kg was used for all mixes. Water contents of concretes containing 10% and 20% of limestone LS2, with and without superplasticizer, were adjusted in order to achieve slumps similar to that of concrete containing pure cement SPC2. Test results (mixes C8A, C8B, C8C, C8D, C8E and C8F) are indicated in Appendix 5.2, Fig. 5.23, 5.24, 5.25 and 5.26.

Compressive Strength

For constant binder content of 350 kg and similar slumps, concretes containing 10% of limestone LS2, without and with superplasticizer dosage of 0.853 kg/m<sup>3</sup>, (W/B = 0.59 and W/B = 0.506, respectively) exhibited 28-day compressive strengths approximately 4% lower and 23% higher, respectively, than that with pure cement (W/B = 0.60) (Fig. 5.23). Similarly, concretes containing 20% of limestone LS2, without and with

superplasticizer dosage of 0.880 kg/m<sup>3</sup> and 1.750 kg/m<sup>3</sup> (W/B = 0.58, W/B = 0.50 and 0.45, respectively) exhibited 28-day compressive strengths approximately 19% lower, 7% and 24% higher, respectively, than that with the pure cement (W/B = 0.60) (Fig. 5.24). The results show that the concrete containing 10% and 20% of limestone LS2 with small amounts of superplasticizer can exhibit compressive strength similar to or higher than that with pure cement. This indicates that, with appropriate combinations of milled limestone and superplasticizer, the compressive strength of concrete is not compromised compared with that without superplasticizer.

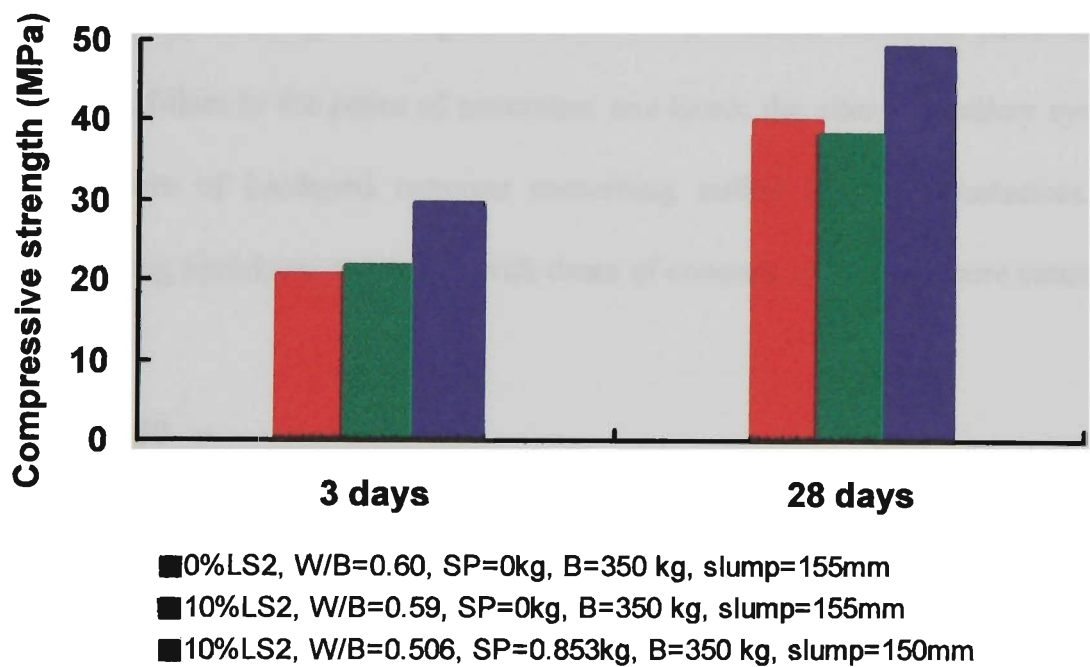


Fig. 5.23: Compressive strength of normal concrete containing 10% of limestone LS2 and high water to binder ratios

Drying Shrinkage

For constant binder content of 350 kg and similar slumps, concretes containing 10% and 20% of limestone LS2, without and with superplasticizer, exhibited drying shrinkage similar to and slightly lower than, respectively, that of concrete with pure cement

(Fig.5.25 and 5.26), although the water to binder ratios of concretes containing limestone LS2 were lower than that of concrete with pure cement. This indicates that for high water to binder ratio, the effect of limestone modified cements on drying shrinkage of concrete is not significant. This can be due to the fact that, for high water to binder ratio, milled limestone acts as small particles surrounded by water membrane rather than as fillers which can fill pores of concretes; and the capillary system in microstructure of hardened cement paste and concretes, with and without milled limestone, can be similar. This leads to the similar drying shrinkage of the concretes. In the case of V-HPC, which usually has low water to binder ratio, the effect of fine milled limestone on drying shrinkage was significant, probably because limestone particles act as small particle fillers in the pores of concretes; and hence the altered capillary system and microstructure of hardened concrete containing milled limestone enhances the reduction of drying shrinkage compared with those of concrete containing pure cement.

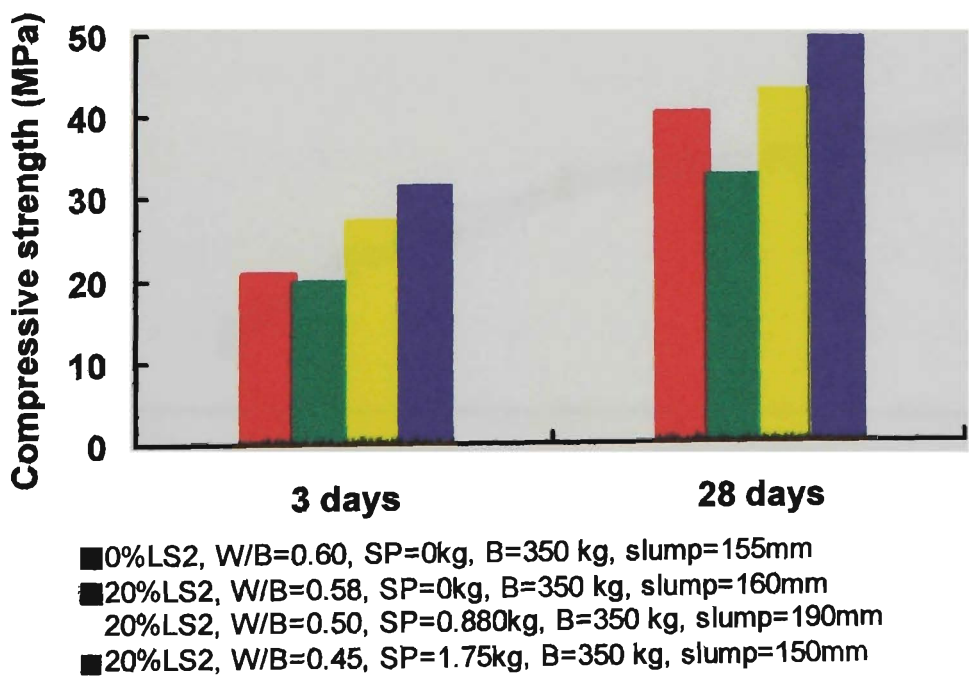


Fig. 5.24: Compressive strength of normal concrete containing 20% of limestone LS2 and high water to binder ratios

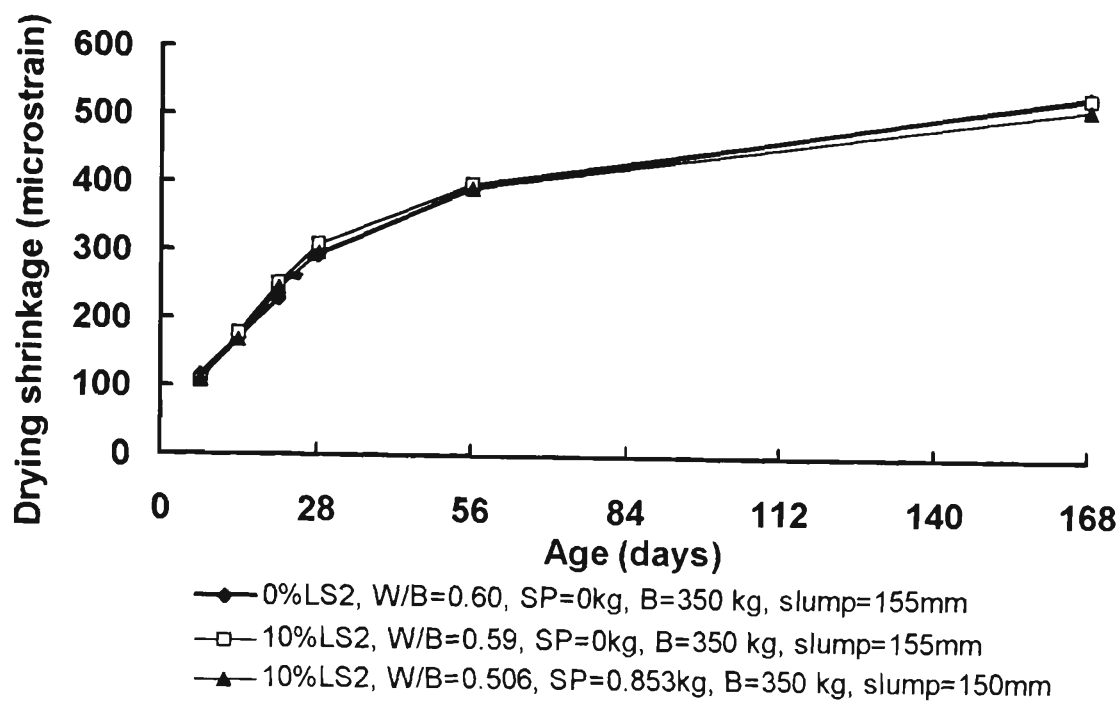


Fig. 5.25: Drying shrinkage of normal concrete containing 10% of limestone LS2 and high water to binder ratios

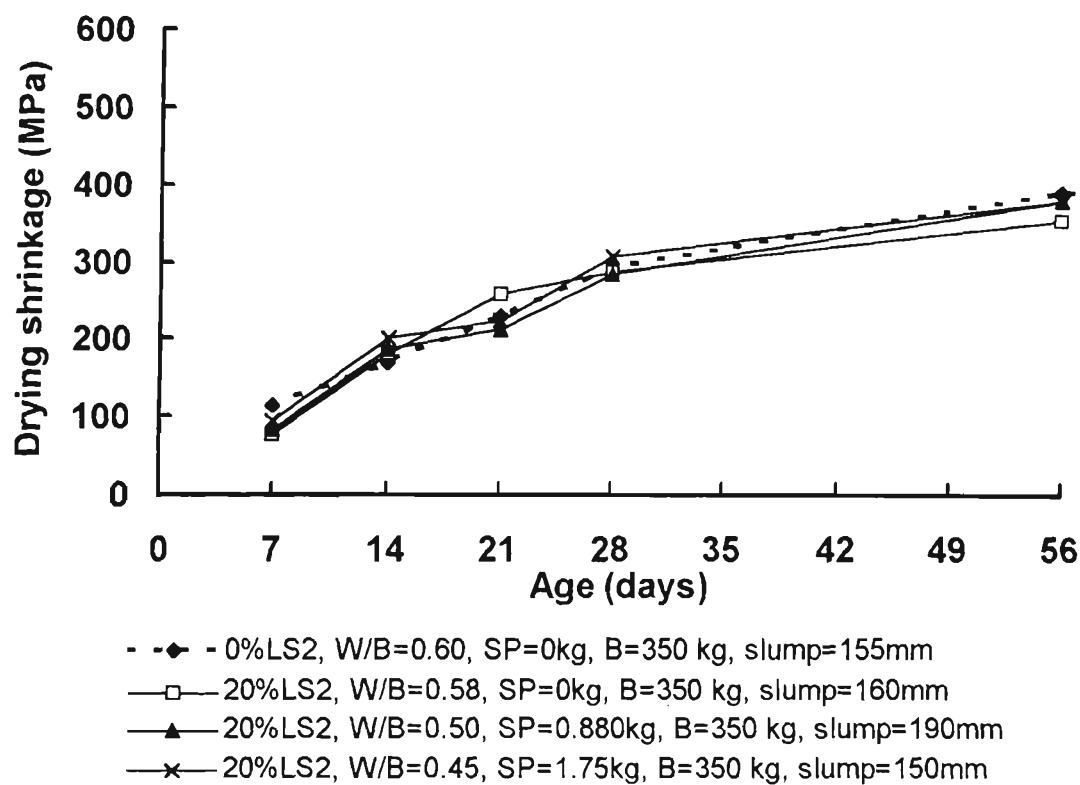


Fig. 5.26: Drying shrinkage of normal concrete containing 20% of limestone LS2 and high water to binder ratios

The test results indicated that the use of 10% and 20% of limestone LS2 is beneficial for normal concrete with high water to binder ratio only if it is combined together with a small amount of superplasticizer, and if the combination proves to be of economic efficiency.

**5.5. MODEL PREDICTING 28-DAY COMPRESSIVE STRENGTH OF V-HPC CONTAINING LMC**

Compressive strength of high performance concrete depends mainly on compressive strength of cement, aggregate type, amount of water, air volume, binder and limestone contents. Based on the experimental results, the classical Feret’s formula and formula proposed by Sedran et al. (1996) is modified as follows:

$$F_c = \frac{K_g R_c}{K_w \left\{ 1 + 3.1 \frac{W + A}{C(1 + K_2)} \right\}^2} \tag{Eq. 5.1}$$

Where:

- $F_c$  is 28-day compressive strength of V-HPC containing limestone modified cement (based on a cylinder of diameter 100 mm and height 200 mm);
- $K_g$  is an aggregate coefficient. Two typical values of  $K_g$  are 5.4 and 4.8 for crushed and rounded aggregates with maximum size of 20 mm, respectively (Sedran et al, 1996). A value of 5.8 should be used for  $K_g$  for crushed aggregate with maximum size of 14 mm;
- $R_c$  is the 28-day cement strength measured on ISO mortar bars (sand:cement:water proportions: 3:1:0.5 by weight);
- $W$  is the water content of concrete ( $\text{kg/m}^3$ );
- $A$  is the volume of air ( $\text{l/m}^3$ );

- B, C and LS are weight of binder, cement and milled limestone, respectively ( $\text{kg/m}^3$ )
- $K_2 = 0.2 \text{ LS/C}$  is an activity coefficient for milled limestone (limestone content ranges from 10% to 40% of total binder by weight); and
- $K_w$  is a new proposed coefficient (effective coefficient) that is dependent on water to binder ratio and on total binder content. From the test results, the value of the effective coefficient  $K_w$  can be calculated according to the following formula:

$$K_w = W/B + m \quad (\text{Eq. 5.2})$$

where  $W/B$  is water to binder ratio, ranging from 0.28 to 0.35;  $m$  is an experimental coefficient which depends on mass of binder and type of test cylinders:

$$m = 0.47 \quad \text{for } B \leq 500 \text{ kg/m}^3 \text{ and specimen cylinder having diameter and height of 100 mm and 200 mm, respectively;}$$

For test cylinder with diameter and height of 150 mm and 300 mm, the formula for the effective coefficient could be different as Patnaik and Patnaikuni (1998) have reported that concrete strength measured using 100-mm diameter cylinders is marginally greater than that measured using 150-mm diameter cylinders made from the same batch of concrete, and for identical curing conditions and testing ages.

The above formulae were used to calculate the analytical 28-day compressive strength of V-HPC. As can be seen from Fig. 5.27 and Fig. 5.28, the analytical and experimental results on 28-day compressive strength of V-HPC containing different limestone contents and different water to binder ratios are similar. Therefore, the modified formula can be useful in predicting 28-day compressive strength of V-HPC containing limestone modified cements.



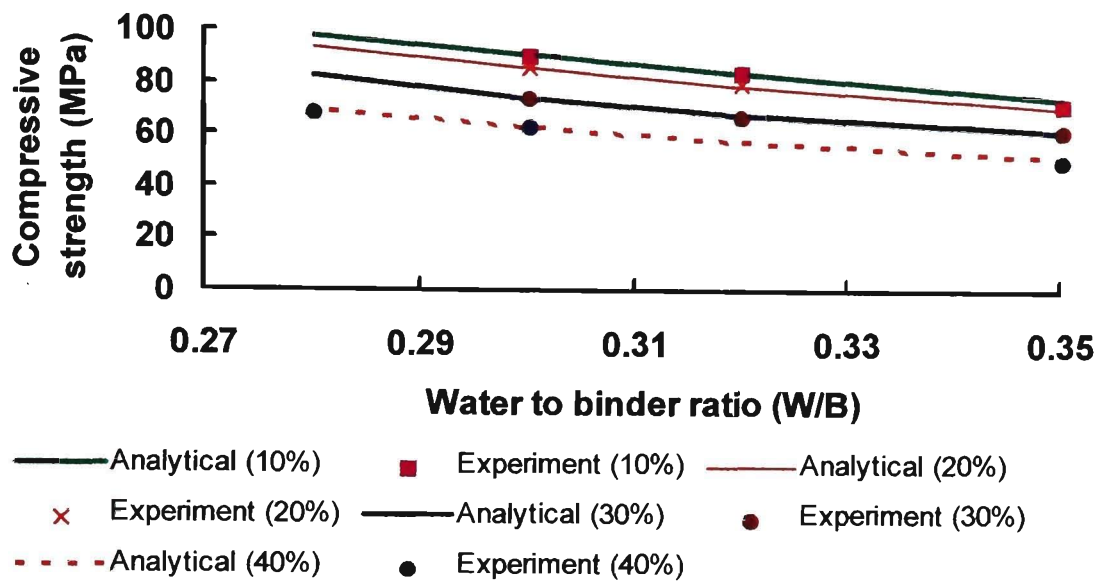


Fig. 5.27: Analytical and experimental results on 28-day compressive strength of vibrated high performance concrete (V-HPC)

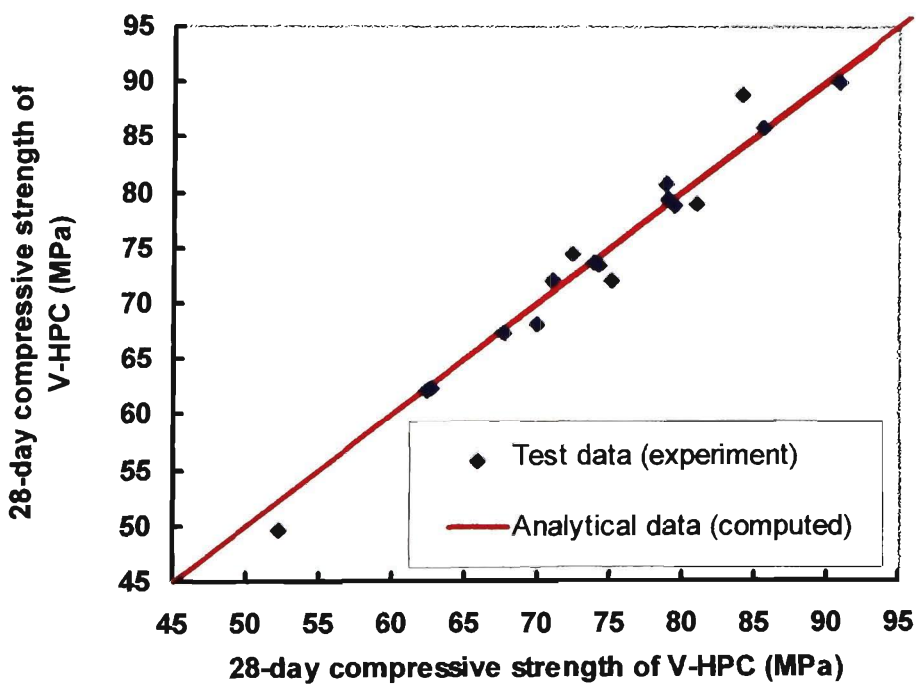


Fig. 5.28: Scatter diagram of analytical and experimental data on 28-day compressive strength of vibrated high performance concrete (V-HPC)

## 5.6. INTERFACE BETWEEN COARSE AGGREGATE AND MORTAR FOR VIBRATED HIGH PERFORMANCE CONCRETE

Specimens of vibrated high performance concrete (V-HPC) containing pure cement and 20% of limestone LS2 with water to binder ratio of 0.30 were made. The interfaces between coarse aggregate and mortar of the V-HPC were investigated by using SEM and typical micrographs are given in Fig. 5.29 and 5.30. Fig. 5.29 and 5.30 show that the interfacial zones between coarse aggregate and mortar appear to be similar, with both micrographs indicating a micro-spacing at the interface between the aggregate particle and the mortar for V-HPC with and without milled limestone (the micro-spacing occurred on one side of the aggregate particle only). Fig. 5.31 and 5.32 indicate the interfaces between coarse aggregate and mortar, at higher magnification, for V-HPC with and without milled limestone LS2 (the indicated locations were resite from the regions exhibiting no micro-spacing at the interface between coarse aggregate and mortar).

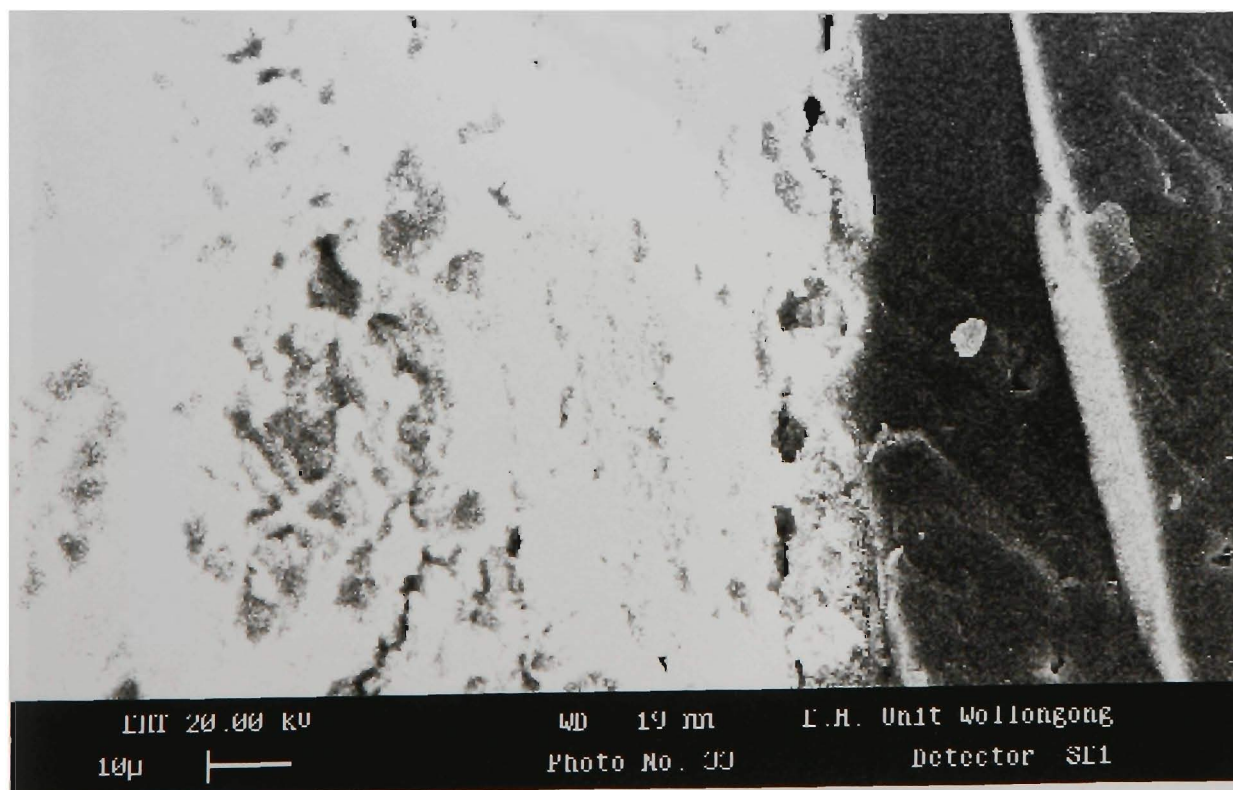


Fig. 5.29: Interface between coarse aggregate and mortar of V-HPC without milled limestone (low magnification)

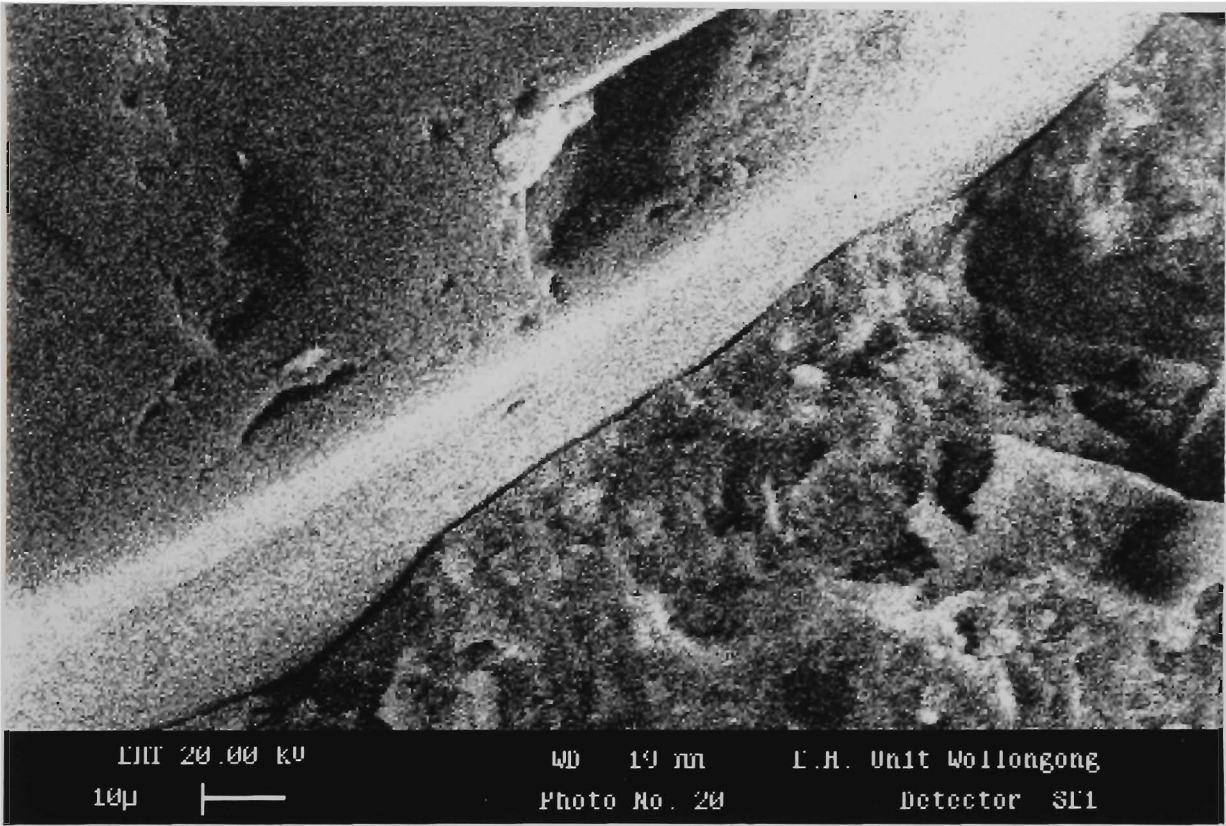


Fig. 5.30: Interface between coarse aggregate and mortar of V-HPC containing 20% of milled limestone LS2 (low magnification)

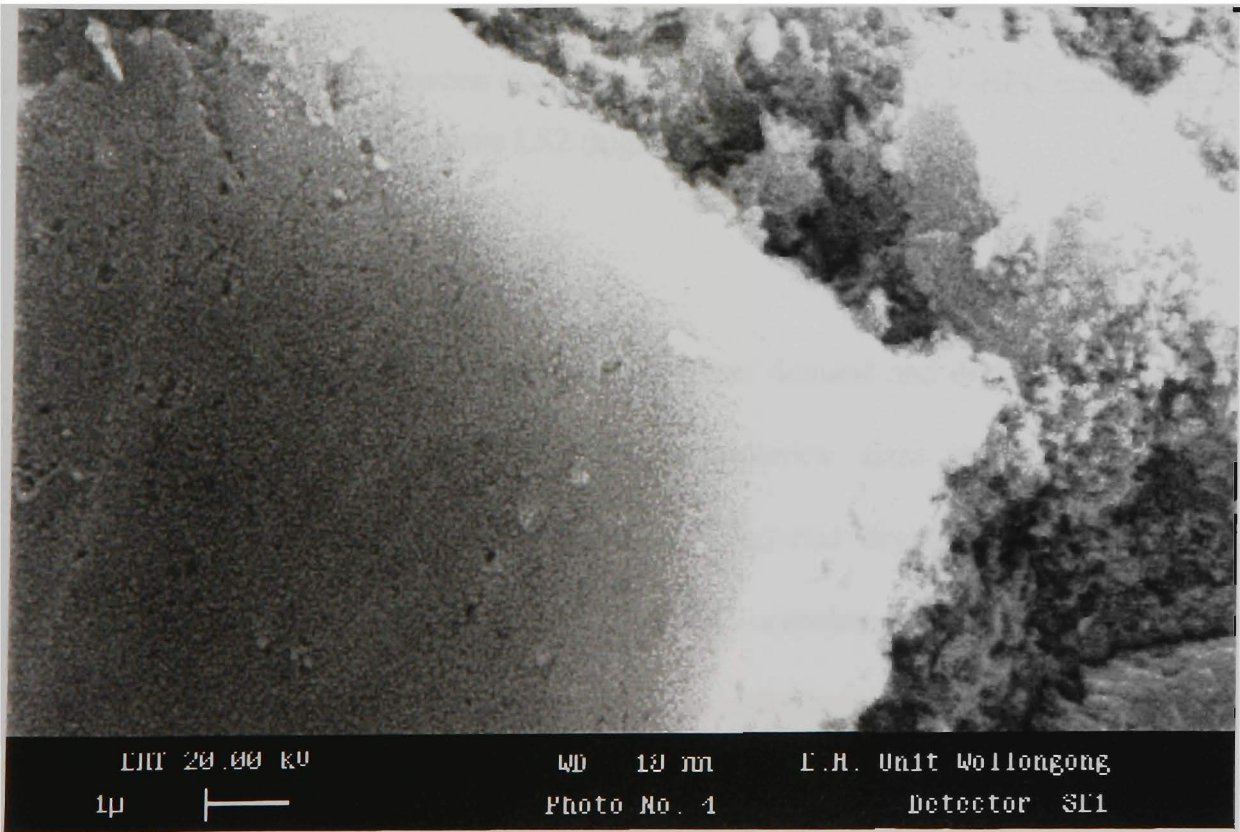


Fig. 5.31: Interface between coarse aggregate and mortar of V-HPC without milled limestone LS2 (high magnification)



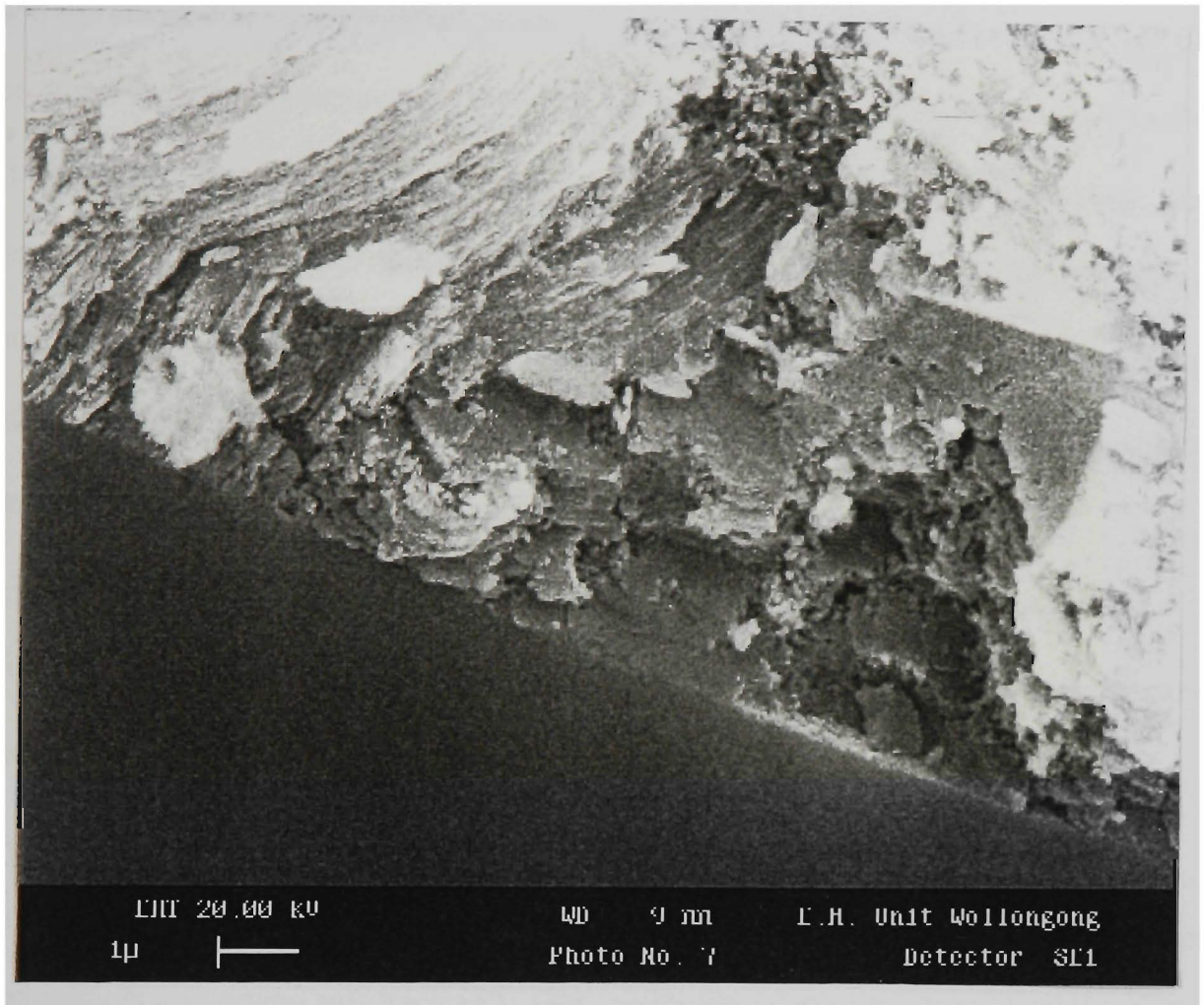


Fig. 5.32: Interface between coarse aggregate and mortar of V-HPC containing 20% of milled limestone LS2 (high magnification)

## 5.7. SUMMARY

Fineness of milled limestone has an effect on water demand and drying shrinkage of V-HPC. Limestones LS2 and LS3, with mean particle sizes about 3 and 6 times, respectively, smaller than pure cement SPC2, reduced drying shrinkage and water demand of V-HPC in comparison with V-HPC containing limestone LS1 and pure cement. When considering superplasticizer requirement, compressive strength and drying shrinkage of V-HPC containing limestone, LS2 is the most suitable of the three tested limestones.

Different contents of limestone LS2 also resulted in different performance of concrete, and the use of limestone modified cements consisting of up to 20% of limestone LS2 can produce high performance concretes with low drying shrinkage, high compressive strength and less superplasticizer dosage in comparison with that containing pure cement. Also, the use of limestone modified cements consisting of 30% and 40% of limestone LS2 can be beneficial for V-HPC with 28-day compressive strength between 50 MPa and 70 MPa, because these concretes exhibited reduced superplasticizer requirement, drying shrinkage and cement content.

For low water to binder ratios between 0.30 and 0.35, the higher water to binder ratio did not always result in higher drying shrinkage of concrete.

Coarse aggregates with different maximum sizes affect mainly superplasticizer requirement and drying shrinkage of V-HPC, and higher maximum size coarse aggregate results in lower superplasticizer requirement and drying shrinkage of V-HPC, due to the fact that, for the same aggregate volume, the higher maximum size coarse aggregate has generally the lower total surface area.

The use of 10% and 20% of limestone LS2 is beneficial for normal concrete with high water to binder ratio only if it is combined with a small amount of superplasticizer, and if the combination proves to be of economic efficiency. This showed that the use of limestone modified cements in V-HPC with low water to binder ratio is more effective than that in normal concrete with high water to binder ratio.

The formula modified from the classical Feret's Equation can be useful in predicting 28-day compressive strength of V-HPC as the experimental results and analytical values calculated from the formula are similar.

Therefore, the use of limestone modified cements containing milled limestone with suitable fineness and content can improve workability, compressive strength and reduce drying shrinkage of vibrated high-performance concrete. Concretes incorporating limestone modified cements can also require reduced superplasticizer dosage and cement content; thereby enabling high-performance concrete to be produced more economically.

## **CHAPTER 6**

### **SELF-COMPACTING HIGH PERFORMANCE CONCRETE CONTAINING LIMESTONE MODIFIED CEMENTS**

#### **6.1. MATERIALS AND EXPERIMENTAL PROGRAM**

##### **6.1.1. Materials**

Materials used for testing self-compacting high performance concrete (SC-HPC) were the same as those used in testing vibrated high performance concrete (V-HPC) (see section 5.1.1, Chapter 5).

##### **6.1.2. Experimental Program**

The experimental program was carried out as follows:

- a) In the first study, concretes with constant water to binder ratio, similar paste volumes and different coarse to total aggregate ratios were tested in order to determine an optimum coarse to total aggregate ratio;
- b) In the second study, concretes with constant water to binder ratio, similar paste volumes, constant coarse to total aggregate ratio and different limestone types were studied in order to investigate the effect of limestone types with different fineness on properties of SC-HPC, and
- c) In the third study, concretes containing different contents of the best limestone type were tested in order to study the effect of limestone content, different water to binder ratios and different paste volumes on properties of concrete.

In addition, test programs were also carried out to study:

- \* Effect of aggregate type;
- \* Effect of blending techniques;

- \* Modelling to predict 28-day compressive strength of SC-HPC containing limestone modified cements; and
- \* Interface between coarse aggregate and mortar of the SC-HPC.

### **6.1.3 Testing Parameters and Procedure**

The main properties of self-compacting concrete in the fresh state are deformability, segregation resistance and blocking behaviour around reinforcements. These properties, together with superplasticizer requirement of SC-HPC were evaluated. The procedures for segregation resistance testing are reported in detail in Chapter 7. The testing parameters of the hardened concrete were compressive strength and drying shrinkage. Mixture proportions of SC-HPC and test results are given in Appendices 6.1, 6.2 and 6.3.

#### Deformability Test

Deformability is defined as the ability of concrete to deform and to fill all corners of formwork without the use of vibration and without occurrence of segregation. The deformability of self-compacting concrete can be evaluated in two cases, namely when concrete flows through the clear spacing of reinforcement bars and when there is no reinforcement. The procedure for testing deformability in the first case is described in Chapter 7. The evaluation of deformability in the second case was carried by measuring slump flow of the concrete. A conventional slump cone was used to measure the slump flow diameter (labelled as  $F_d$  in Fig. 6.1). The slump cone is filled with concrete without vibration, then it is lifted vertically, and the average value of two final slump flow diameters of concrete recorded. Larger slump flow diameters indicate higher deformability, provided the concrete does not segregate.



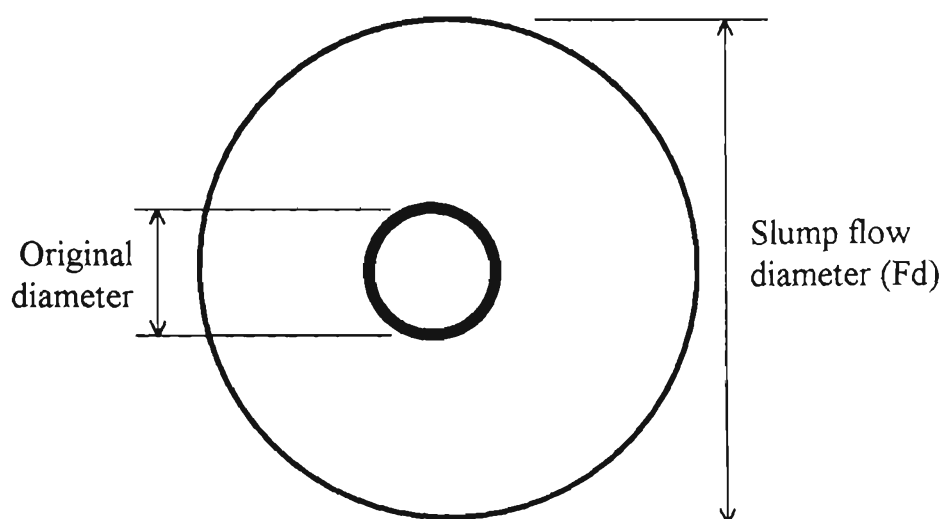
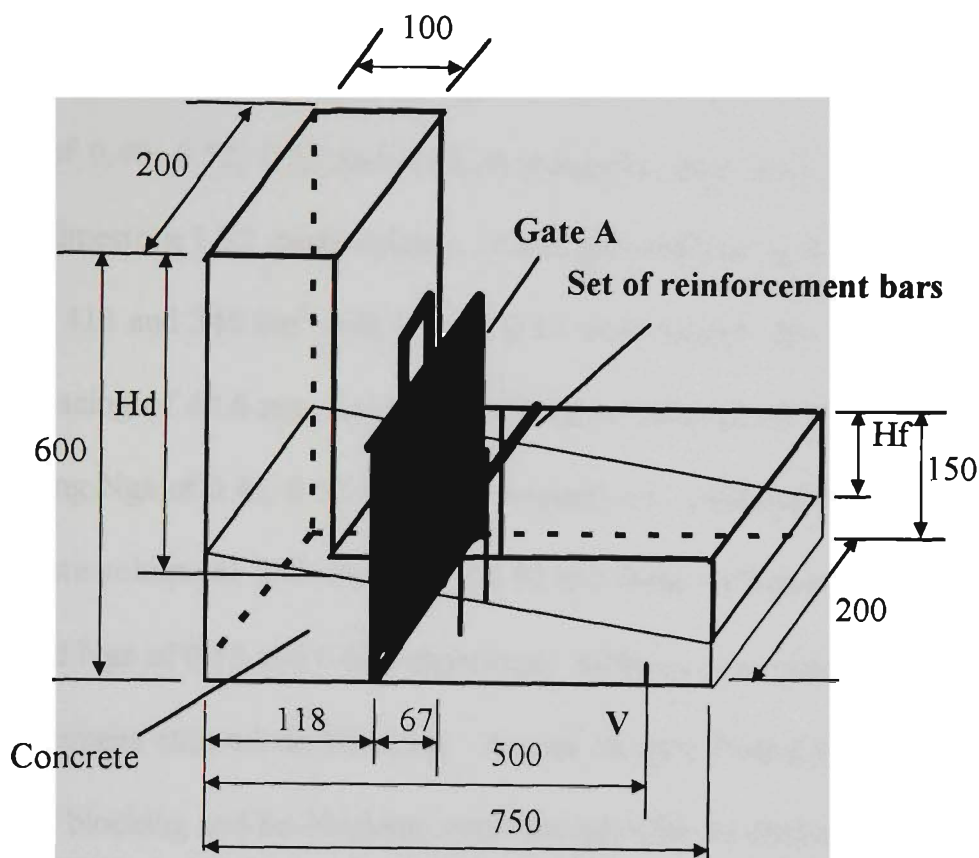


Fig.6.1: Measurement of slump flow diameter (Fd)

#### Blocking Behaviour Around Reinforcements

To assess blocking behaviour around reinforcements for self-compacting concrete, a modified L-box apparatus (Fig. 6.2) was used to measure filling head drop. In measurement of filling head drop (Hd), gate A is closed, and fresh concrete is filled to the highest position of the L-box apparatus. After 2 minutes, gate A is lifted vertically, and concrete is allowed to flow through the reinforcement set. The filling head drop (labeled as Hd in Fig. 6.2) is the difference between the height of the L-box and the height of the concrete surface when it stops flowing. Higher values of filling head drop indicate better filling ability of the concrete when it flows through clear spacing of reinforcement bars. The procedure for and assessment of blocking behaviour is explained in detail in Chapter 7.



(All dimensions in mm)

Fig. 6.2: Filling ability testing apparatus (L-box)

## 6.2. OPTIMUM COARSE TO TOTAL AGGREGATE RATIO

### 6.2.1 Minimum Required Paste Volume in Considering Blocking Behaviour

A previous study on blocking criteria (Bui. K. V., 1994 and Tangtermsirikul et al., 1995) shows that for certain aggregate types and clear spacing between reinforcement bars, higher coarse to total aggregate weight ratio ( $N_{ga}$ ) requires larger paste volume in order to achieve free flow of concrete around reinforcement bars. For aggregates used in this study, clear spacing of 40.6 mm and  $N_{ga}$  of 0.40, 0.52, 0.55 and 0.60, the minimum required paste volumes calculated on the basis of the previous work are 350, 392, 402 and 418 litres per  $m^3$ , respectively. For clear spacing of 58.3 mm and  $N_{ga}$  of 0.40, 0.52,

0.55 and 0.60, the minimum paste volumes are 250, 274, 280 and 289 l/m<sup>3</sup>, respectively. For concrete containing limestone LS3, paste volumes of 353, 393, 413 and 413 l/m<sup>3</sup> with Nga of 0.40, 0.52, 0.55 and 0.60, respectively, were investigated. For concrete containing limestone LS2, paste volumes of 393 and 346 l/m<sup>3</sup> with Nga of 0.52 and paste volumes of 413 and 346 l/m<sup>3</sup> with Nga of 0.55 were tested. The test results show that for clear spacing of 40.6 mm, concretes with paste volumes of 353, 395 and 413 litres per m<sup>3</sup> having Nga of 0.40, 0.52 and 0.55, respectively, exhibited no blocking, while that with the paste volume of 346 and Nga of 0.52 and those with paste volumes of 346 and 413 l/m<sup>3</sup> and Nga of 0.55 and 0.60, respectively did block. For clear spacing of 58.3 mm, all test specimens showed no blocking. As can be seen from Fig. 6.3, the test results verified that blocking and no-blocking zones comply with an analytical line dependent on aggregate grading analysis and clear spacing of reinforcement bars which was derived from a previous study (Bui, 1994 and Tangtermsirikul, 1995), which is summarised in Chapter 8.

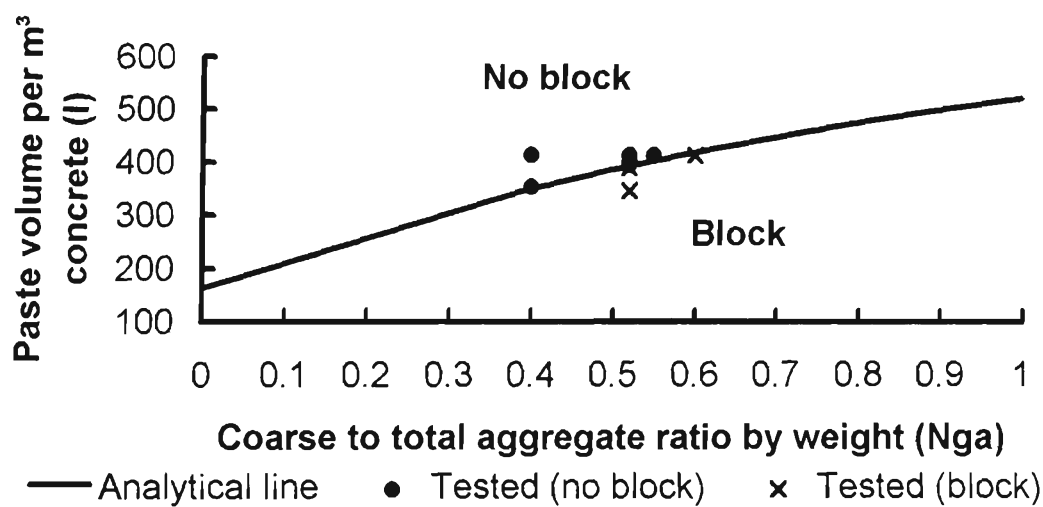


Fig. 6.3: Minimum required calculated paste volume (analytical line) and test results indicating blocking behaviour when concrete flows through clear spacing of 40.6 mm

### 6.2.2. Optimum Coarse to Total Aggregate Ratio

As discussed above, blocking criteria can be used to predict a minimum paste volume required for certain coarse to total aggregate ratios in order not to cause blocking around reinforcements. However, there is a question as to what coarse to total aggregate ratio is the optimum one from the view point of superplasticizer requirement, compressive strength and drying shrinkage. In order to answer this question, concretes containing 20% of limestone LS3, with constant paste volume of  $413 \text{ l/m}^3$  and coarse to total aggregate ratios of 0.40, 0.52, 0.55 and 0.60, were initially tested. Subsequently, concretes containing 20% of limestone LS2, with constant paste volume of  $346 \text{ l/m}^3$  and coarse to total aggregate ratios of 0.485, 0.52 and 0.55, were also studied in order to confirm the first tests. 50% of solid volume of compacted coarse aggregate was chosen according to the mixture proportioning method proposed by Okamura et al. (1997), and when this coarse aggregate volume was chosen, the coarse aggregate to total aggregate ratio by weight was 0.485 (void content and solid volume of compacted coarse aggregate  $395.9 \text{ l/m}^3$  and  $604.1 \text{ l/m}^3$ , respectively; therefore, 50% of solid volume ( $604.1 \text{ l/m}^3$ ) of compacted coarse aggregate was  $302.05 \text{ l/m}^3$ ).

Fig. 6.4 shows that, for constant water to binder ratio and similar paste volumes of about  $413 \text{ l/m}^3$ , concrete containing 20% of limestone LS3 with lower coarse to total aggregate ratio required higher superplasticizer dosage in order to achieve similar slump flow diameters (Fd). This is due to the fact that, for paste volume of  $413 \text{ l/m}^3$ , concrete with lower coarse aggregate ratio had smaller average spacing (Dss) between aggregate particle surfaces (Fig. 8.22 in Chapter 8) (average spacing between aggregate particle surfaces which is a function of aggregate void content and particle distribution was calculated according to a formula proposed in a previous study (Bui, 1994)) (Eq. 8.28

and 8.29 in Chapter 8). For paste volumes of 346 l/m<sup>3</sup>, concretes containing 20% of limestone LS2 with coarse to total aggregate ratio (Nga) of 0.52 and 0.55 required similar superplasticizer dosages, being considerably lower than that with Nga of 0.485 (Fig. 6.5); while their slump flow diameters were similar. This can be explained by the fact that concrete with Nga of 0.52 and 0.55 had average spacing (Dss) between aggregate particle surfaces higher than that with Nga of 0.485 (Fig. 8.21 in Chapter 8).

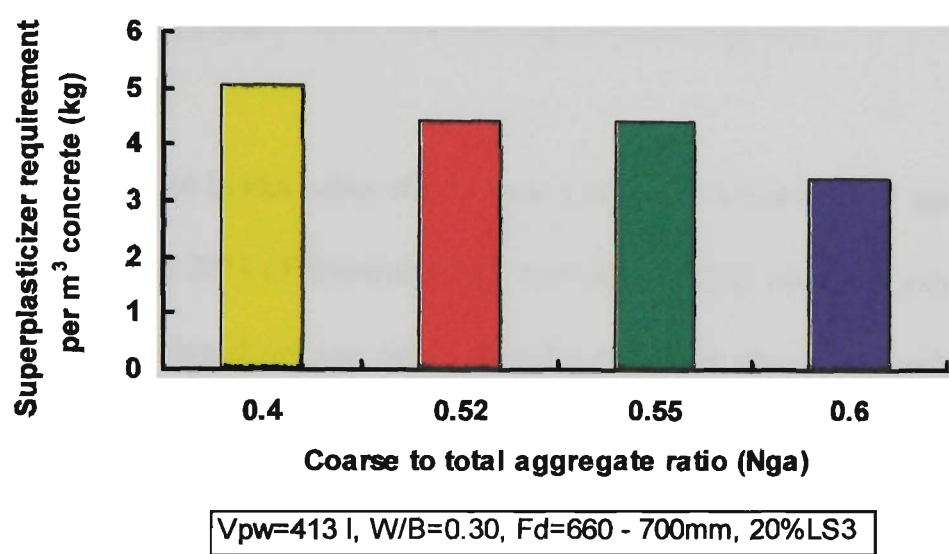


Fig. 6.4: Superplasticizer requirement of SC-HPC containing 20% of limestone LS3 with similar paste volumes of 413 l/m<sup>3</sup> and different coarse to total aggregate ratios

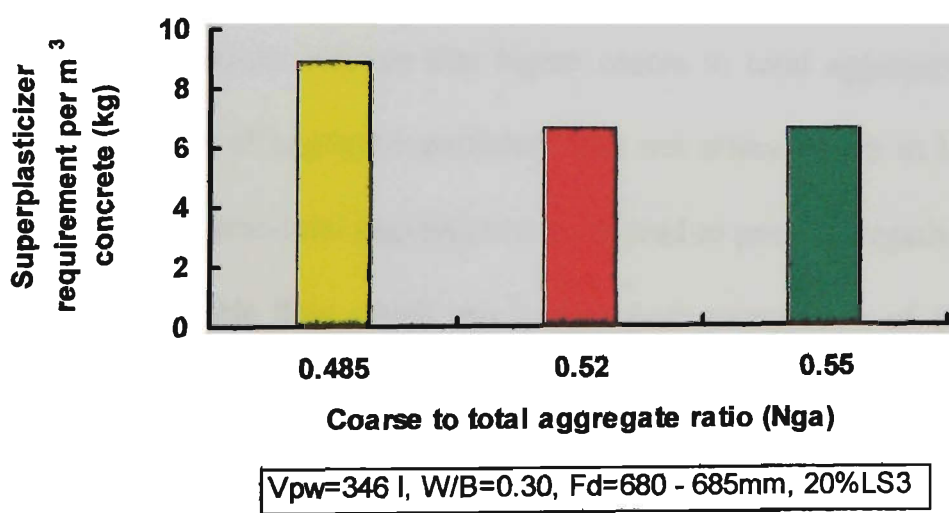


Fig. 6.5: Superplasticizer requirement of SC-HPC containing similar paste volumes of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.485, 0.52 and 0.55 (W/B=0.30)

Fig. 6.6 indicates that, for constant water to binder ratio of 0.30 and similar paste volumes of about  $413 \text{ l/m}^3$ , concrete containing 20% of limestone LS3 with Nga of 0.52 exhibited the highest 28-day compressive strength; while concretes with Nga of 0.40, 0.55 and 0.60 had similar 28-day compressive strengths, being slightly lower than that with Nga of 0.52. For similar paste volume of about  $346 \text{ l/m}^3$ , concrete containing 20% of limestone LS2 with Nga of 0.485 and 0.52 also exhibited similar 28-day compressive strength, being slightly higher than that with Nga of 0.55 (Fig. 6.7).

For constant water to binder ratio of 0.30 and similar paste volumes of about  $413 \text{ l/m}^3$ , concretes containing 20% of limestone LS3 with Nga of 0.52 and 0.55 exhibited similar values of 56-day drying shrinkage, being considerably lower than those with Nga of 0.40 and 0.60 (Fig. 6.8). Concretes with Nga of 0.52 and 0.55 also had similar drying shrinkage at age of 168 days. For constant water to binder ratio of 0.30 and similar paste volumes of about  $346 \text{ l/m}^3$ , concretes containing 20% of limestone LS2 with Nga of 0.485 and 0.52 exhibited the highest and lowest drying shrinkage, respectively; the drying shrinkage of concrete with Nga of 0.55 was slightly higher than that with Nga of 0.52 (Fig. 6.9). The results indicate that higher coarse to total aggregate ratio (e.g. lower total surface area of aggregate particles) does not always result in lower drying shrinkage as too high coarse-total aggregate ratio can lead to poor segregation resistance of SC-HPC and unsuitable flow which can lead to poor compaction of SC-HPC. It seems that both the total surface area of aggregate particles and the compactability of concrete affect drying shrinkage of SC-HPC, and there is an optimum coarse to total aggregate ratio which enhances the highest degree of compaction of SC-HPC.

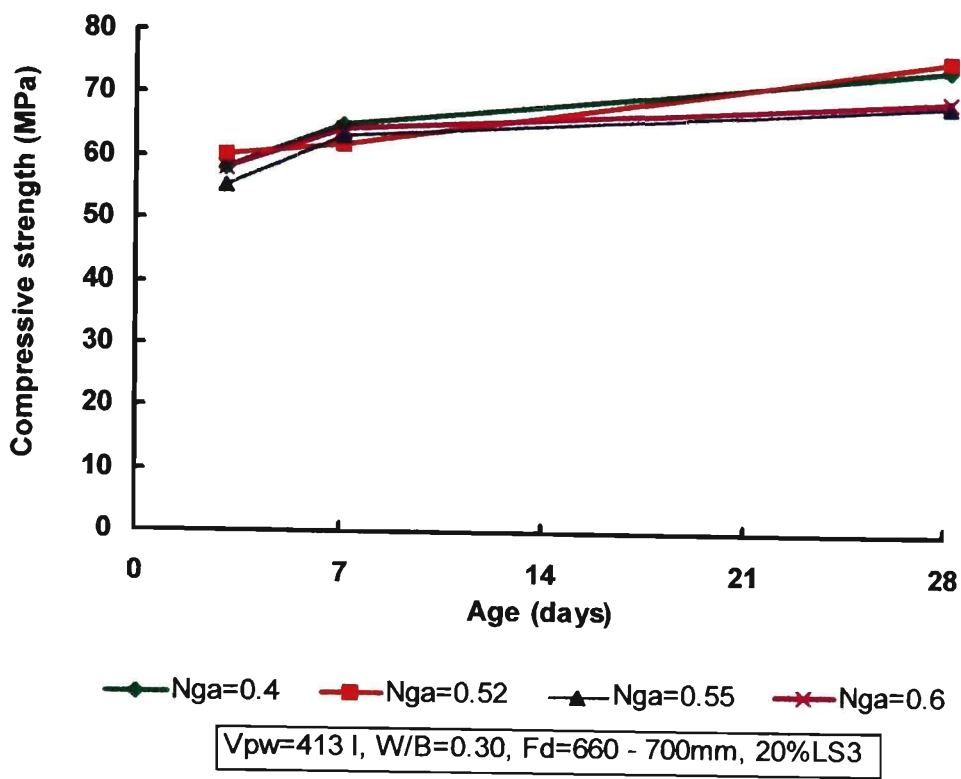


Fig. 6.6: Compressive strength of SC-HPC containing 20% of limestone LS3 with constant paste volume of 413 l/m<sup>3</sup> and different coarse to total aggregate ratios

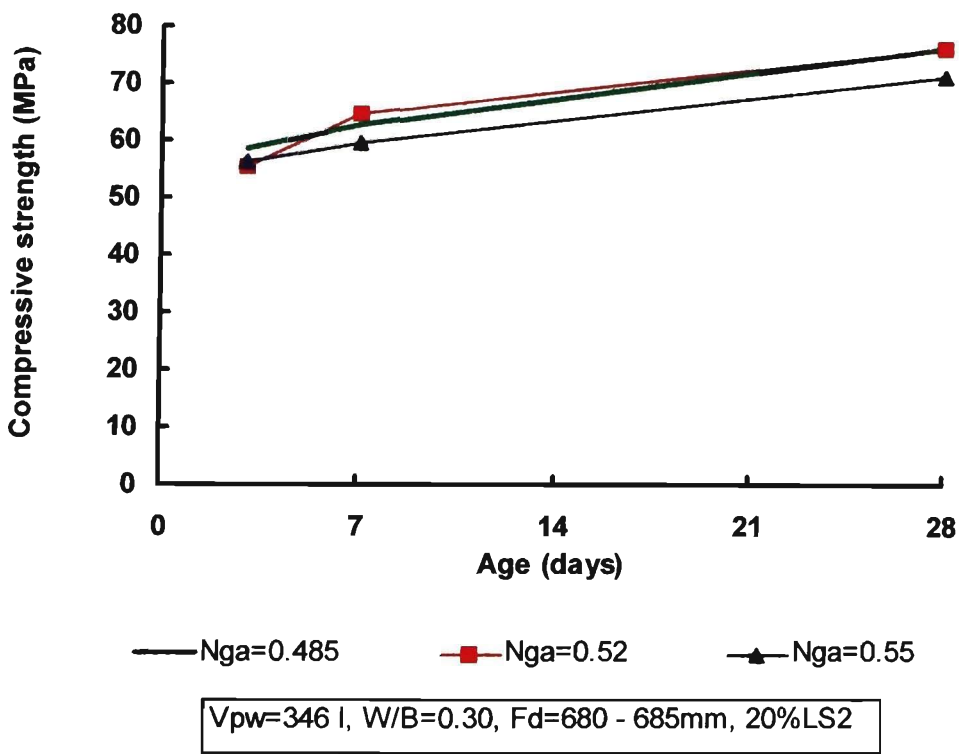


Fig. 6.7: Compressive strength of SC-HPC containing 20% of limestone LS2 with constant paste volume of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.485, 0.52 and 0.55 (W/B=0.30)

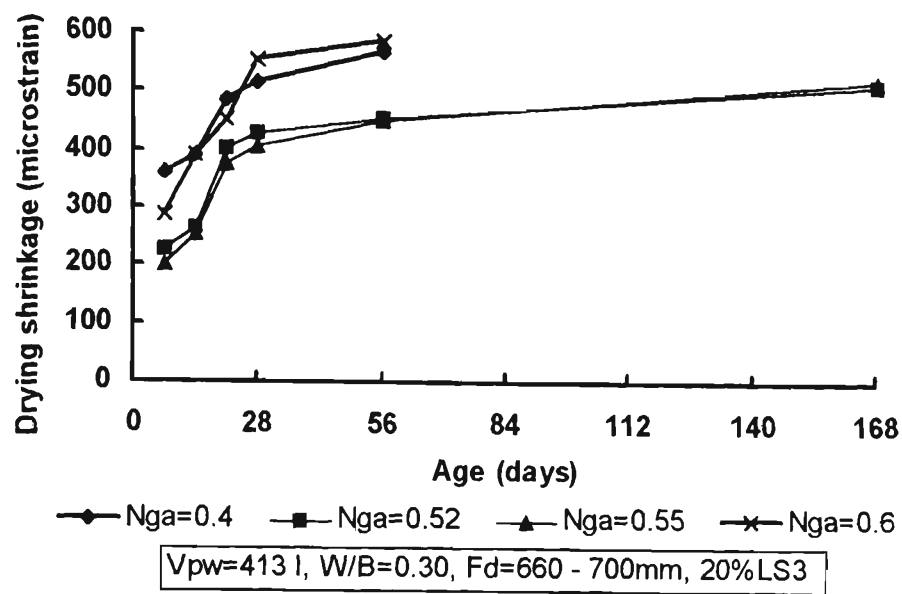


Fig. 6.8: Drying shrinkage of SC-HPC containing 20% of limestone LS3 with constant paste volume of 413 l/m<sup>3</sup> and different coarse to total aggregate ratios

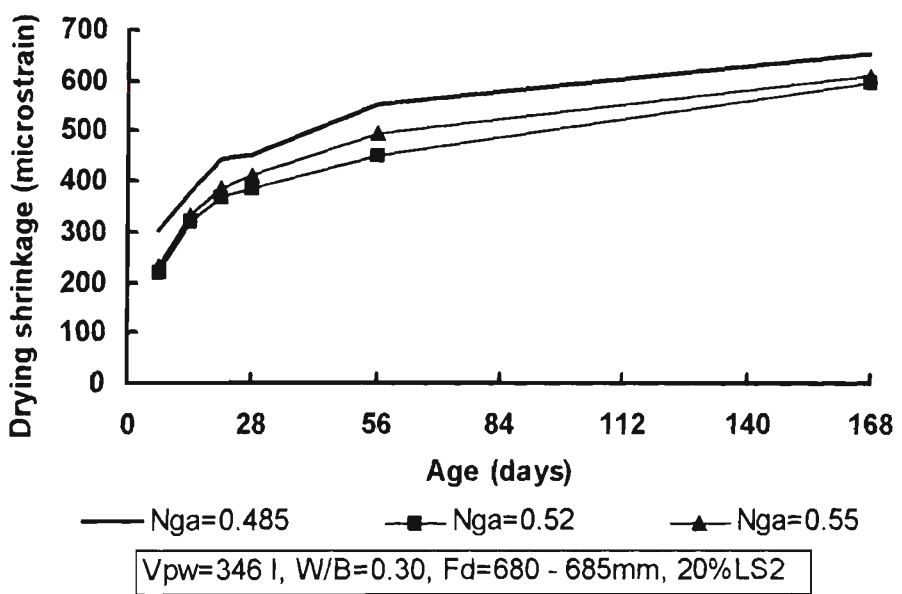


Fig. 6.9: Drying shrinkage of SC-HPC containing 20% of limestone LS2 with constant paste volume of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.485, 0.52 and 0.55 (W/B = 0.30)

Similarly to the case of water to binder ratio of 0.30, for water to binder ratio of 0.35, the coarse aggregate volume of 302.05 l/m<sup>3</sup>, which equals to 50% of solid volume of compacted coarse aggregate was also chosen to produce concrete with total paste



volume of about 346 l/m<sup>3</sup> and coarse to total aggregate ratio of 0.483. This is compared with respect to concrete with a similar paste volume of 346 l/m<sup>3</sup>, water to binder ratio of 0.35 and Nga of 0.52. As can be seen from Appendices 6.1, 6.2, 6.3, Fig. 6.10, 6.11 and 6.12, for constant water to binder ratio of 0.35 and similar paste volume of 346 l/m<sup>3</sup>, SC-HPC with Nga of 0.52 reduced the superplasticizer requirement, exhibited similar compressive strength and lower drying shrinkage, in comparison with that having Nga of 0.483. This is due to the fact that, for the same aggregate volume (i.e., the same paste volume), concrete with Nga of 0.52 had lower aggregate particle surface area and void content in aggregate mixture; therefore, the value of Dss was larger than that with Nga of 0.483. This led to the lower superplasticizer requirement and lower drying shrinkage of SC-HPC with Nga of 0.52.

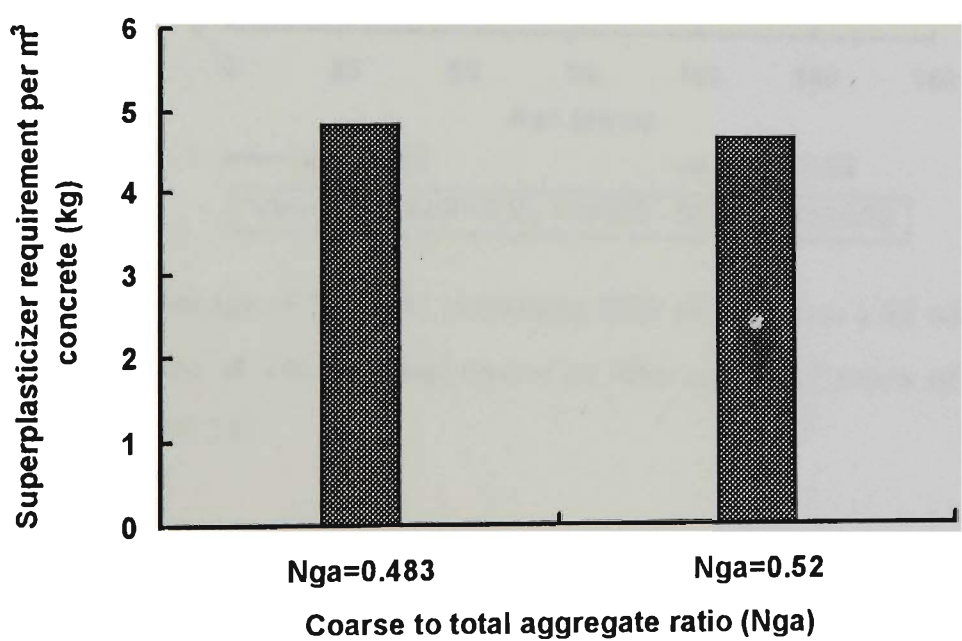


Fig. 6.10: Superplasticizer requirement of SC-HPC containing 20% of limestone LS2 with constant paste volume of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.483 and 0.52 (W/B=0.35)

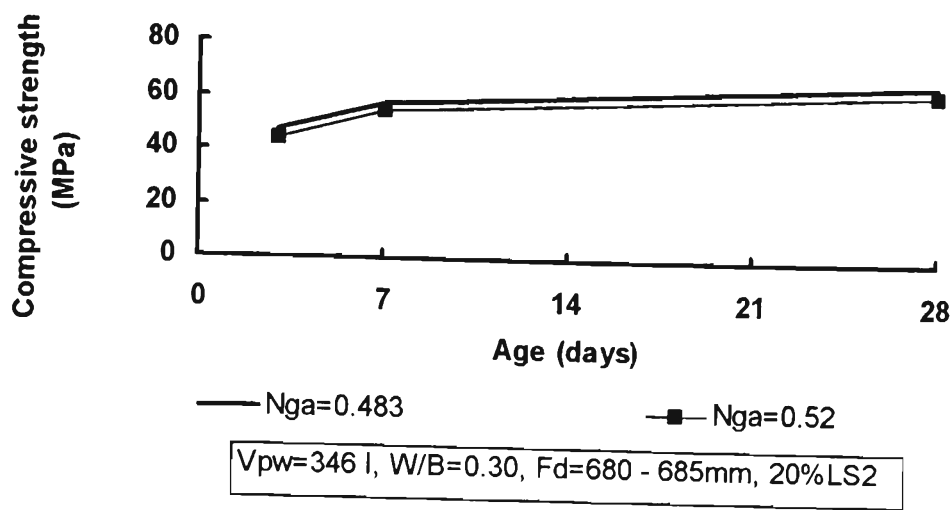


Fig. 6.11: Compressive strength of SC-HPC containing 20% of limestone LS2 with constant paste volume of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.483 and 0.52 (W/B=0.35)

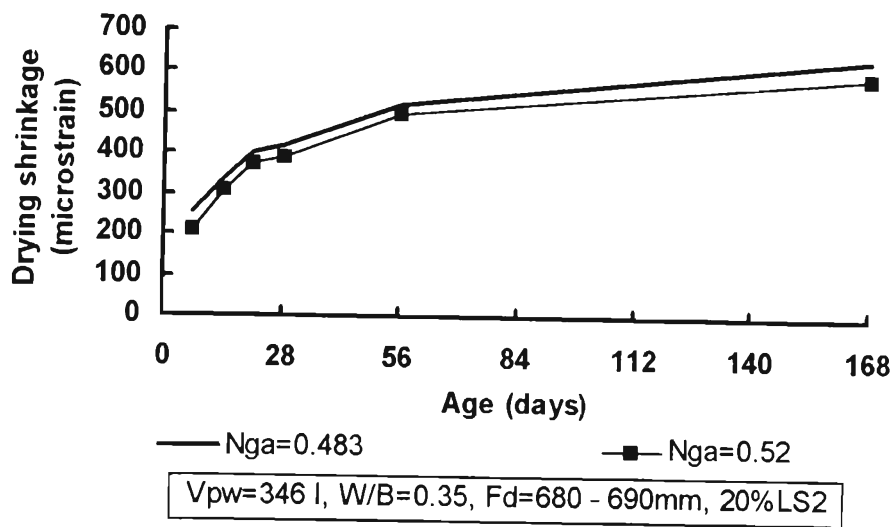


Fig. 6.12: Drying shrinkage of SC-HPC containing 20% of limestone LS2 with constant paste volume of 346 l/m<sup>3</sup> and coarse to total aggregate ratios of 0.483 and 0.52 (W/B=0.35)

In summary, test results indicate that coarse to total aggregate ratio affects considerably not only the blocking property, but also on the superplasticizer requirement and drying shrinkage of SC-HPC; and there is an optimum coarse to total aggregate ratio which enhances low drying shrinkage of SC-HPC. Coarse to total aggregate ratio of 0.52 was the most suitable Nga when considering blocking property, superplasticizer requirement, drying shrinkage and compressive strength of SC-HPC.

### **6.3. EFFECT OF FINENESS OF MILLED LIMESTONE ON PROPERTIES OF SELF-COMPACTING HIGH PERFORMANCE CONCRETE**

In order to investigate the effect of fineness of milled limestone on properties of SC-HPC, concretes containing 20% of limestones LS1 (coarse), LS2 (fine) and LS3 (very fine) with similar paste volumes and constant coarse to total aggregate ratio (Nga) of 0.52 (by weight) were tested.

#### **6.3.1. Superplasticizer Requirement**

For similar paste volumes of about  $413 \text{ l/m}^3$ , constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, as well as similar slump flow diameters, concrete containing 20% of limestones LS2 and LS3 required similar superplasticizer dosage, being about 49% lower than that containing 20% of limestone LS1 (Fig. 6.13). The results were similar to those for vibrated high performance concrete (V-HPC). Again, this is due to the fact that limestones LS2 and LS3 had average particle sizes smaller (e.g. higher fineness) than limestone LS1 and pure cement; and they can fill the pores in the cement paste and therefore voids in the concrete matrix.

Similarly, for paste volumes of about  $393 \text{ l/m}^3$ , constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, concrete containing 20% of limestones LS2 and LS3 also required similar superplasticizer dosage (Fig. 6.14).

It is clear that the use of limestones LS2 and LS3, which had average particle size of about three and six times smaller than that of pure cement, can reduce considerably the required superplasticizer dosage in comparison with that when using limestone LS1.

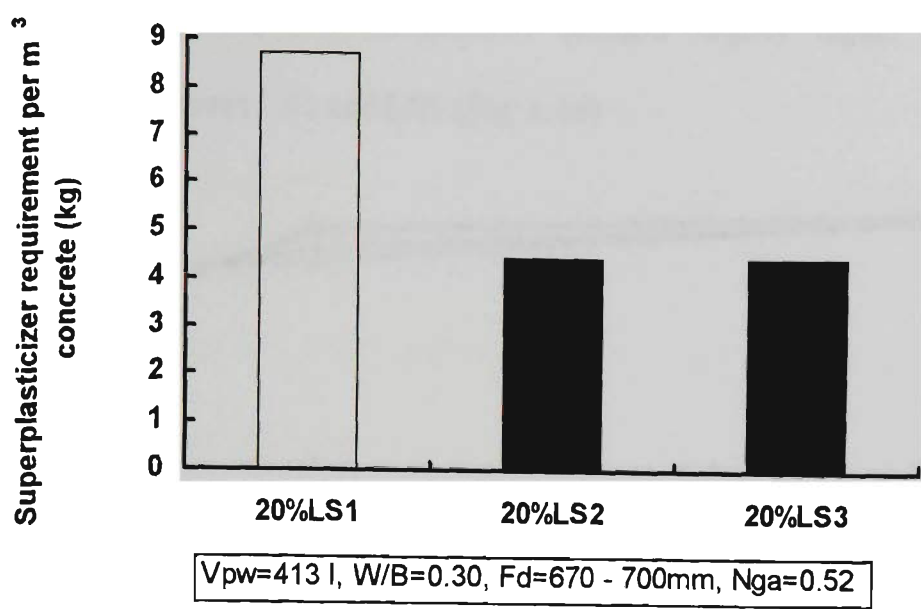


Fig. 6.13: Superplasticizer requirement of SC-HPC containing similar volumes of about 413 l/m³ and different limestone types

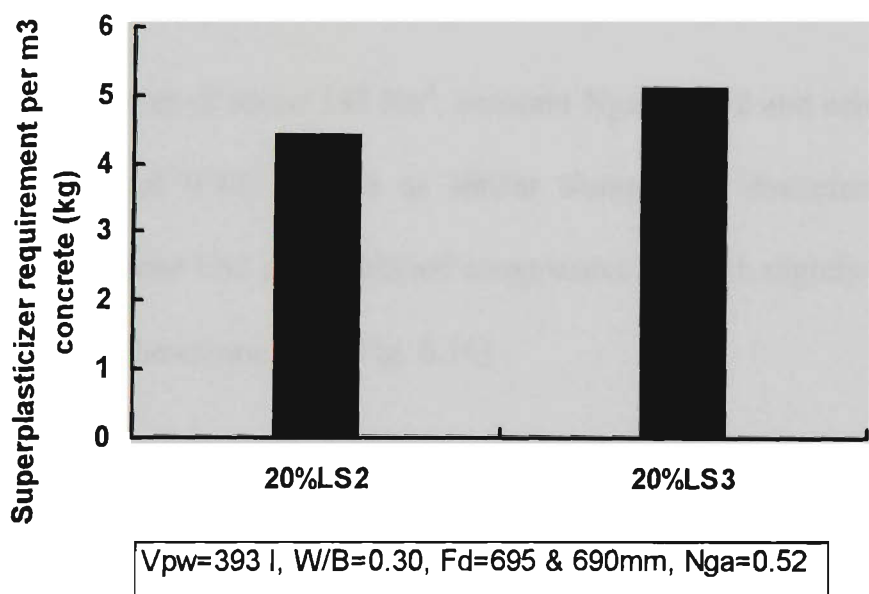


Fig. 6.14: Superplasticizer requirement of SC-HPC containing similar volumes of about 413 l/m³ and limestones LS2 and LS3

6.3.2. Compressive Strength

For similar paste volumes of about 413 l/m³, constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, as well as similar slump flow diameters, concrete containing

20% of limestone LS2 exhibited compressive strength slightly higher than those containing 20% of limestones LS1 and LS3 (Fig. 6.15).

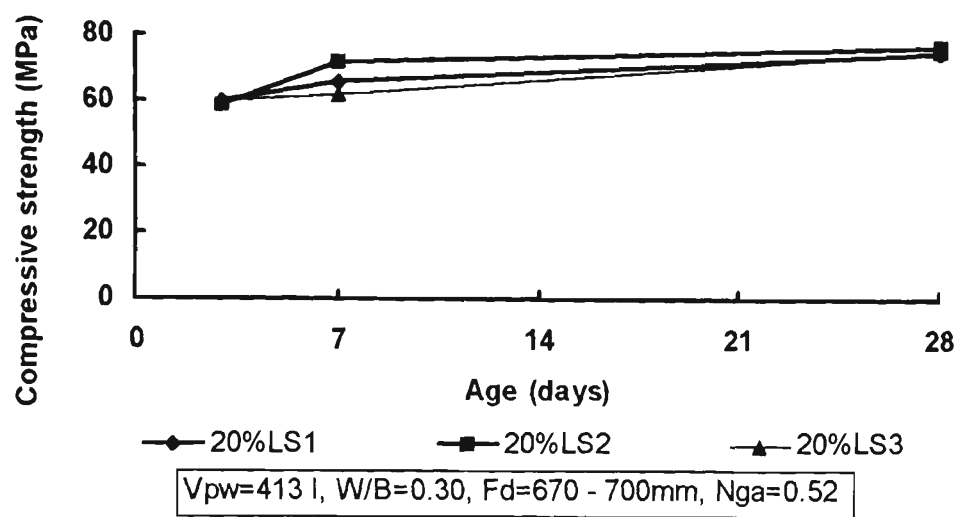


Fig. 6.15: Compressive strength of SC-HPC containing similar volumes of about 413 l/m<sup>3</sup> and different limestone types

Similarly, for paste volumes of about 393 l/m<sup>3</sup>, constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, as well as similar slump flow diameters, concrete containing 20% of limestone LS2 also exhibited compressive strength slightly higher than those containing 20% of limestone LS3 (Fig. 6.16).

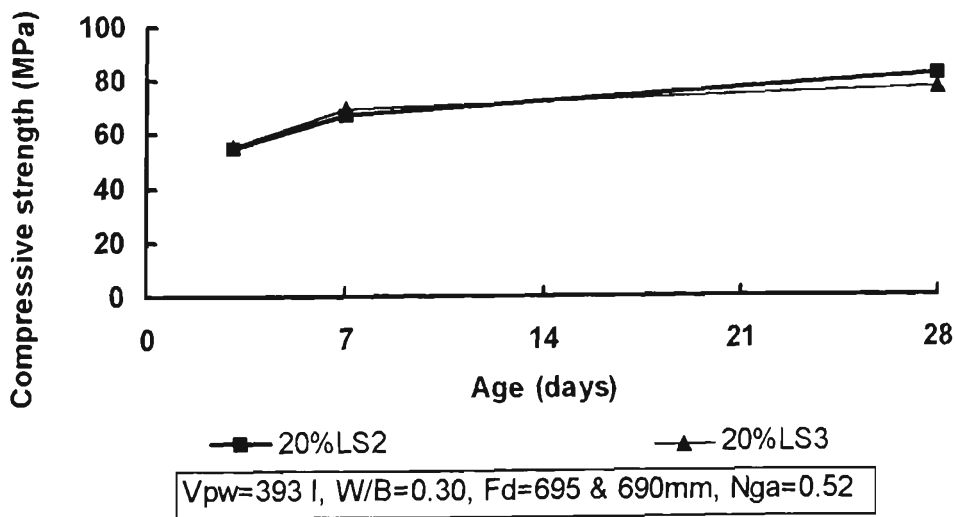


Fig. 6.16: Compressive strength of SC-HPC containing similar volumes of about 393 l/m<sup>3</sup> and limestones LS2 and LS3

6.3.3. Drying Shrinkage

For similar paste volumes of about 413 l/m<sup>3</sup>, constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, as well as similar slump flow diameters, concrete containing 20% of limestone LS1 exhibited the highest drying shrinkage at all ages in comparison with those containing 20% of limestones LS2 and LS3 (56-day drying shrinkage was about 36% and 53% higher than that of concrete containing 20% of limestones LS2 and LS3, respectively (Fig. 6.17)). Drying shrinkage of concrete containing 20% of limestone LS2 was 12% higher than that with 20% of limestone LS3 at 56 days and similar at 168 days.

For similar paste volumes of about 393 l/m<sup>3</sup>, constant Nga of 0.52 and constant water to binder ratio (W/B) of 0.30, as well as similar slump flow diameters, concrete containing 20% of limestone LS2 exhibited drying shrinkage, at all ages, lower than that with limestone LS3 (Fig. 6.18).

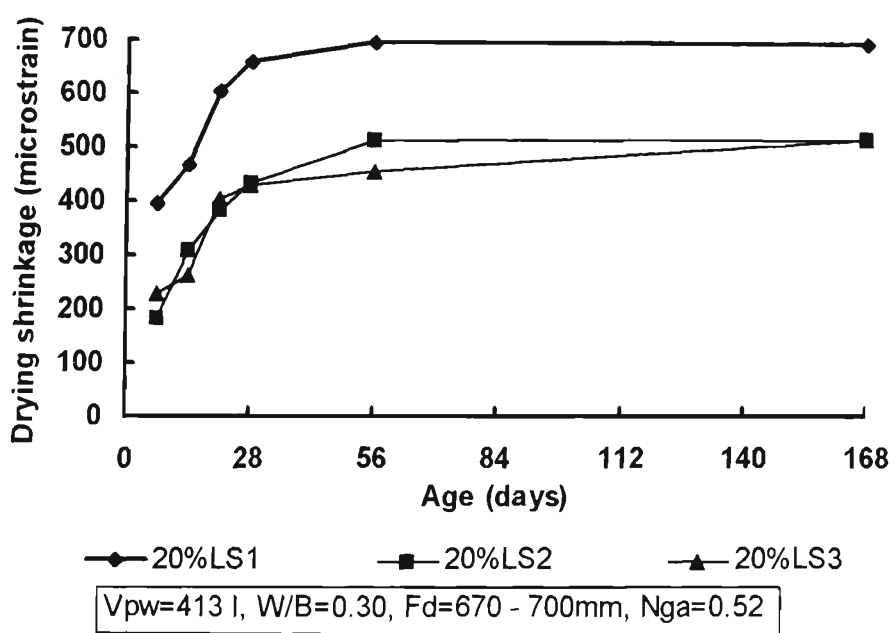


Fig. 6.17: Drying shrinkage of SC-HPC containing similar volumes of about 413 l/m<sup>3</sup> and different limestone types

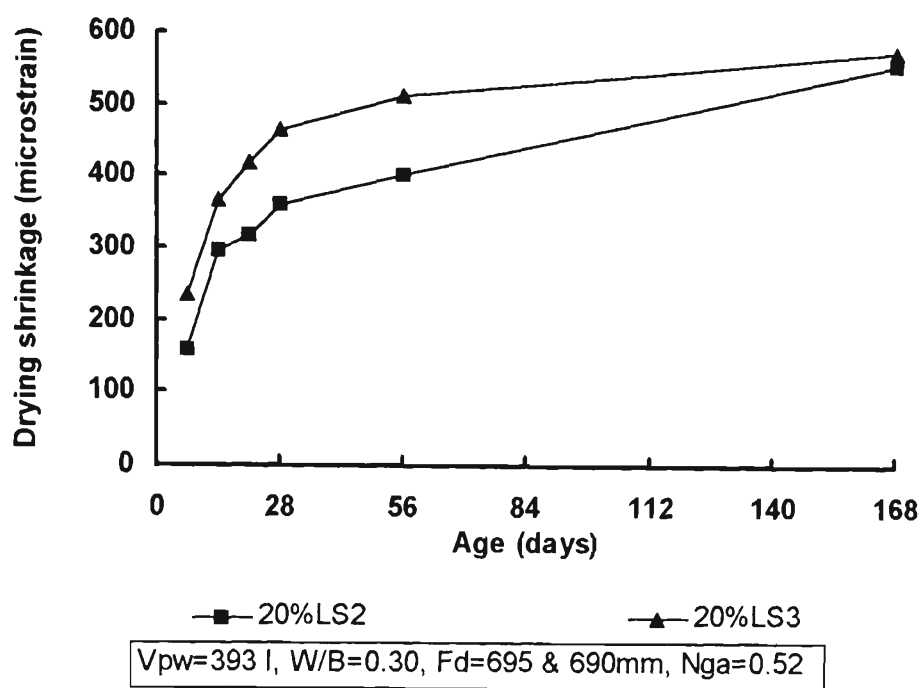


Fig. 6.18: Drying shrinkage of SC-HPC containing similar volumes of about 393 l/m<sup>3</sup> and limestones LS2 and LS3

As discussed above, limestone fineness has an effect mainly on superplasticizer requirement and drying shrinkage of SC-HPC. The use of milled limestones LS2 and LS3, with average particle size of about three and six times, respectively, smaller than pure cement, reduces considerably superplasticizer requirement and drying shrinkage of SC-HPC in comparison with that containing limestone LS1 which had average particle size slightly higher than that of pure cement. The reduction of superplasticizer requirement and drying shrinkage of concrete containing limestones LS2 and LS3 can be explained by the fact that the fine and very fine limestones can fill pores in cement paste and concrete, and this leads to more freely moving water in the concrete.

Test results also showed that limestone LS2 was the most suitable for SC-HPC from the view point of superplasticizer requirement, compressive strength and drying shrinkage. Therefore, limestone LS2 was used in subsequent tests in order to investigate the effect

of limestone content, water to binder ratio, paste volume and maximum aggregate sizes on properties of SC-HPC.

#### **6.4. EFFECT OF LIMESTONE CONTENT, WATER TO BINDER RATIO AND PASTE VOLUME ON PROPERTIES OF SC-HPC**

Concretes containing 10%, 20%, 25%, 30% and 40% of limestone LS2 with paste volumes of about 393 l/m<sup>3</sup> and 346 l/m<sup>3</sup> were tested. Water to binder ratios of 0.30 and 0.35 were used in the tests.

##### **6.4.1. Superplasticizer Requirement**

For constant water to binder ratio of 0.30, similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, concretes containing 10%, 20%, 25%, 30% and 40% of limestone LS2 required reduced superplasticizer dosages, being about 22%, 39%, 37%, 36% and 39%, respectively, lower than that with pure cement SPC2 (Fig.6.19). This indicated that the use of limestone LS2 reduced significantly the superplasticizer requirement. Concretes containing 20% and 40% of limestone LS2 required similar superplasticizer dosages, being the lowest ones in comparison with those of 10%, 25% and 30% of limestone LS2. Similarly, for constant water to binder ratio of 0.30, similar paste volumes of about 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 20% and 40% of limestone LS2 required similar superplasticizer dosages, being lower than that containing 30% of limestone LS2 (Fig. 6.20).

For constant water to binder ratio of 0.35, similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, concretes containing 10%, 20% and 40% of limestone LS2 required superplasticizer dosages being about 10%, 17% and 26%, respectively, lower



than that with pure cement SPC2 (Fig. 6.21). Also, for constant water to binder ratio of 0.35, similar paste volumes of about 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 10%, 20% and 40% of limestone LS2 required reduced superplasticizer dosages being about 16.3%, 21.0% and 44.3%, respectively, lower than that with pure cement SPC2 (Fig. 6.22).

As can be seen from Fig. 6.23, for similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, percentage reductions of required superplasticizer for concretes containing limestone LS2 with water to binder ratio of 0.30 were larger than those for concretes containing limestone LS2 with water to binder ratio of 0.35. This indicates that the use of limestone LS2 in concrete with low water to binder ratio is more effective in reducing superplasticizer requirement than for that with high water to binder ratio.

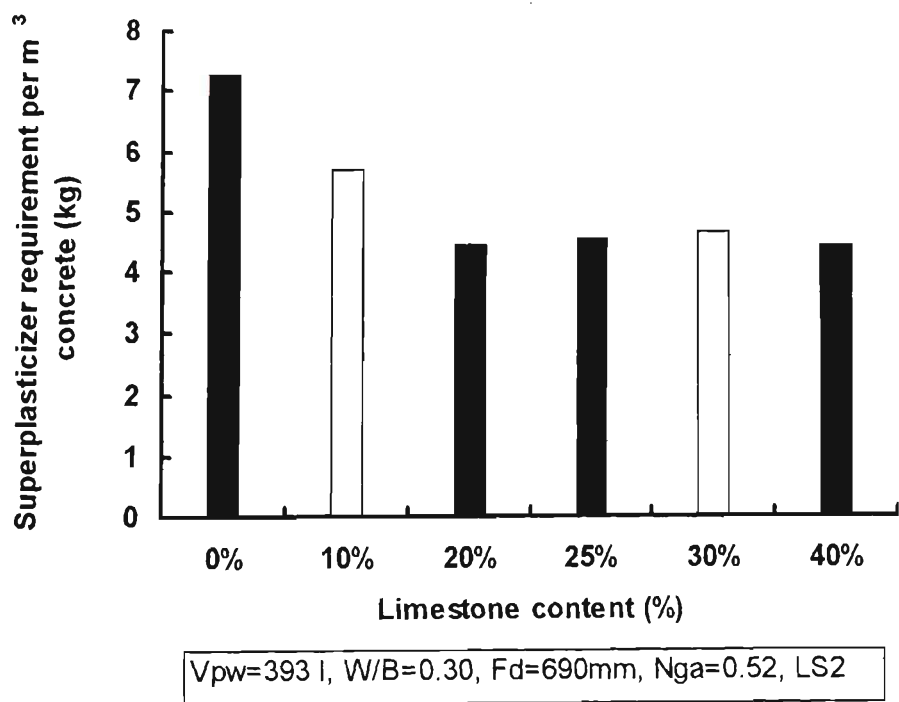


Fig. 6.19: Superplasticizer requirement for SC-HPC containing different contents of limestone LS2, similar paste volumes of about 393 l/m<sup>3</sup> (W/B = 0.30)

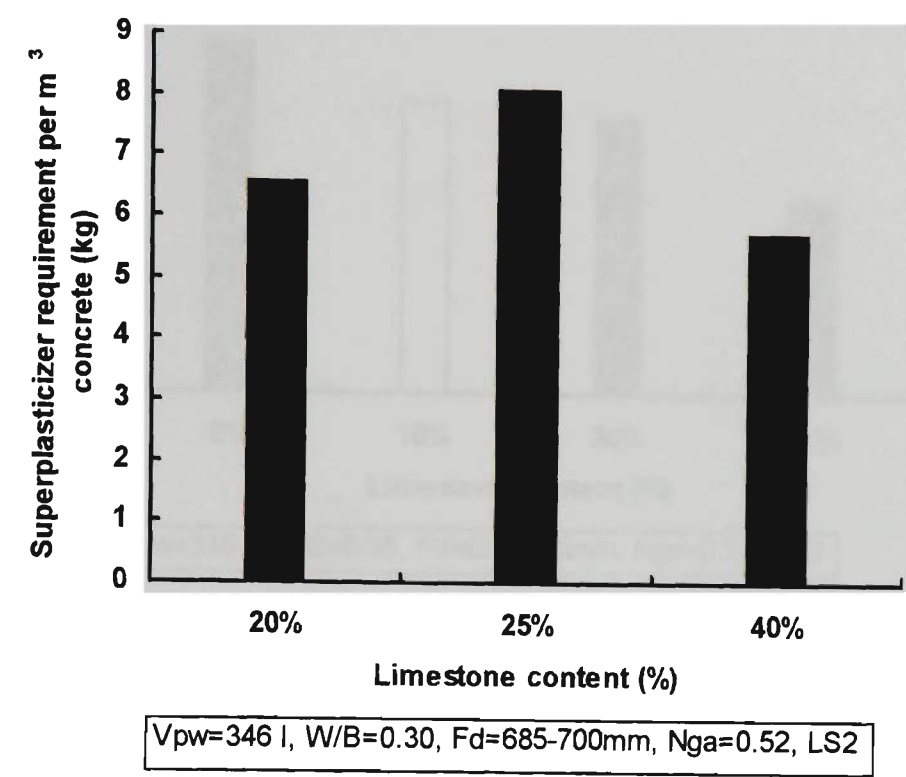


Fig. 6.20: Superplasticizer requirement for SC-HPC containing different contents of limestone LS2, similar paste volumes of about 346 l/m³ (W/B = 0.30)

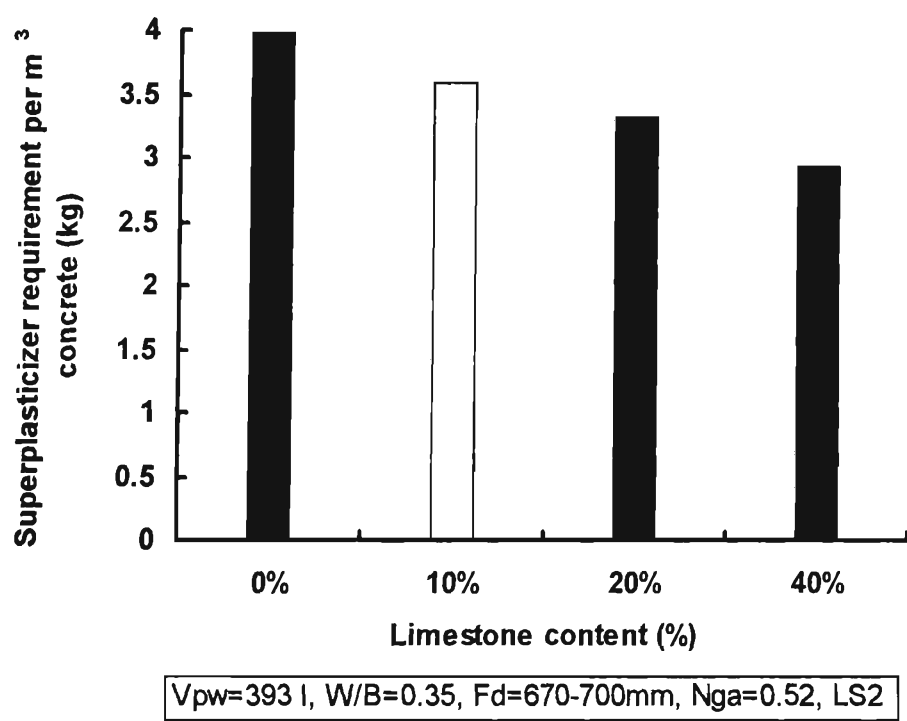


Fig. 6.21: Superplasticizer requirement for SC-HPC containing different contents of limestone LS2, similar paste volumes of about 393 l/m³ (W/B = 0.35)

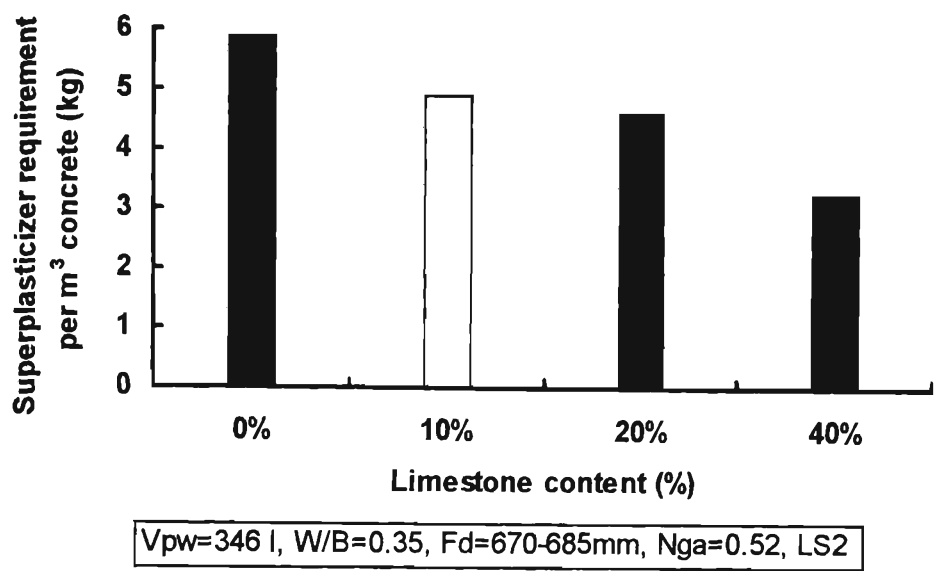


Fig. 6.22: Superplasticizer requirement for SC-HPC containing different contents of limestone LS2, similar paste volumes of about 346 l/m<sup>3</sup> (W/B = 0.35)

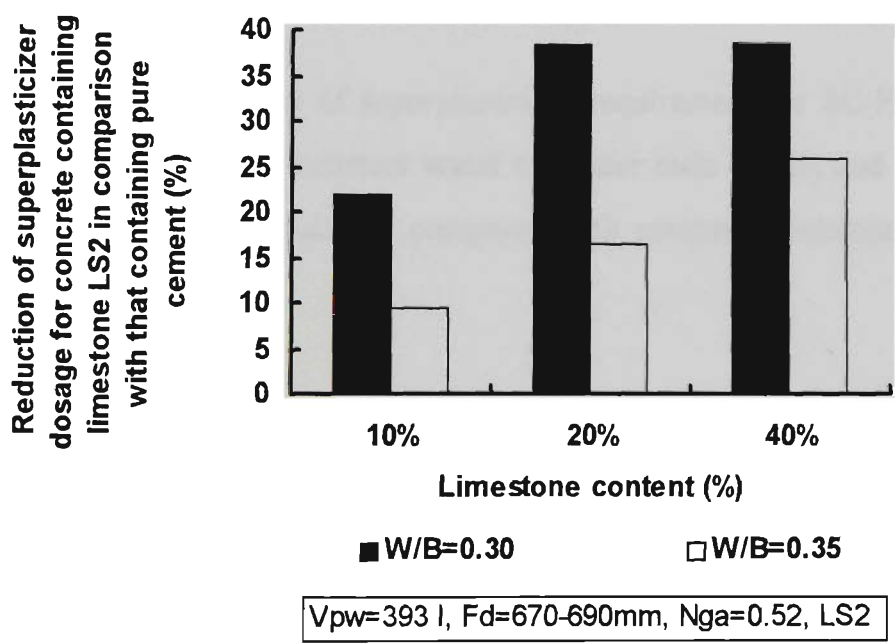


Fig. 6.23: Percentage reduction of superplasticizer requirement for SC-HPC containing limestone LS2 with different water to binder ratios (reductions compared with concrete containing pure cement SPC2)

Fig. 6.24 shows that, for constant water to binder ratio of 0.35 and similar slump diameters, percentage reductions of required superplasticizer for concretes containing limestone LS2 with paste volume (Vpw) of 346 l/m<sup>3</sup> were larger than those for concretes

containing limestone LS2 with paste volume (Vpw) of 393 l/m<sup>3</sup> This indicates that the use of limestone LS2 in concrete with low paste volume (Vpw) is more effective in reducing superplasticizer requirement than for that with high paste volume.

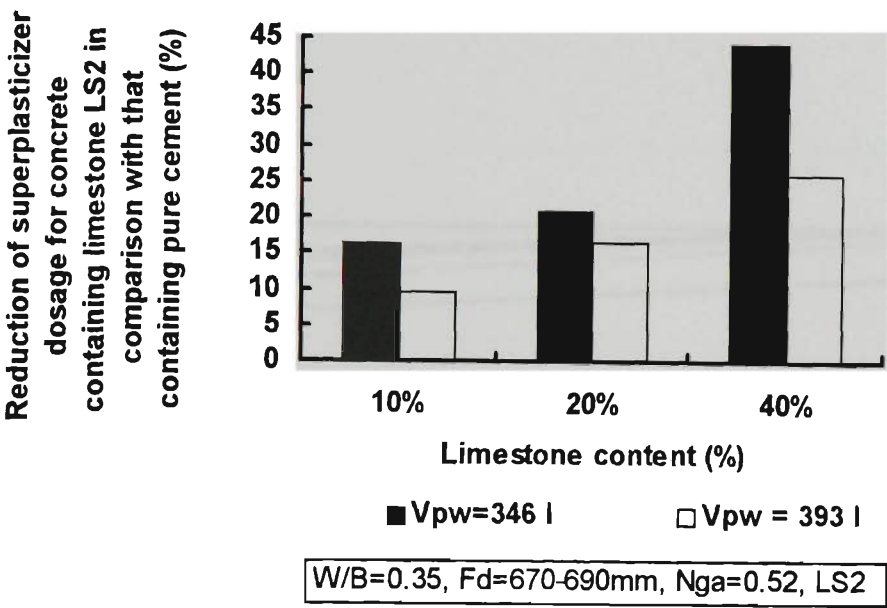


Fig. 6.24: Percentage reduction of superplasticizer requirement for SC-HPC containing limestone LS2 with constant water to binder ratio (W/B) and different paste volumes (Vpw) (reductions compared with concrete containing pure cement SPC2)

6.4.2. Compressive Strength

For constant water to binder ratio of 0.30, similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, concrete containing 10% of limestone LS2 exhibited the highest 28-day compressive strength; while concretes containing pure cement SPC2 and 20% of limestone LS2 had similar 28-day compressive strength, being about 2%, 10% and 22% higher than those containing 25%, 30% and 40% of limestone LS2, respectively (Fig.6.25 and Appendix 6.2). Concretes containing pure cement SPC2, 10%, 20% and 25% of limestone LS2 exhibited similar 362-day compressive strength, being about 4% and 16% higher than those containing 30% and 40% of limestone LS2 (Fig.6.25 and Appendix 6.2).

All concretes containing limestone content of up to 40% had compressive strength at age of 362 days higher than that at age of 28 days, except for the case of concrete containing 10% of limestone LS2, which exhibited similar compressive strength at ages of 28 days and 362 days.

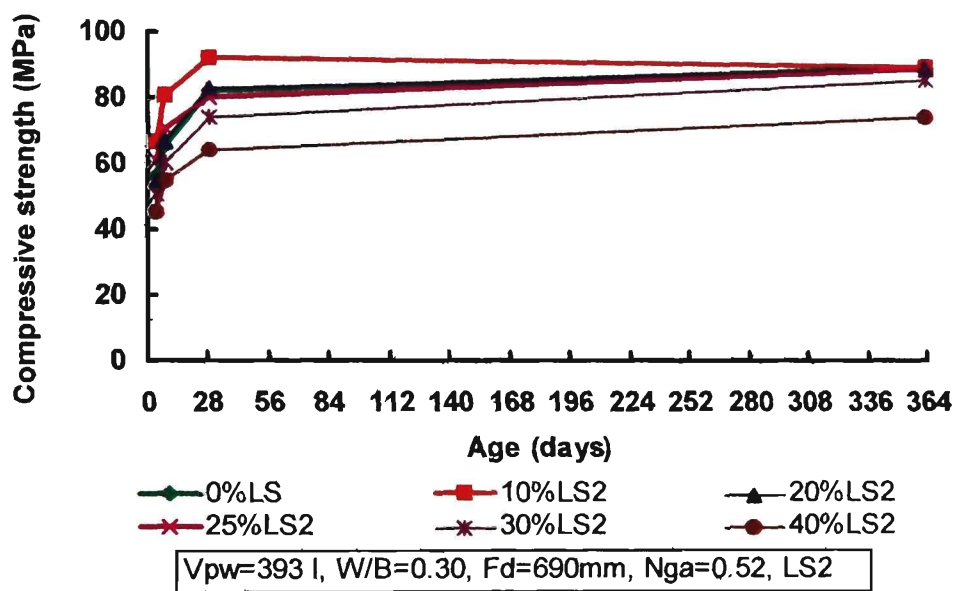


Fig. 6.25: Compressive strength of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 393 l/m<sup>3</sup> (W/B = 0.30)

For constant water to binder ratio of 0.30, similar paste volumes of about 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 25% and 40% of limestone LS2 exhibited 28-day compressive strength, being about 2% and 17% lower than that containing 20% of limestone LS2 (Fig. 6.26 and Appendix 6.2).

For water to binder ratio of 0.30 and paste volume between 346 l/m<sup>3</sup> and 393 l/m<sup>3</sup>, concretes containing limestone content between 10% and 40% exhibited 28-day compressive strength between 92 MPa and 63 MPa. This indicates that even with high limestone content (40%), compressive strength is still high.

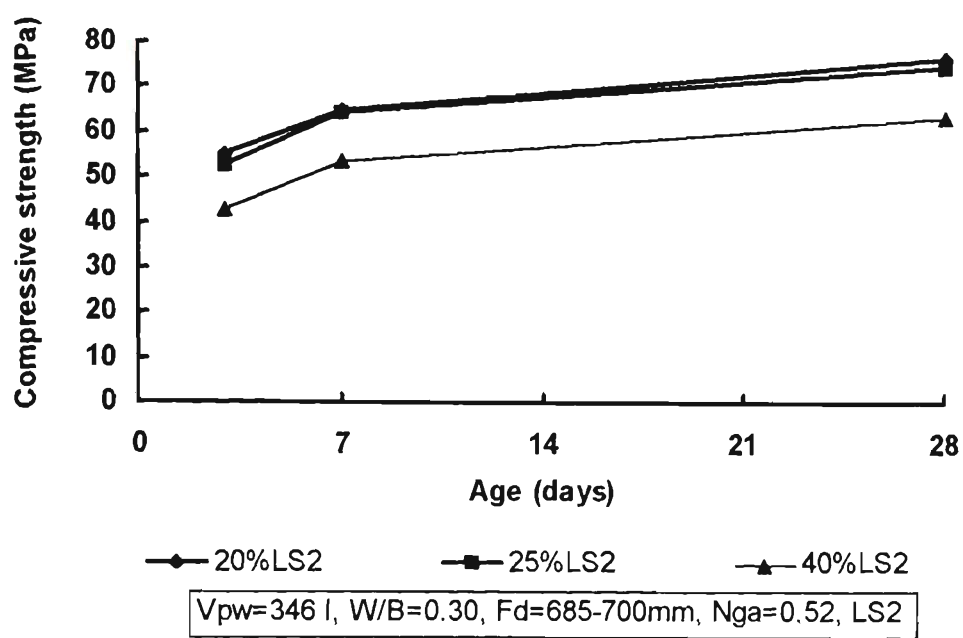


Fig. 6.26: Compressive strength of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 346 l/m<sup>3</sup> (W/B = 0.30)

For constant water to binder ratio of 0.35, similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, concrete containing 10%, 20% and 40% of limestone LS2 exhibited 28-day compressive strength about 4%, 18% and 43% lower than that with pure cement SPC2 (Fig. 6.27 and Appendix 6.2).

For constant water to binder ratio of 0.35, similar paste volumes of about 346 l/m<sup>3</sup> and similar slump diameters, concrete containing 10%, 20% and 40% of limestone LS2 exhibited 28-day compressive strength about 2%, 14% and 34% lower than that with pure cement SPC2 (Fig. 6.28 and Appendix 5.2).

As can be seen from Fig. 6.29, with regard to 28-day compressive strength, the use of limestone LS2 in SC-HPC with low water to binder ratio (W/B = 0.30) is more effective than that with high water to binder ratio (W/B = 0.35).

For water to binder ratio of 0.35, concretes containing limestone LS2 with low paste volume ( $V_{pw} = 346 \text{ l/m}^3$ ) exhibited 28-day compressive strength reduction marginally lower than that with high paste volume ( $V_{pw} = 393 \text{ l/m}^3$ ) (Fig. 6.30).

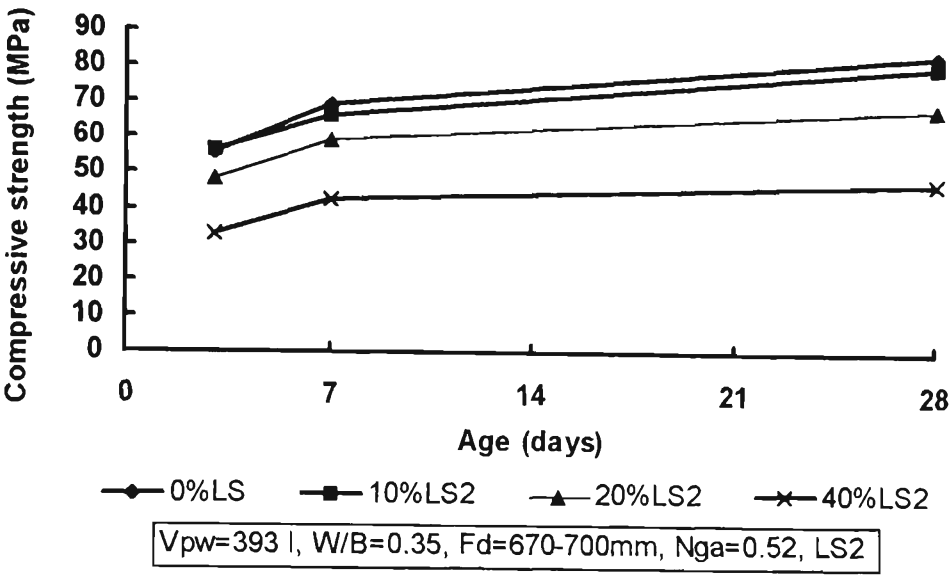


Fig. 6.27: Compressive strength of SC-HPC containing different contents of limestone LS2, similar paste volumes of about  $393 \text{ l/m}^3$  ( $W/B = 0.35$ )

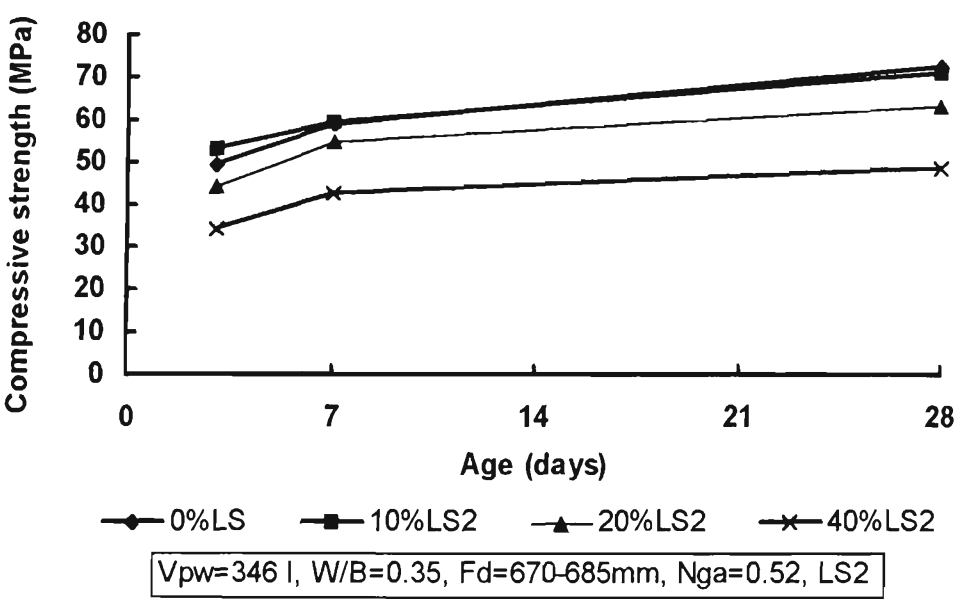


Fig. 6.28: Compressive strength of SC-HPC containing different contents of limestone LS2, similar paste volumes of about  $346 \text{ l/m}^3$  ( $W/B = 0.35$ )

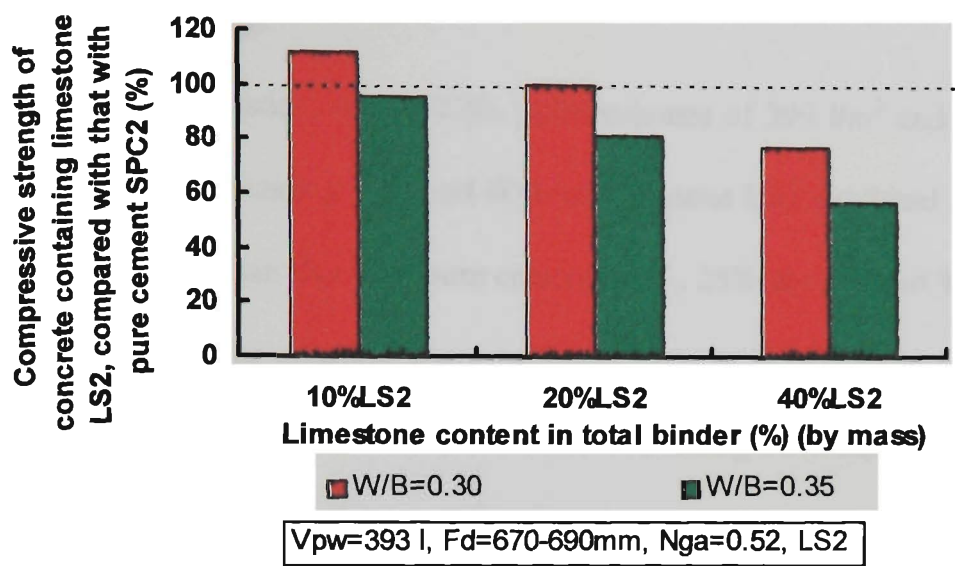


Fig. 6.29: Comparison of 28-day compressive strength of SC-HPC containing different contents of limestone LS2 with different water to binder ratios

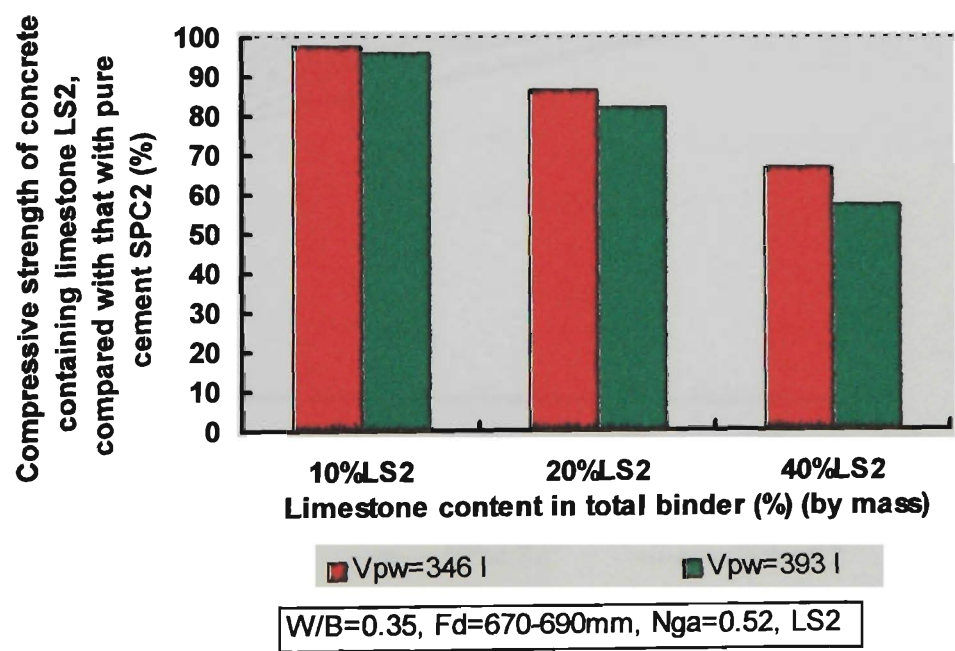


Fig. 6.30: Comparison of 28-day compressive strength of SC-HPC containing different contents of limestone LS2 with different paste volumes (Vpw)

For water to binder ratio of 0.35, concretes containing limestone content between 10% and 40% of total binder mass exhibited 28-day compressive strength between 81 MPa and 48 MPa, respectively (Appendix 6.2).



6.4.3. Drying Shrinkage

For constant water to binder ratio of 0.30, paste volumes of 393 l/m<sup>3</sup> and similar slump diameters, concretes containing 20% and 40% of limestone LS2 exhibited similar drying shrinkage, being lower than that with pure cement, 10%, 25% and 30% of limestone LS2 (Fig. 6.31). Likewise, for constant water to binder ratio of 0.30, similar paste volumes of 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 20% and 40% of limestone LS2 exhibited similar drying shrinkage, being lower than that with 25% of limestone LS2 (Fig. 6.32).

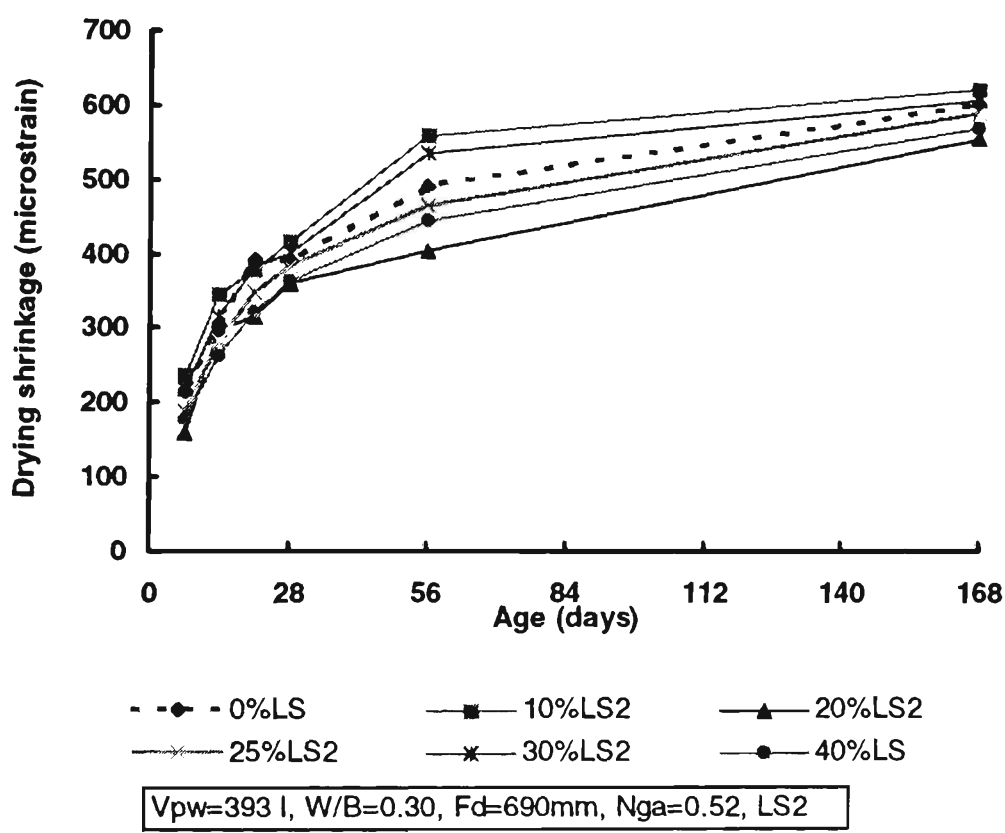


Fig. 6.31: Drying shrinkage of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 393 l/m<sup>3</sup> (W/B = 0.30)

For constant water to binder ratio of 0.35, paste volumes of 393 l/m<sup>3</sup> and 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 10%, 20% and 40% of limestone LS2 exhibited drying shrinkage, at all ages, lower than that with pure cement; drying

shrinkage of concrete containing 40% of limestone being lowest (Fig. 6.33 and 6.34). For water to binder ratio of 0.35, the effect of limestone on drying shrinkage reduction of self-compacting HPC was similar to that for vibrated HPC with the same water to binder ratio (Fig. 5.11 in Chapter 5).

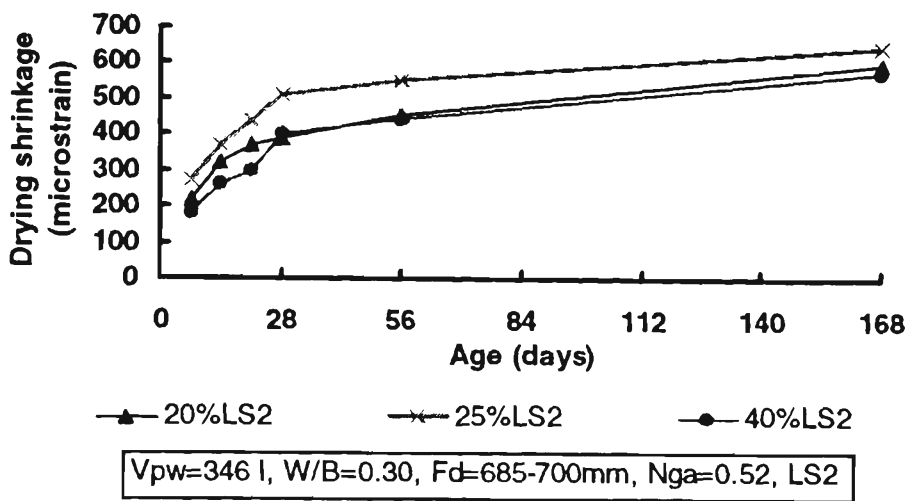


Fig. 6.32: Drying shrinkage of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 346 l/m<sup>3</sup> (W/B = 0.30)

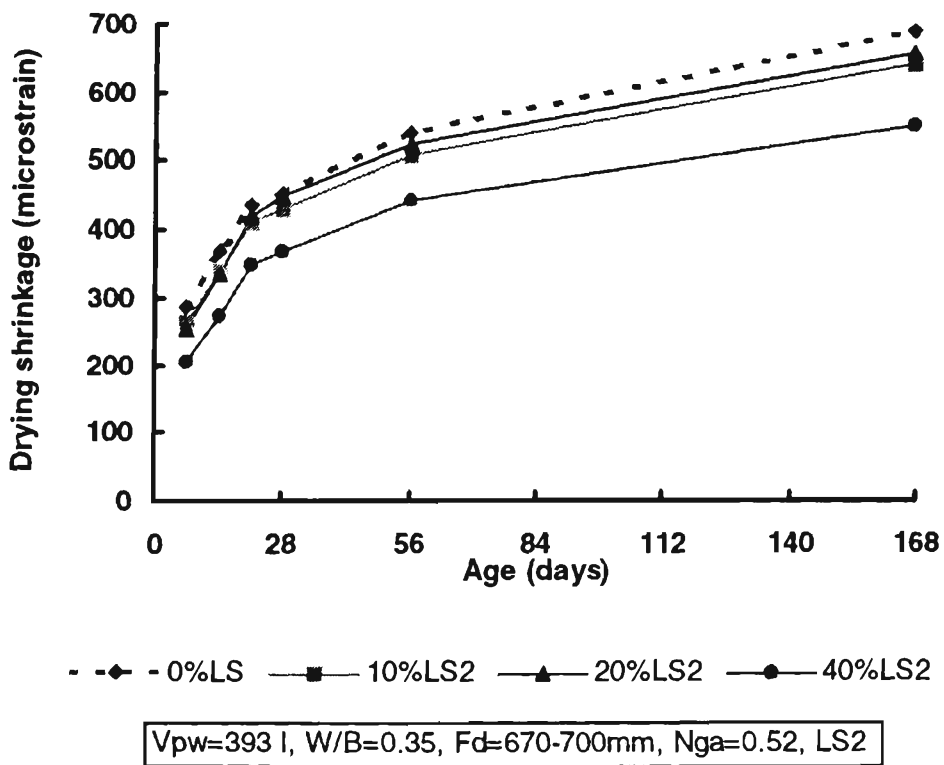


Fig. 6.33: Drying shrinkage of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 393 l/m<sup>3</sup> (W/B = 0.35)

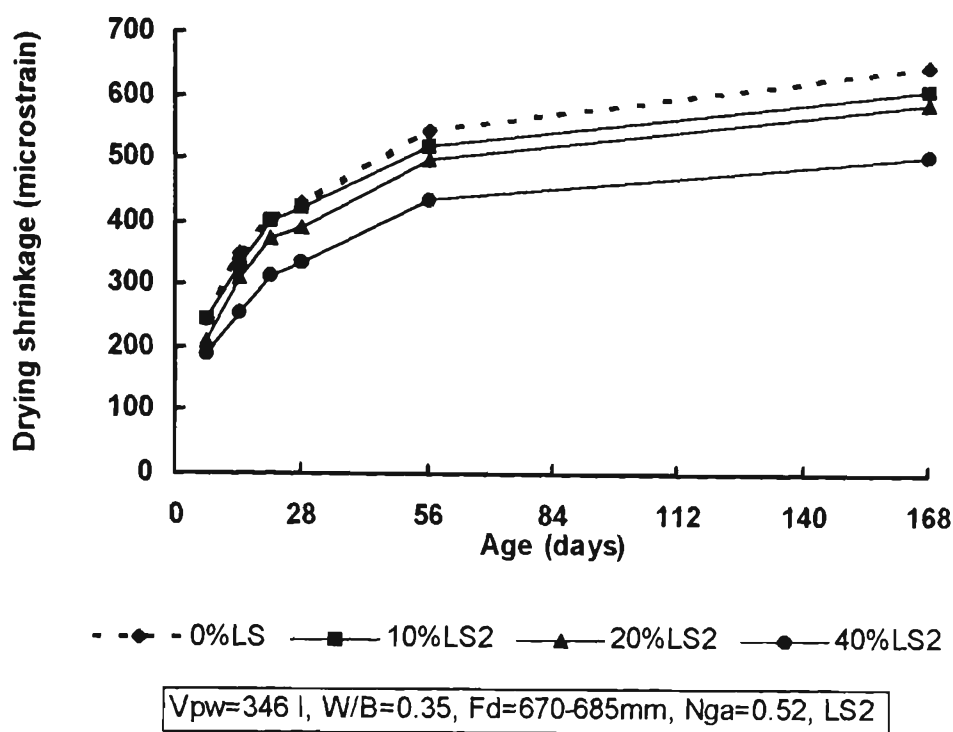


Fig. 6.34: Drying shrinkage of SC-HPC containing different contents of limestone LS2, similar paste volumes of about 346 l/m<sup>3</sup> (W/B = 0.35)

For similar paste volumes of about 393 l/m<sup>3</sup> and similar slump diameters, concretes containing 10%, 20% and 40% of limestone LS2 with water to binder ratio of 0.30 exhibited 168-day drying shrinkage generally lower than those containing limestone LS2 with high water to binder ratio of 0.35 (Fig. 6.35). Conversely, for similar paste volumes of about 346 l/m<sup>3</sup> and similar slump diameters, concretes containing 20% and 40% of limestone LS2 with water to binder ratio of 0.30 exhibited 168-day drying shrinkage generally higher than those containing limestone LS2 with high water to binder ratio of 0.35 (Fig. 6.36). This is likely due to the fact that, for low water to binder ratio of 0.30, the lower paste volume of 346 l/m<sup>3</sup> was not sufficient to ensure good compaction of SC-HPC; while this paste volume can be sufficient for the case with the higher water to binder ratio of 0.35.

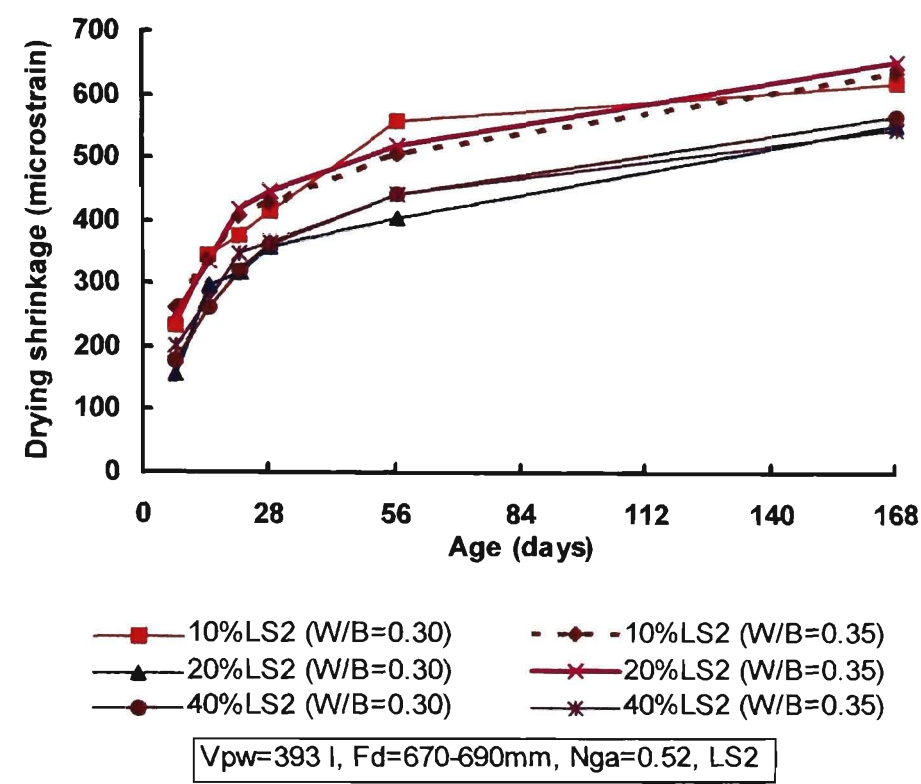


Fig. 6.35: Drying shrinkage of SC-HPC containing similar paste volumes of about 393 l/m<sup>3</sup> and different water to binder ratios

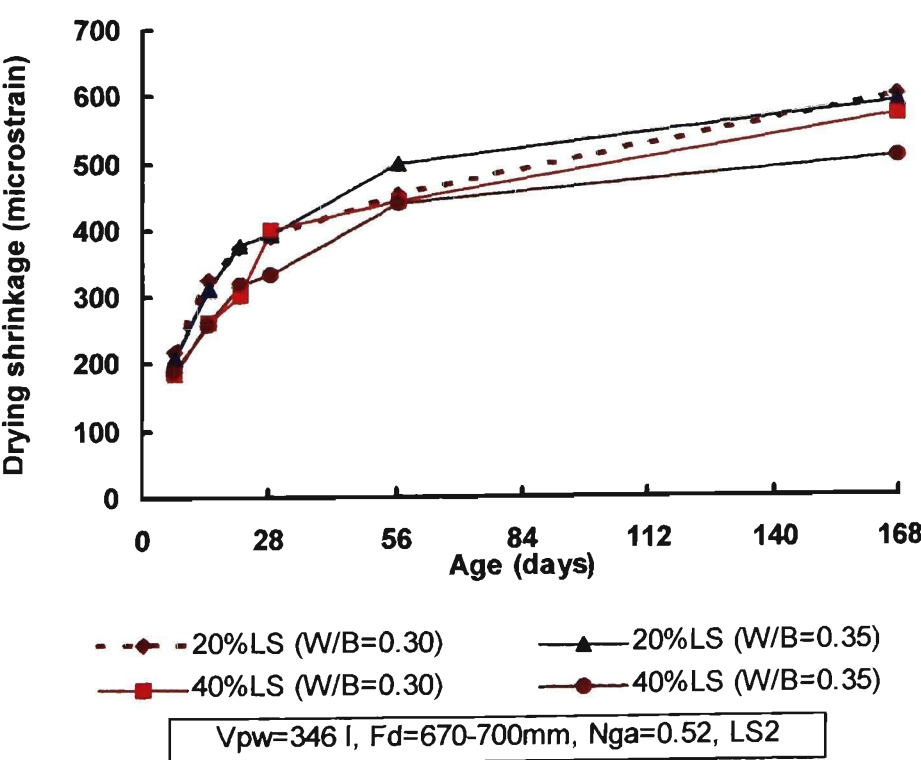


Fig. 6.36: Drying shrinkage of SC-HPC containing similar paste volumes of about 346 l/m<sup>3</sup> and different water to binder ratios

For constant water to binder ratio of 0.30 and similar slump diameters, concretes containing 20%, 25% and 40% of limestone LS2 with paste volume of 393 l/m<sup>3</sup> exhibited drying shrinkage, at all ages, lower than those containing limestone LS2 with paste volume of 346 l/m<sup>3</sup> (Fig. 6.37 and 6.38). Conversely, for constant water to binder ratio of 0.35 and similar slump diameters, concretes containing 10%, 20% and 40% of limestone LS2 with paste volume of 393 l/m<sup>3</sup> exhibited drying shrinkage, at all ages, higher than those containing limestone LS2 with paste volume of 346 l/m<sup>3</sup> (Fig. 6.39 and 6.40). These results support the previous hypothesis, and showed that, in order to have good compaction, the minimum required paste volume of SC-HPC depends not only on particle size distribution and void content of aggregates, but also on water to binder ratio. This finding is discussed in detail later (see section 8.4 “minimum paste volume in considering liquid-phase criteria of SCC” in Chapter 8) and contributes to development of the mixture proportioning method of SC-HPC described in Chapter 8.

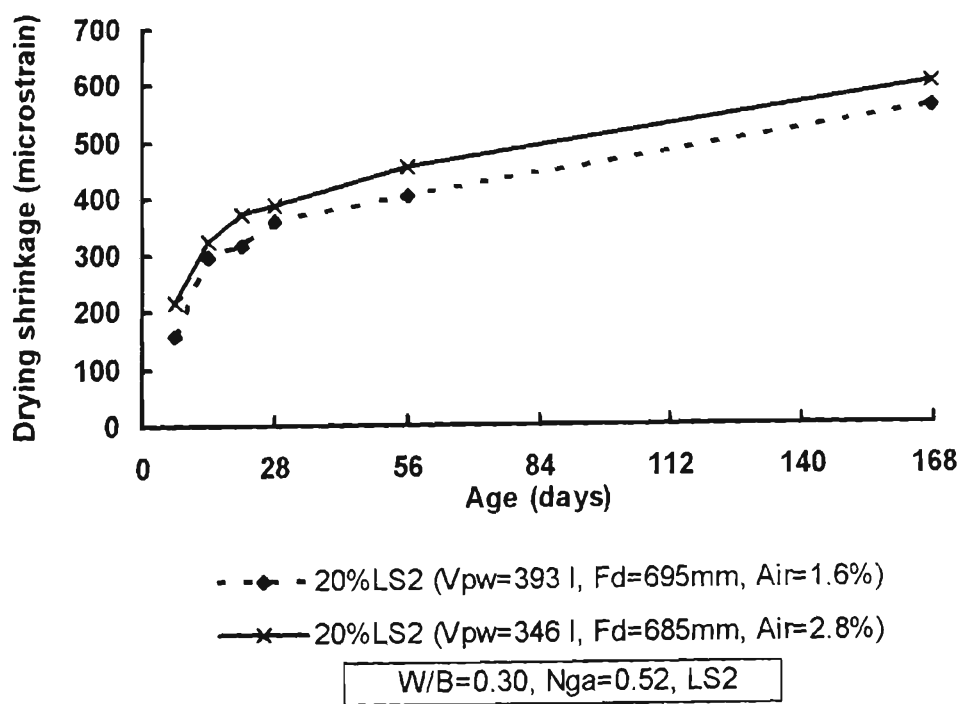


Fig. 6.37: Drying shrinkage of SC-HPC containing 20% of limestone LS2 with constant water to ratio of 0.30 and different paste volumes

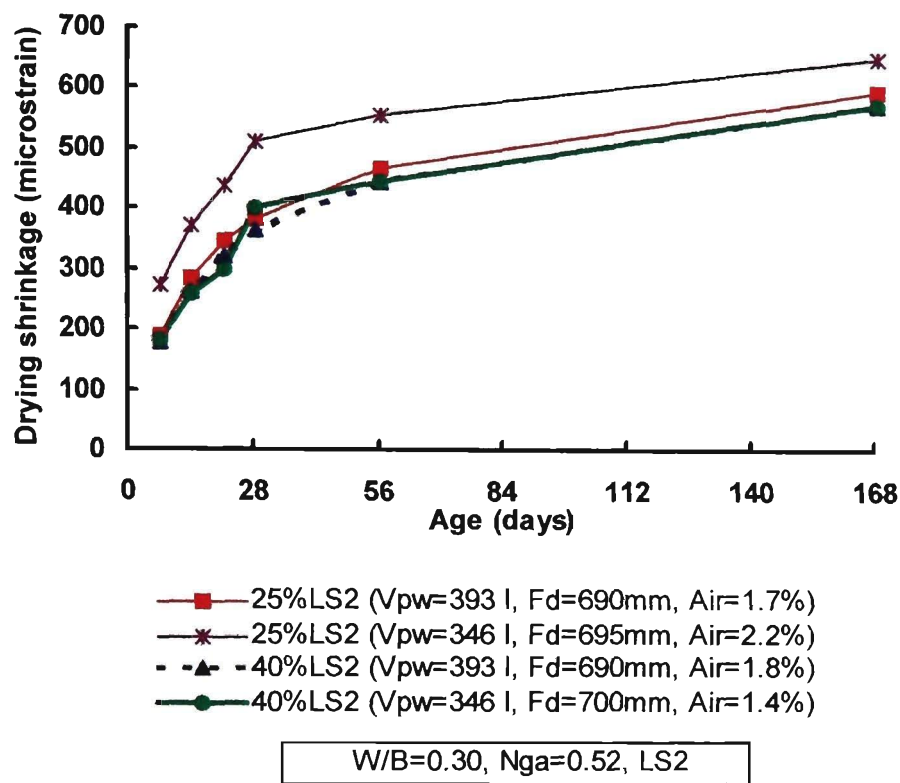


Fig. 6.38: Drying shrinkage of SC-HPC containing 25% and 40% of limestone LS2 with constant water to ratio of 0.30 and different paste volumes

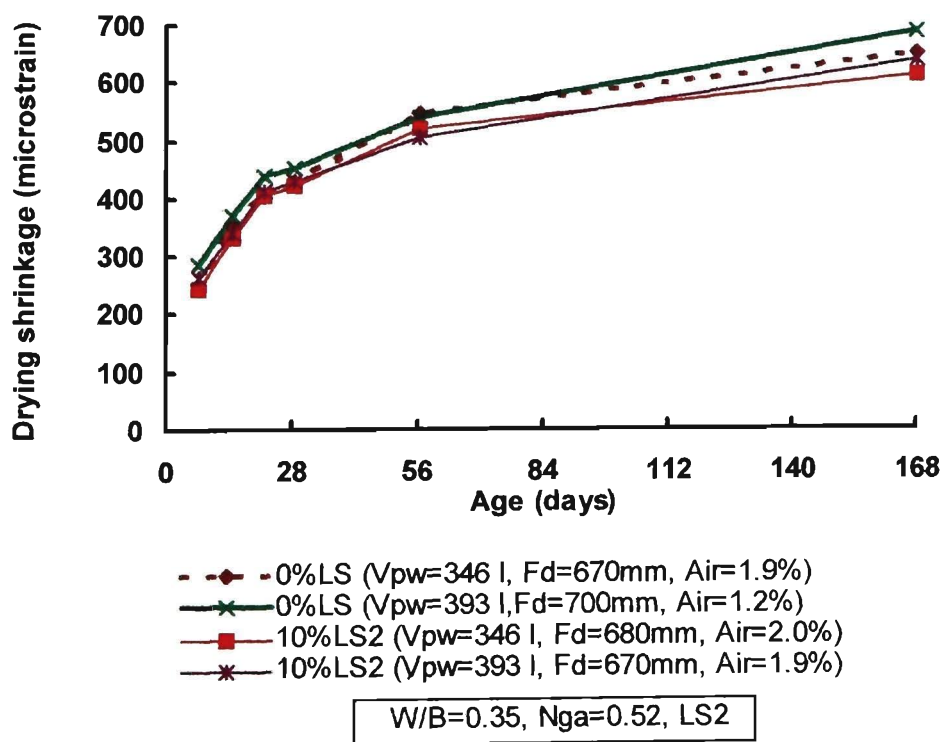


Fig. 6.39: Drying shrinkage of SC-HPC containing 0% and 10% of limestone LS2 with constant water to ratio of 0.35 and different paste volumes

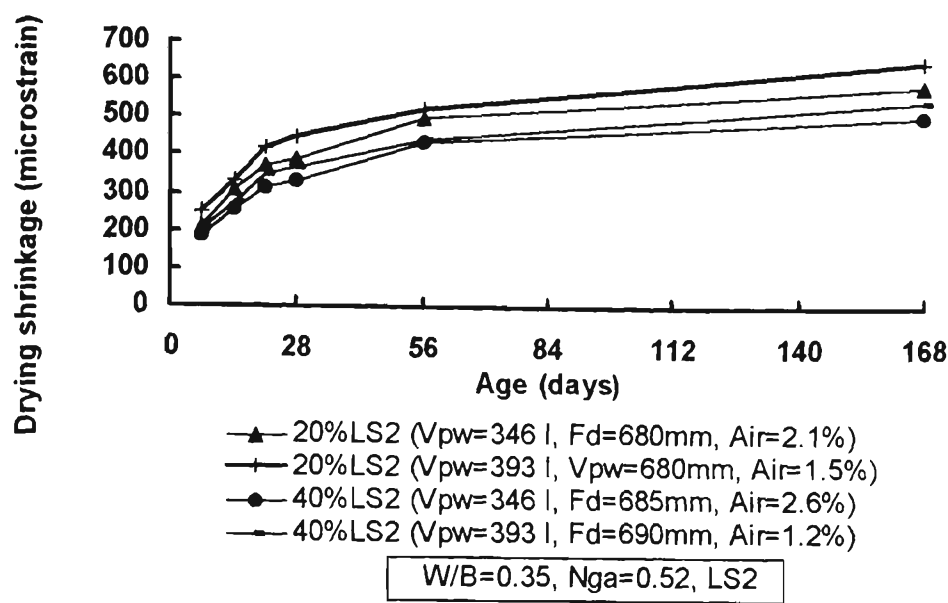


Fig. 6.40: Drying shrinkage of SC-HPC containing 20% and 40% of limestone LS2 with constant water to ratio of 0.35 and different paste volumes

In summary, the use of 10%, 20%, 25%, 30% and 40% of limestone LS2 reduced considerably the superplasticizer requirement and drying shrinkage of self-compacting high performance concrete. SC-HPC containing 10 to 40% of limestone LS2 with water to binder ratios of 0.30 and 0.35 exhibited 28-day compressive strength between 92 MPa and 48 MPa.

With regard to superplasticizer requirement, compressive strength and drying shrinkage, the use of limestone LS2 in SC-HPC with low water to binder ratio ( $W/B = 0.30$ ) was more beneficial than with high water to binder ratio ( $W/B = 0.35$ ). The use of limestone LS2 in SC-HPC with low paste volumes resulted in higher percentage reduction of superplasticizer dosage, lower reduction in compressive strength and lower drying shrinkage, than for those with high paste volume. However, lower water to binder ratio requires higher minimum paste volume in order to achieve good compaction and satisfactory performance of SC-HPC.

## **6.5. EFFECT OF AGGREGATE WITH DIFFERENT MAXIMUM SIZES ON PROPERTIES OF SC-HPC**

In order to investigate the effect of coarse aggregate maximum sizes on properties of SC-HPC, coarse aggregate with maximum sizes of 20 mm and 14 mm were combined with 10-mm maximum size aggregate with mass ratios of 62 : 38 and 70 : 30, respectively. Shrinkage limited portland cement SPC1 and 20% of limestone LS2 were used in concretes. Mixture proportions were the same for the concretes except for the coarse aggregate combination and superplasticizer dosage that was adjusted in order to obtain similar slumps. Test results are presented in Fig. 6.41, 6.42 and 6.43.

For constant content of all components and similar slumps, concrete containing 20% of limestone LS2 with coarse aggregate having maximum size of 20 mm and 14 mm required similar superplasticizer dosage, being considerably lower than that containing pure cement SPC1 with 20-mm coarse aggregate (Fig. 6.41).

With the use of 20-mm coarse aggregate, concrete containing 20% of limestone LS2 and pure cement exhibited similar 28-day compressive strengths, being slightly lower than that with 14-mm coarse aggregate (Fig. 6.42). The 56-day drying shrinkage of concrete containing 20% of limestone LS2 with 20-mm and 14-mm coarse aggregate was lowest and highest, respectively (Fig. 6.43). Test results suggest that attention to control of drying shrinkage of SC-HPC may be necessary if the 14-mm coarse aggregate is used.



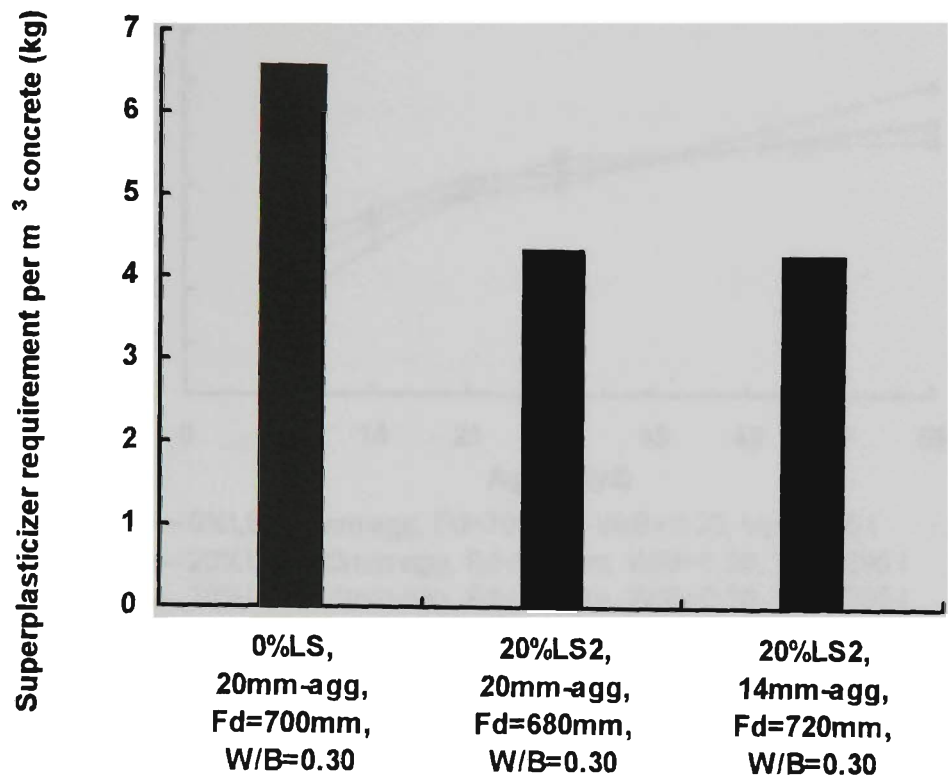


Fig. 6.41: Superplasticizer requirement of SC-HPC containing 20% of limestone LS2 with coarse aggregate with maximum sizes of 20 mm and 14 mm

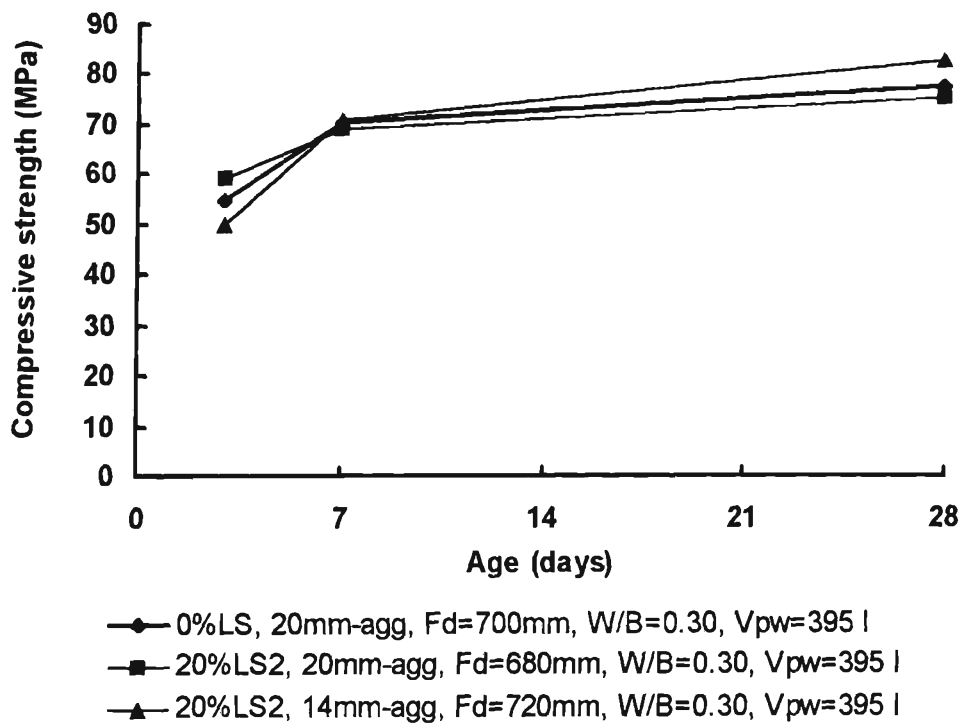


Fig. 6.42: Compressive strength of SC-HPC containing 20% of limestone LS2 with coarse aggregate with maximum sizes of 20 mm and 14 mm

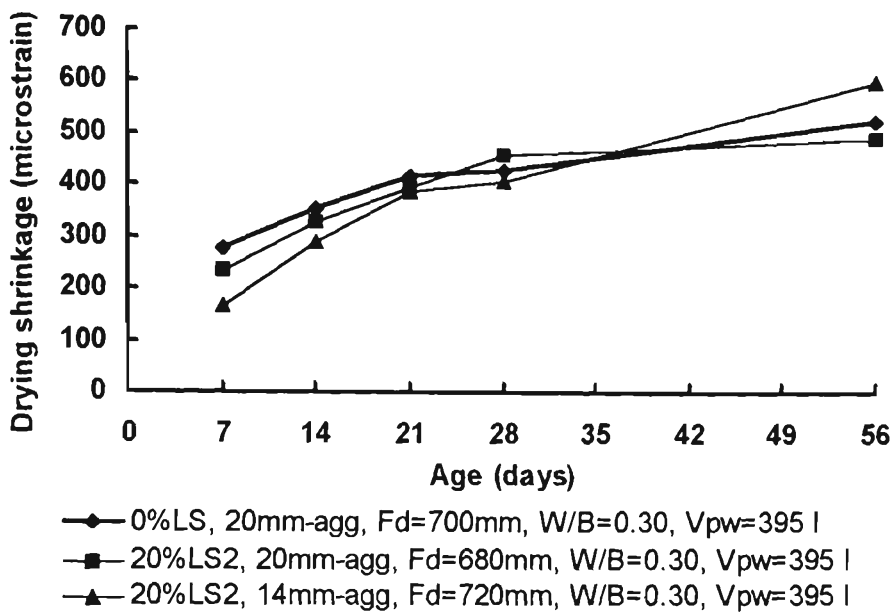


Fig. 6.43: Drying shrinkage of SC-HPC containing 20% of limestone LS2 with coarse aggregate with maximum sizes of 20 mm and 14 mm

6.6. EFFECT OF BLENDING TECHNIQUES ON PROPERTIES OF SC-HPC CONTAINING MILLED LIMESTONE

Portland clinker, gypsum and 10% and 20% of limestone were interground in a laboratory mill. The Blaine fineness indices of the interground binders containing 10% and 20% of limestone LS2 were 444 and 480 m<sup>2</sup>/kg, respectively. The binders were used in SC-HPC with similar paste volume of about 393 l/m<sup>3</sup> and constant water to binder ratio of 0.30. The proportions of mixes and test results are given in Appendix 6.1, 6.2 and 6.3 (mixes SG2 and SG3 contained binders interground with 10% and 20% of limestone, respectively). Test results are compared with those of SC-HPC containing milled limestone LS2 which were separately blended during concrete mixing (mixes SN13 and SN9A contained binders having 10% and 20% of milled limestone LS2 that were added during concrete mixing). Test results of SC-HPC containing limestone are also compared with pure cements SPC2 and SPC3 that had the same clinker source and fineness indices of 357 and 329 m<sup>2</sup>/kg, respectively.

Fig. 6.44 shown that SC-HPC containing limestone modified cements which were interground (cements SPC3) had percentage superplasticizer reductions lower than those of SC-HPC containing limestone modified cements which were blended (cement SPC2). Note that the percentage superplasticizer reductions were obtained by comparing the limestone modified cements with the respective pure cement. This is due to the fact that, in comparison with pure cement SPC2, the pure cement SPC3 which had a lower Blaine fineness index required a lower superplasticizer dosage for SC-HPC. (The required superplasticizer dosage would be higher if the fineness index of pure cement SPC3 are higher, then the percentage superplasticizer reductions of SC-HPC containing interground limestone modified cements would be higher).

SC-HPC containing limestone modified cements interground with pure cements SPC3 had percentages of 28-day compressive strength, slightly lower than those of SC-HPC containing limestone modified cements blended with pure cement SPC2 (Fig. 6.45). This probably is due to that the fineness indices of clinker particles in interground cements were lower than that of pure cement SPC3, and that leads to less chemical reaction of the interground cements.

As can be seen from Fig. 6.46, SC-HPC containing interground limestone modified cements exhibited 168-day drying shrinkage lower than that containing pure cement SPC3. Drying shrinkage of SC-HPC containing interground limestone were generally higher than that of SC-HPC containing blended milled limestone (Fig. 6.46). However, in comparison with respective pure cement, the 168-day drying shrinkage reductions of SC-HPC containing interground limestone cements were considerably higher than those of SC-HPC containing blended limestone cements (Fig. 6.47).

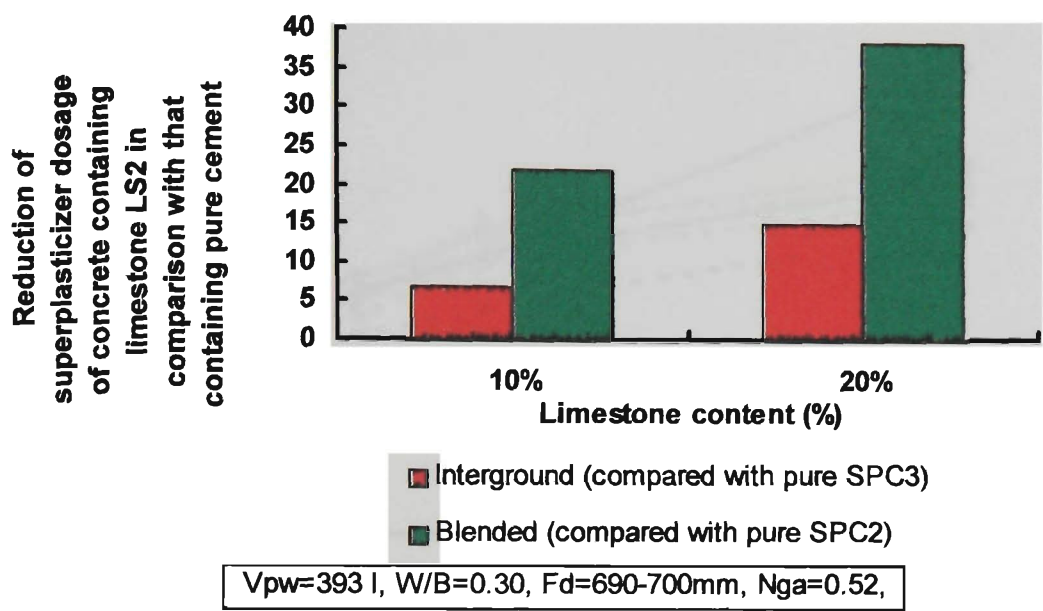


Fig. 6.44: Superplasticizer percentage reduction of SC-HPC containing interground and blended limestone modified cements, compared with those containing pure cements

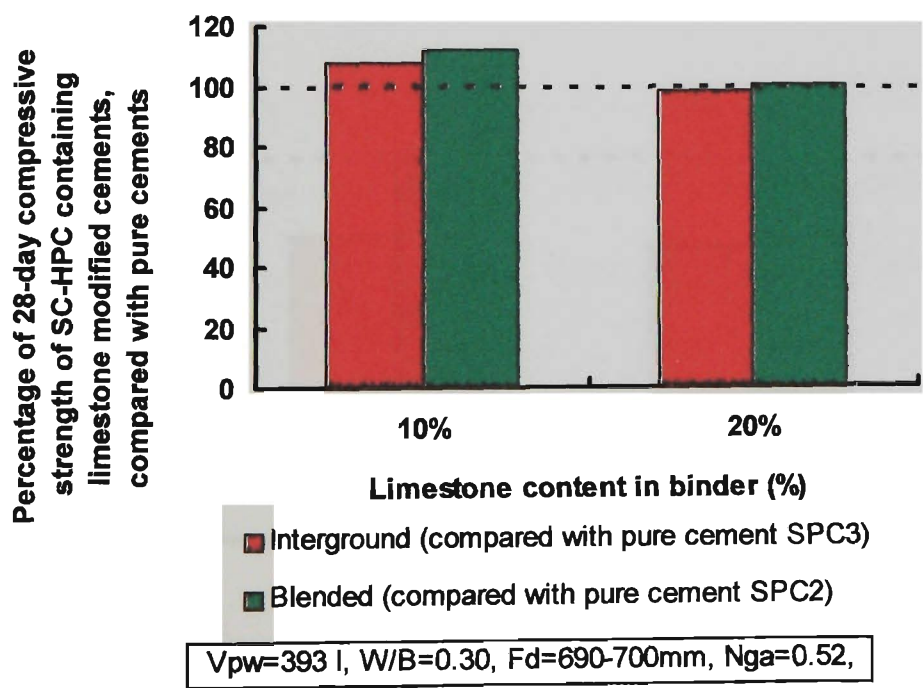


Fig. 6.45: Percentage of 28-day compressive strength of SC-HPC containing interground and blended limestone modified cements, compared those with pure cements SPC2 and SPC3

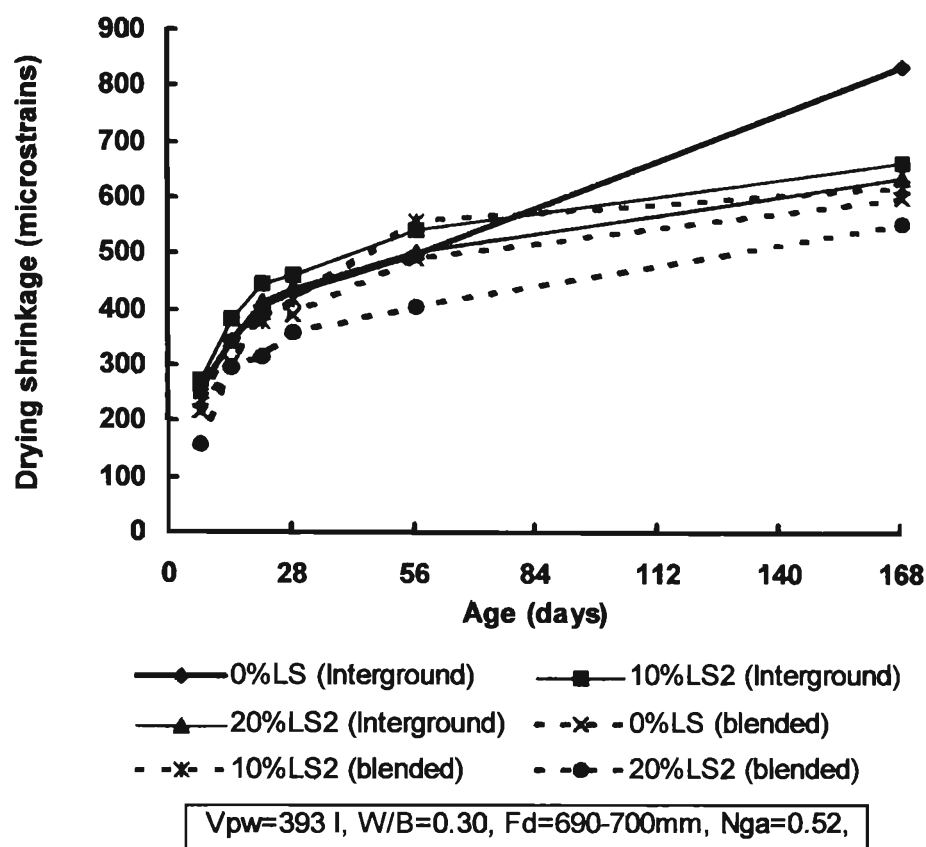


Fig. 6.46: Drying shrinkage of SC-HPC containing interground and blended limestone modified cements

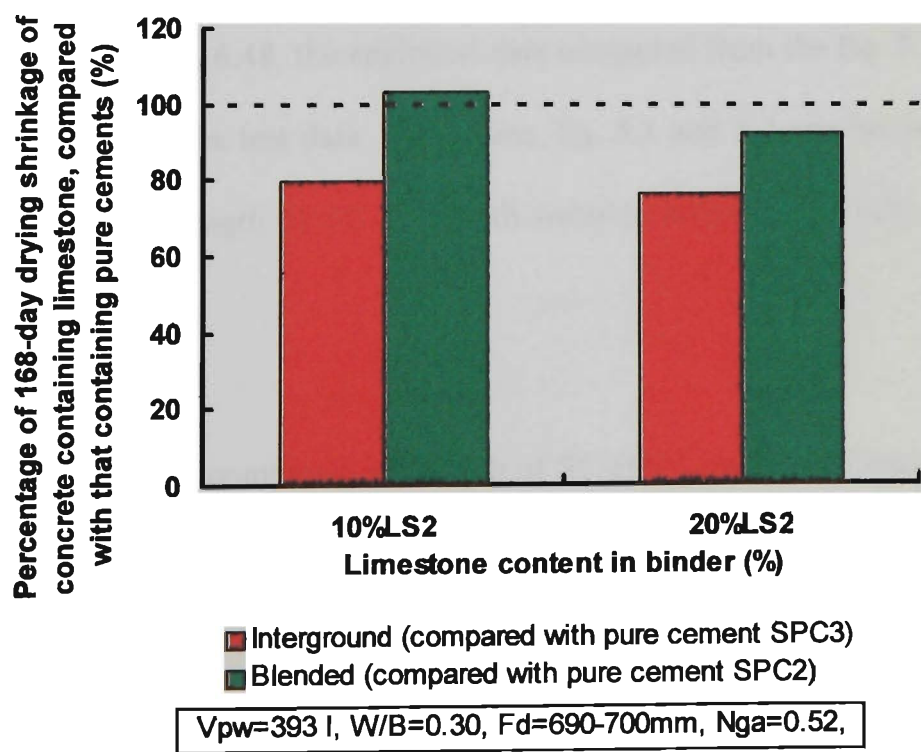


Fig. 6.47: Percentage of 168-day drying shrinkage of SC-HPC containing interground and blended limestone modified cements, compared with those of pure cements SPC2 and SPC3

## 6.7. MODEL PREDICTING 28-DAY COMPRESSIVE STRENGTH OF SC-HPC CONTAINING LMC

Equations 5.1 and 5.2 in chapter 5 are used to calculate 28-day compressive strength. However, the coefficient  $m$  that depends on mass of binder and type of tested cylinders is proposed as follows:

$m = 0.52$  for  $470 \text{ kg/m}^3 < B < 600 \text{ kg/m}^3$  and specimen cylinder having diameter and height of 100 mm and 200 mm, respectively; and

$m = 0.58$  for  $B \geq 600 \text{ kg/m}^3$  and specimen cylinder having diameter and height of 100 mm and 200 mm, respectively.

The values of coefficient  $m$  are different due to the fact that for high binder content, the increase in compressive strength is not always linear in relation to the increase of binder content.

As can be seen from Fig. 6.48, the analytical data computed from the Eq. 5.1 and 5.2 are very closely related to the test data. Therefore, Eq. 5.1 and 5.2 can be used to predict 28-day compressive strength of SC-HPC with water to binder ratios between 0.30 and 0.35.

The results indicate that compressive strength of SC-HPC containing limestone modified cements depends not only on the classic factors, namely aggregate type, cement strength, water content, air volume in concrete and content of limestone and cement, but also on water to binder ratio and the dimensions of test specimens.

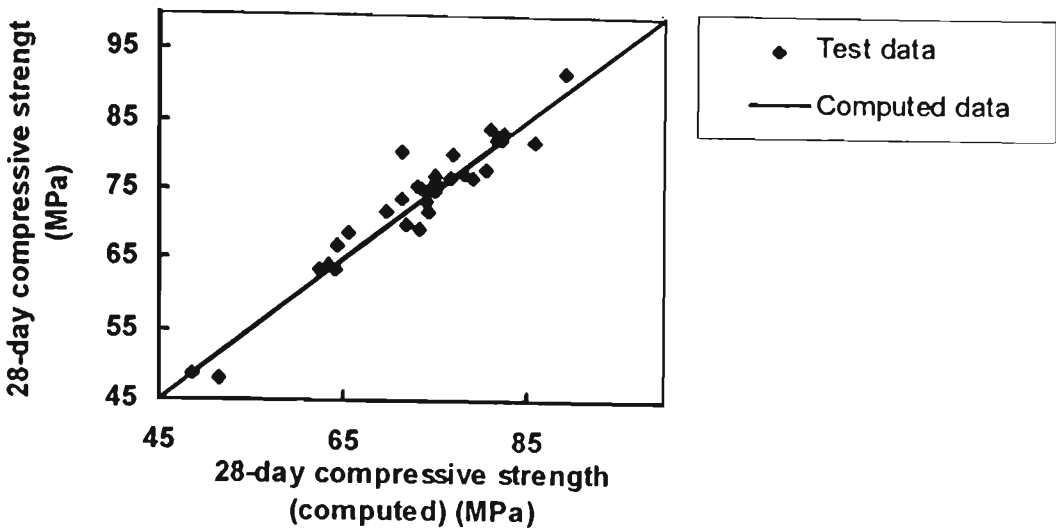


Fig. 6.48: Scatter diagram for test data and analytical (computed) data on 28-day compressive strength of SC-HPC containing limestone modified cements

**6.8. INTERFACE BETWEEN COARSE AGGREGATE AND MORTAR FOR SELF-COMPACTING HIGH PERFORMANCE CONCRETE**

Specimens of self-compacting high performance concrete (SC-HPC) containing pure cement and 20% of limestone LS2 with water to binder ratio of 0.30 were made. The interfaces between coarse aggregate and mortar of the SC-HPC were investigated by using SEM, and typical micrographs are given in Fig. 6.49 and 6.50. Fig. 6.49 and 6.50 show that the interfaces between coarse aggregate and mortar appeared to be similar, and micro-spacing at the interfaces for SC-HPC with and without milled limestone is not seen (micro-spacing at the interfaces for V-HPC with and without milled limestone is clearly seen in Fig. 5.29 and 5.30). This shows the bond between the aggregate and mortar for SC-HPC is likely to be superior to that of V-HPC. Fig. 6.51 and 6.52 indicate the interfaces between coarse aggregate and mortar (at higher magnification of SC-HPC with and without milled limestone LS2).





Fig. 6.49: Interface between coarse aggregate and mortar of SC-HPC without milled limestone (low magnification)

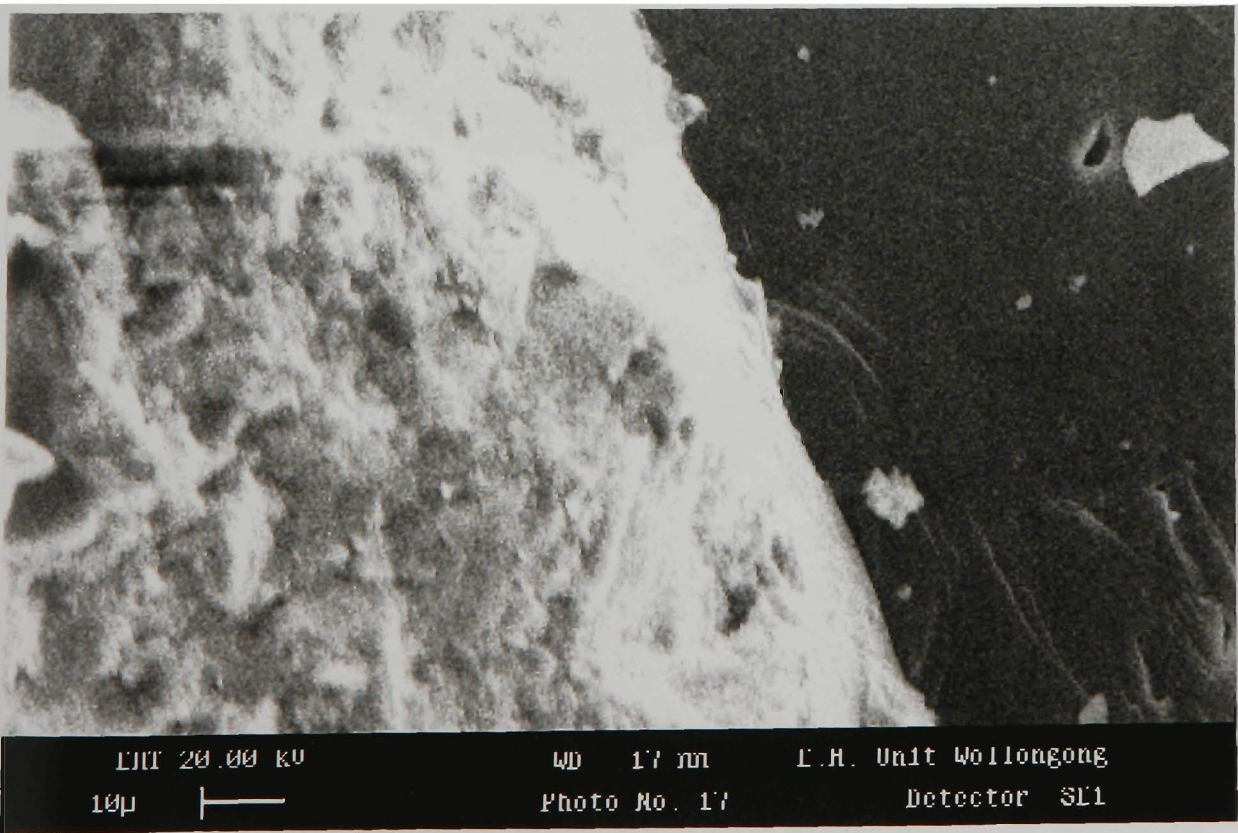


Fig. 6.50: Interface between coarse aggregate and mortar of SC-HPC containing 20% of milled limestone LS2 (low magnification)



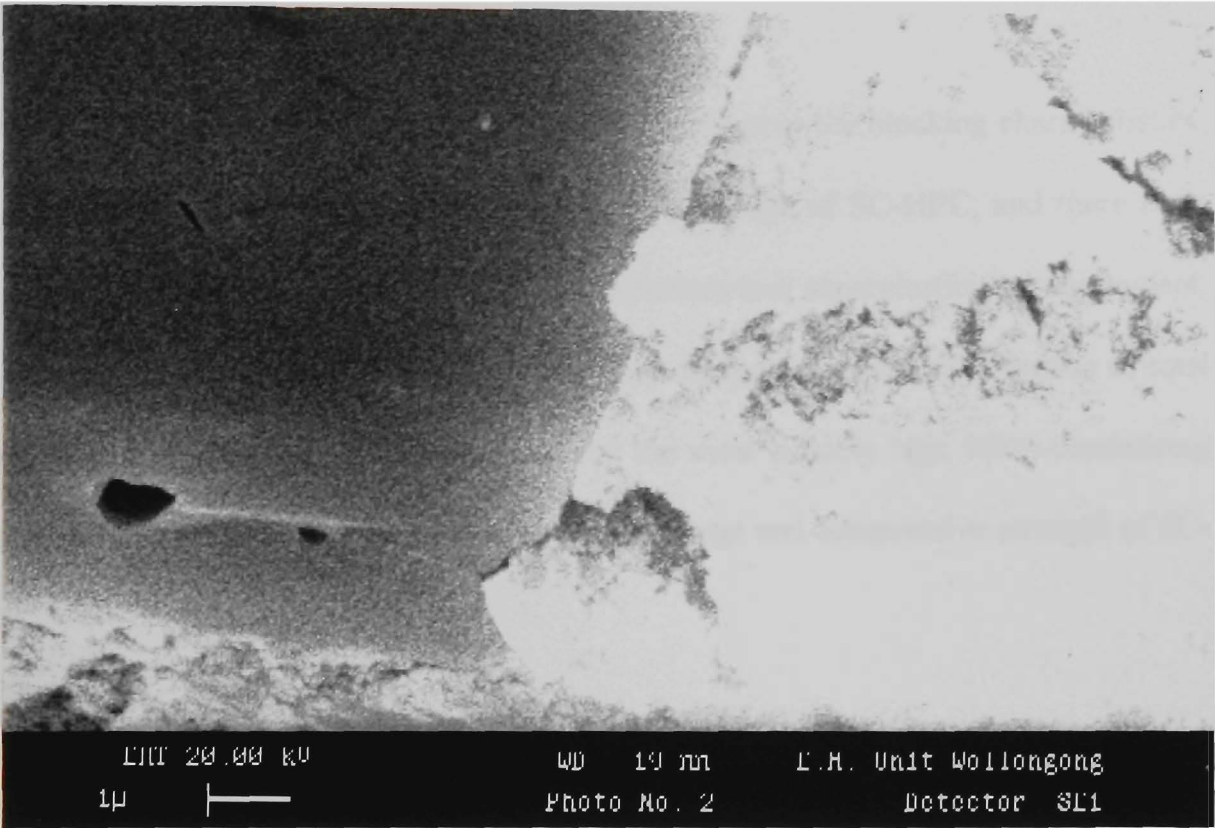


Fig. 6.51: Interface between coarse aggregate and mortar of SC-HPC without milled limestone LS2 (high magnification)

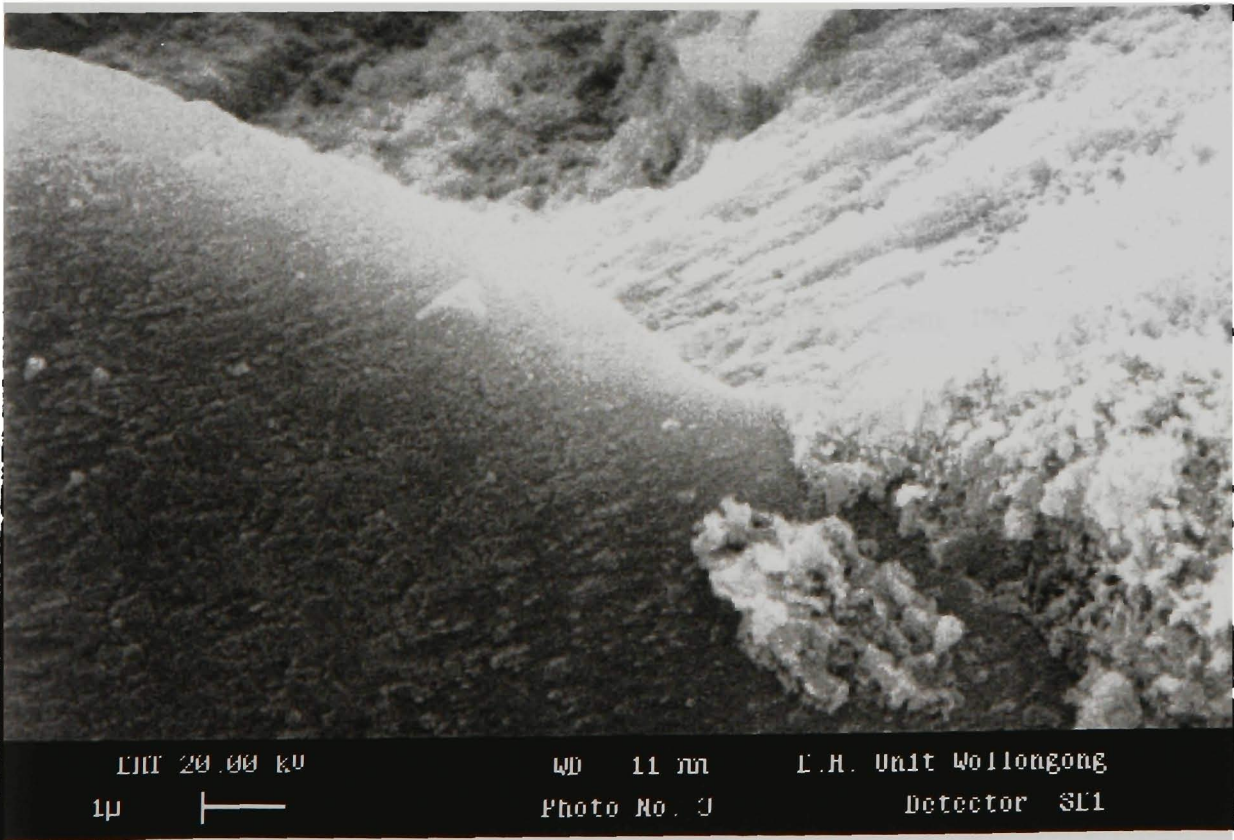


Fig. 6.52: Interface between coarse aggregate and mortar of SC-HPC containing 20% of milled limestone LS2 (high magnification)

## **6.9. SUMMARY**

Coarse to total aggregate ratio affects considerably not only the blocking characteristics, but also superplasticizer requirement and drying shrinkage of SC-HPC; and there is an optimum coarse to total aggregate ratio that enhances low superplasticizer requirement, low drying shrinkage of SC-HPC and satisfactory compressive strength. Coarse to total aggregate ratio of 0.52 was determined to be the most suitable *Nga* when considering blocking, superplasticizer requirement, drying shrinkage and compressive strength of SC-HPC.

Limestone fineness affects mainly superplasticizer requirement and drying shrinkage of SC-HPC. The use of milled limestones LS2 and LS3, with average particle size of about three and six times, respectively, smaller than pure cement, reduce considerably superplasticizer requirement and drying shrinkage of SC-HPC in comparison with that containing limestone LS1 which had average particle size slightly higher than that of pure cement.

Limestone LS2 was the most suitable for SC-HPC from the view point of superplasticizer requirement, compressive strength and drying shrinkage.

The use of 10%, 20%, 25%, 30% and 40% of limestone LS2 reduced considerably the superplasticizer requirement and drying shrinkage of self-compacting high performance concrete. SC-HPC containing 10 to 40% of limestone LS2 with water to binder ratios of 0.30 and 0.35 exhibited 28-day compressive strength between 92 MPa and 48 MPa.

With regard to superplasticizer requirement, compressive strength and drying shrinkage, the use of limestone LS2 in SC-HPC with low water to binder ratio ( $W/B = 0.30$ ) was more beneficial than with high water to binder ratio ( $W/B = 0.35$ ). The use of limestone LS2 in SC-HPC with low paste volumes resulted in higher percentage reduction of superplasticizer dosage, lower reduction in compressive strength and lower drying shrinkage, than for those with high paste volume. However, lower water to binder ratio requires higher minimum required paste volume in order to achieve good compaction and satisfactory performance of SC-HPC.

In comparison with 20-mm coarse aggregate, the use of coarse aggregate having maximum size of 14 mm requires reduced minimum paste volume to prevent blocking behaviour; similar required superplasticizer dosage and may increase slightly the compressive strength of SC-HPC. However, attention should be paid to the control of drying shrinkage of SC-HPC containing 14-mm coarse aggregate.

The proposed formulae, which were modified from the classical Feret's equation, can be used to predict 28-day compressive strength of SC-HPC. The formulae involve not only classic factors, such as aggregate types, cement strength, water content, air volume in concrete and content of limestone and cement, but also include water to binder ratio and the dimensions of test specimens.

## CHAPTER 7

### RAPID TESTING METHODS FOR DETERMINING THE QUALITY OF SELF-COMPACTING CONCRETE

#### 7.1. BACKGROUND

Self-compacting concrete (SCC) is a new type of concrete that can fill all corners of formwork without vibration. In order to achieve this property, self-compacting concrete must have good deformability, high segregation resistance and no blocking around reinforcement bars. These are the main characteristics of the concrete. Also, because this type of concrete is quite sensitive to quality control, it requires suitable testing methods to ensure uniform quality. Appropriate testing methods should be simple, non-laborious and capable of being used in the laboratory and on site in order to design mixes and to rapidly assess quality. Several testing methods for self-compacting concrete have been previously developed as described in section 2.2.5 of Chapter 2, however, none are specifically devoted to rapid testing of segregation.

Self-compacting concrete in its fresh state should have good filling ability and segregation resistance. Good filling ability means that the self-compacting concrete can fill all corners of the formwork without requiring vibration and without causing honeycombing, as well as without causing blocking around reinforcement bars. Good segregation resistance of concrete means that the distributions of aggregate particles in the concrete are relatively equivalently distributed at all locations and at all levels. Therefore, self-compacting concrete should have satisfactory segregation resistance, good deformability and no tendency for blocking when it flows through reinforcement bars. In this study, the rapid testing methods for quality of self-compacting concrete

have been developed in order to rapidly evaluating the main properties of self-compacting concrete, namely blocking characteristic, deformability and segregation resistance. The L-box apparatus, which has been used in previous studies by the author and co-workers (Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al., 1996) has been modified, and a simple Penetration Apparatus has been developed. These have been used in an extensive testing program. This chapter illustrates the blocking and deformability testing method using a modified L-box apparatus, and describes the segregation testing method which can be used in the laboratory and on-site for self-compacting concrete. Laboratory test results are also presented and discussed.

## **7.2. MATERIALS**

Five types of cement, comprising two types of shrinkage limited portland cement, one type of ordinary portland cement and two types of blast furnace slag cement, were used. The two types of shrinkage limited portland cement and ordinary portland cement are designated as SPC1, SPC2 and OPC, respectively. Two types of blast furnace slag cement which contain 30% and 65% of blast furnace slag are designated as BFC1 and BFC2, respectively. Five types of mineral admixtures, namely three sources of milled limestone, fly ash and blast furnace slag were also used in laboratory tests. These are specified as LS1, LS2, LS3, FA and BFS, respectively. The specific gravities, fineness and chemical analysis of the cements and mineral admixtures are shown in Appendix 3.1.

Six sources of crushed basalt coarse aggregate and two sources of river sand were used in the concrete testing program. The six types of the coarse aggregates, which include two types with maximum size of 20 mm, two types with maximum sizes of 14 mm and two types with maximum size of 10 mm, are nominated as A, B, C, D, E and F,

respectively. Two sources of river sand are specified as RS1 and RS2. Particle size distributions and specific gravity of the coarse aggregates and river sands are given in Appendix 3.2. Naphthalene sulphonate superplasticizer in dry form was used in all mixes.

### **7.3. APPARATUS AND EXPERIMENTAL PROCEDURES**

#### **7.3.1. Apparatus for Rapid Testing of Blocking Characteristics, Deformability and Segregation Resistance of SCC**

In this study, a mould with height of 420 mm and cross section of 100 mm x 100 mm was used in conjunction with the conventional apparatus used for testing the compacting factor of normal concrete (Australian Standard AS 1012.2) (Fig. 7.1 and 7.4), in order to cast specimens for evaluating segregation resistance of self-compacting concrete in the vertical direction. This mould is specified as mould type M. Small cylinder moulds, designated as type N, with height of 70 mm and diameter of 80 mm were used to assess segregation resistance of concrete in the horizontal direction (Fig. 7. 2).

A simple apparatus (Fig. 7.3, 7.6), called the Penetration Apparatus (PA), was also developed and used for rapid testing of segregation resistance of self-compacting concrete. The structure of the apparatus is indicated in Fig. 7.3 and consists of a frame F, slot E, reading scale M, screw D and penetration head P. The penetration head P is assembled from a thin walled cylinder C and rod K. The inner diameter, height and thickness of the cylinder are 75 mm, 50 mm and 1 mm, respectively. The total mass of the penetration head is 28 g.

The L-box apparatus (Fig. 7.2, 7.5) was used together with the Penetration Apparatus (PA) to rapidly test segregation resistance, deformability and blocking behaviour of self-compacting concrete. The set of reinforcement bars of the L-box apparatus was manufactured in such fashion as to permit: adjustment of the clear spacing between the reinforcement bars; replacement of the bars with different diameters; and easy removal of the reinforcement bars from the box.

### **7.3.2. Testing Procedure**

The testing procedure is carried out according to the following steps:

1. With gate A of the L-box closed, fresh concrete is placed into the vertical leg of the L-box. The upper surface of the concrete is levelled.
2. After 2 minutes, locate the penetration apparatus on the top of the vertical leg of the L-box, adjust the penetration cylinder to just touch the upper surface of concrete, then allow the cylinder to penetrate freely into the concrete. After 45 seconds, the penetration depth (Pd) of the cylinder head is recorded from the scale. Average penetration depth (Pd) of three measurements at two sides and the centre is calculated and is used together with data from steps 6, 9 and 10 to assess the segregation resistance of self-compacting concrete.
3. Lift gate A in a vertical direction to allow the concrete to flow through the clear spacing between the reinforcement bars.

4. When the concrete stops flowing, the filling head drop  $H_d$  (defined as the height difference between L-box's height and upper surface of concrete) is measured (Fig. 7.2). The filling head drop is used to evaluate blocking behaviour for self-compacting concrete.
5. Remove set of bars from L-box and measure the height  $H_f$  (Fig. 7.2) of concrete at the end of L-box (the height  $H_f$  is the vertical distance between the upper surface of the horizontal leg of the L-box and the upper surface of concrete measured at the end of the L-box). The height  $H_f$ , which is called the final depth, is used to assess deformability for self-compacting concrete.
6. Then take fresh concrete from a position located at the bottom of the vertical leg of L-box, fill it into a pair of small moulds (type N) and level it off (without vibration). Similarly, take fresh concrete from the end of horizontal leg of L-box, then again fill another pair of small moulds (type N) and level it off (without vibration). Immediately, wash out the concrete from the small moulds (type N), and then separate, dry, weigh coarse aggregate particles larger than 9.5 mm. The average masses of the coarse aggregate in each pair of the small moulds are calculated and compared in order to assess segregation resistance of concrete in the horizontal direction. Concrete is deemed to be of satisfactory segregation resistance if the difference (specified as  $R_h$ ) between the average masses of coarse aggregate at the bottom of the vertical leg and at the end of L-box is less than 10% because if the value of  $R_h$  is greater than 10%, segregation resistance calculated according to Eq. 2.2 in Chapter 2 is less than 95%, and a sudden drop in the strength occurs (Umehara et al, 1994).



7. The difference  $R_h$  and the penetration depth  $P_d$  are compared to determine the optimum range of penetration depth  $P_d$  which can be used to rapidly evaluate the segregation resistance of self-compacting concrete in the horizontal direction.
8. Separately, fresh concrete from the same batch as used for the L-box test, having a volume of 4.3 litres, is placed into the upper cone of the compacting factor apparatus (Fig. 7.1, 7.4) (compacting factor apparatus is modified by removal of the lower cone for this test), and after one minute, the concrete is released, falling freely into the moulding box (type M). After setting, the concrete is demoulded and the specimens are cut vertically into two halves (Fig. 7.8 and 7.9). One half is then sectioned into 6 equal sized pieces in the horizontal direction (a diamond saw used to cut SCC is shown in Fig. 7.7). The six pieces are put into an oven at a temperature of about 23°C. Increase temperature in oven to 900°C over a period of 3 hours, then keep constant temperature of 900°C for 12 hours, then cool to a final temperature of about 23°C over period of 48 hours. Finally, coarse aggregate particles (larger than 9.5 mm) from each piece are separated and weighed (after heating and cooling, the cohesion between coarse aggregate particles and mortar is very weak due to the expansion of hardened cement paste, therefore, the coarse aggregate particles can be easily separated by a sieve, and then any retaining cement paste on coarse aggregate is cleaned by a small knife and brush).
9. The average mass and the variation  $R_v$  of the mass of the coarse aggregate in the vertical direction are calculated as follows (Otsuki et al., 1996):

$$V = \frac{\sum V_{gi}}{6} \quad (\text{Eq. 7.1})$$

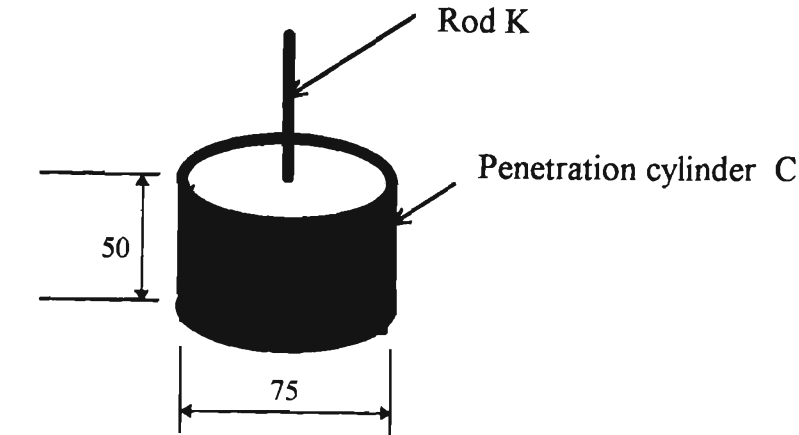
$$R_v = \sqrt{\frac{\sum \left( \frac{V_{gi} - V}{V} \times 100 \right)^2}{6}} \quad (\text{Eq. 7.2})$$

where  $V_{gi}$  and  $V$  are the mass of each piece and average mass of the coarse aggregate with particle size larger than 9.5 mm, respectively, and  $R_v$  is the variation of the mass of the coarse aggregate in the vertical direction. Segregation resistance of self-compacting concrete is deemed to be satisfactory if the value  $R_v$  is less than 10% (after Otsuki et al, 1996).

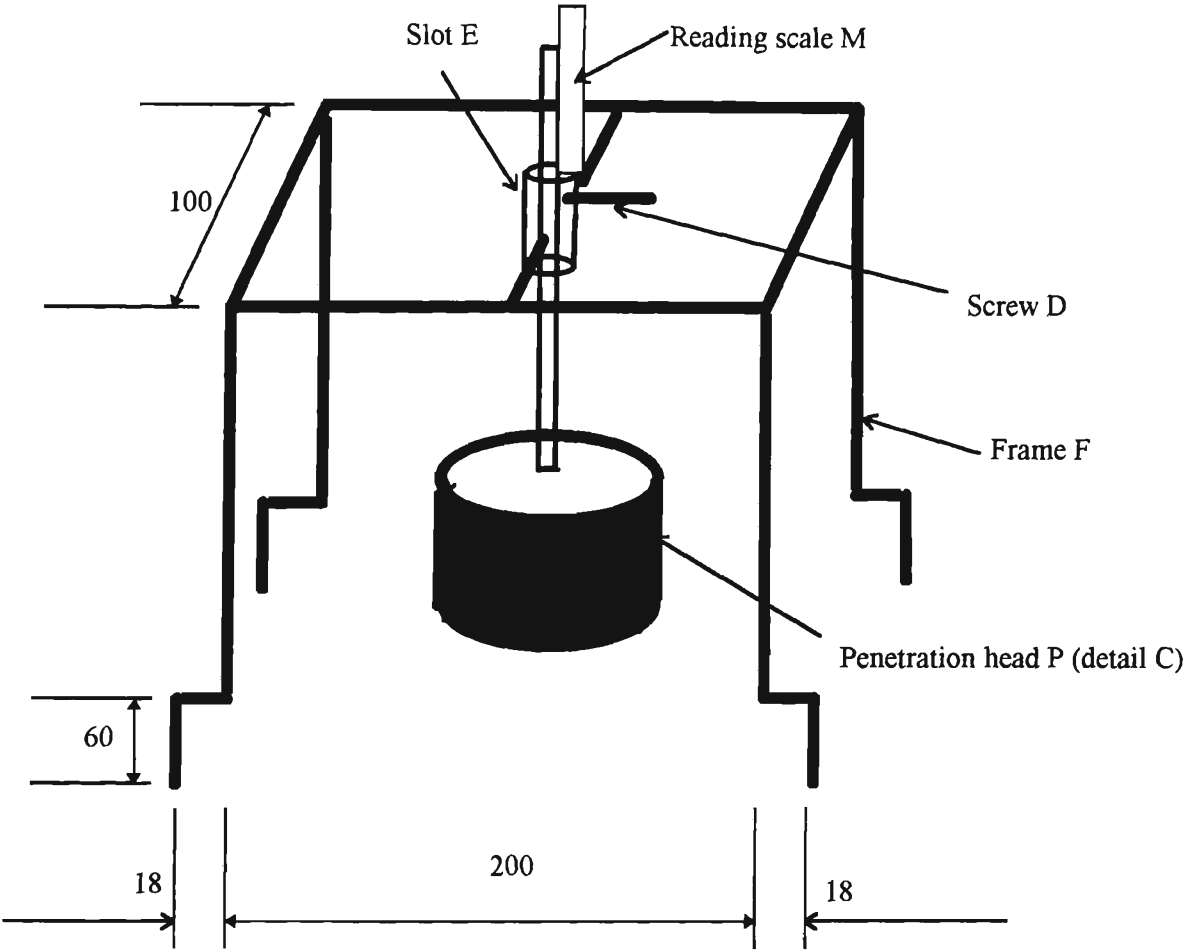
10. The average depth ( $H_a$ ) (Fig. 7.8 and 7.9) of aggregate particles in the upper area of the uncut half is measured (the aggregate depth ( $H_a$ ) is the mean of two depths which are the distances between the upper surface of the concrete specimen and the upper surface of the two coarse aggregate particles (with size not smaller than 9.5 mm) closest to the upper surface of the concrete specimen). The aggregate depth ( $H_a$ ) is compared with the variation  $R_v$  in order to determine the maximum allowable value at which the concrete specimen is of satisfactory segregation resistance.

11. Similarly to step 7, the variation  $R_v$ , aggregate depth  $H_a$  and the penetration depth  $P_d$  are compared to determine the optimum range of penetration depth  $P_d$  which can be used to rapidly evaluate the segregation resistance of self-compacting concrete in the vertical direction.





Detail C: Penetration Head P



(All dimensions in mm)

Fig. 7.3: Penetration apparatus for segregation tests

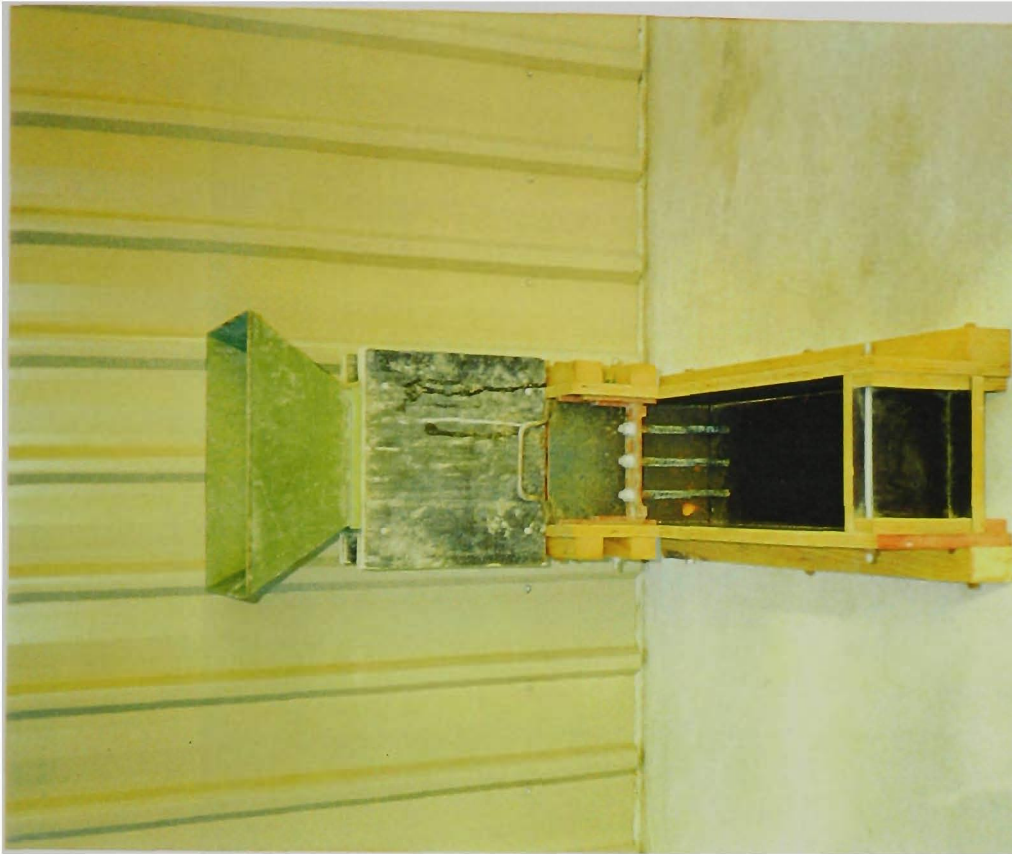


Fig. 7.5: Modified L-box apparatus used in rapid testing quality of self-compacting concrete



Fig. 7.4: Mould type M with the conventional apparatus used for test the compaction factor of normal concrete



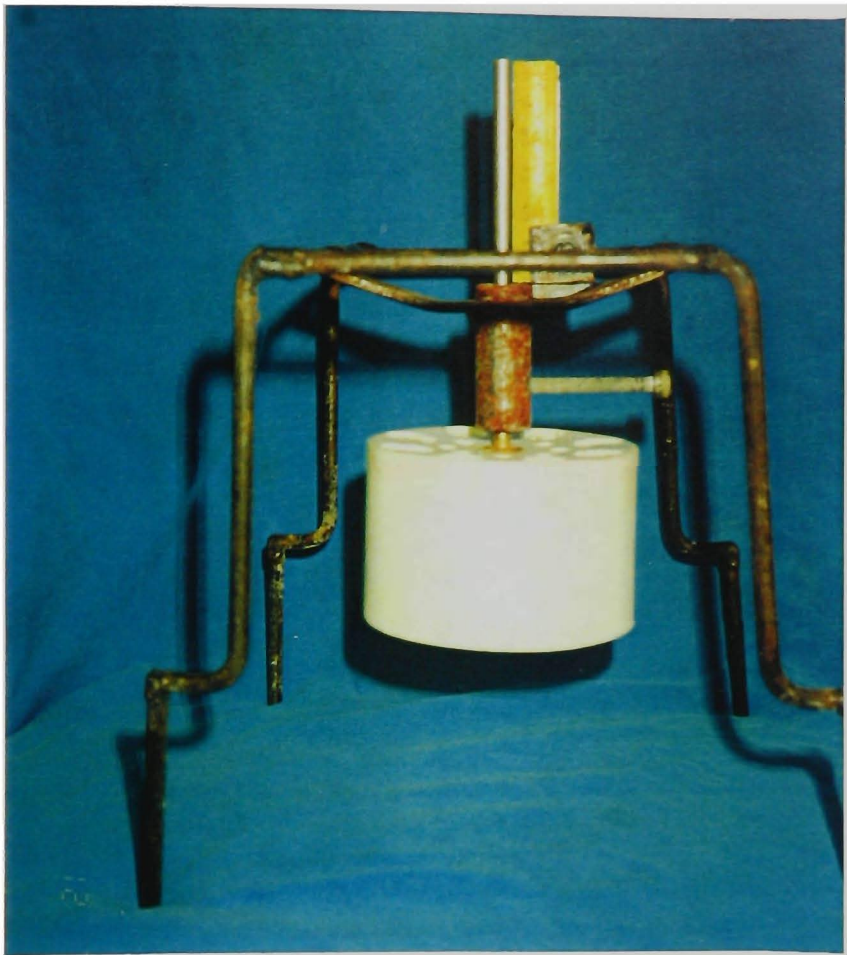


Fig. 7.6: Penetration Apparatus used in rapid testing of segregation resistance of SCC

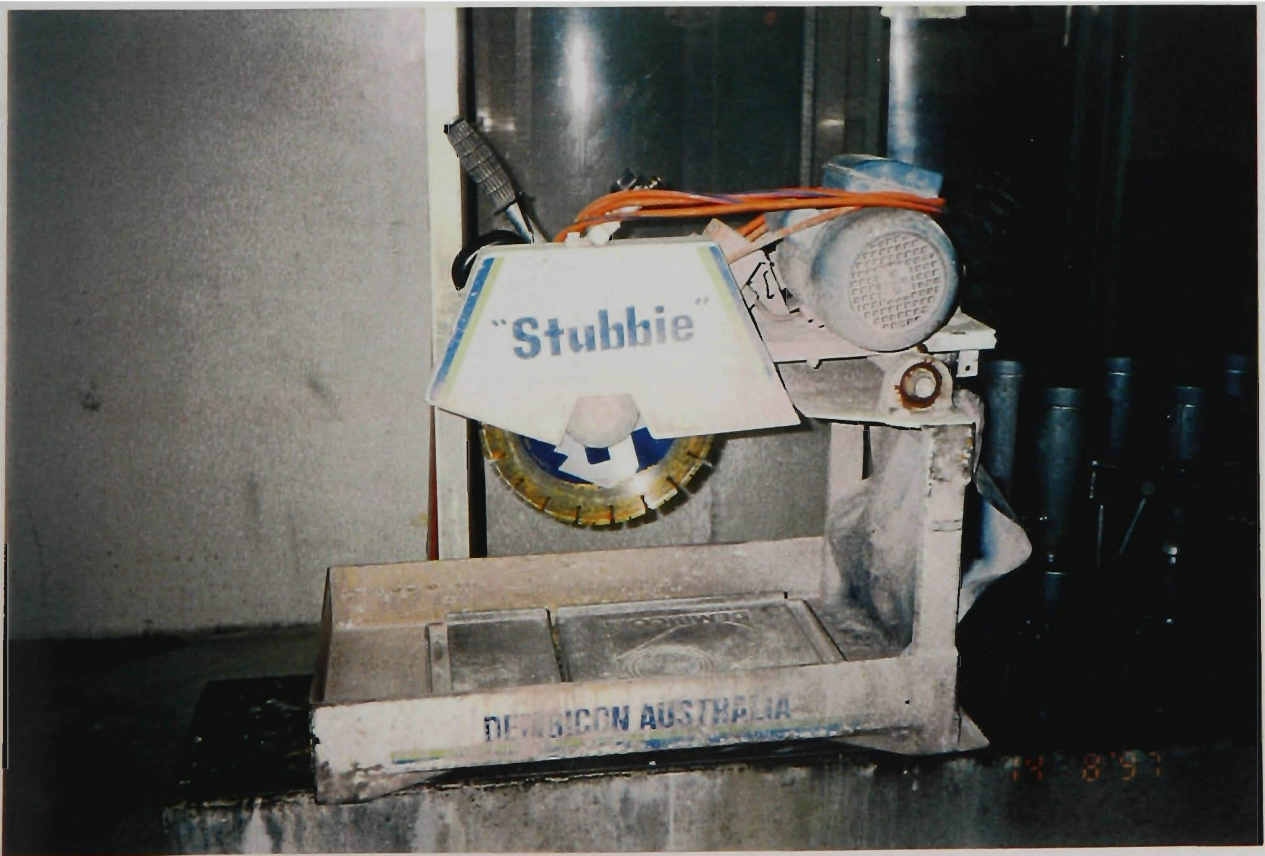


Fig. 7.7: Diamond saw



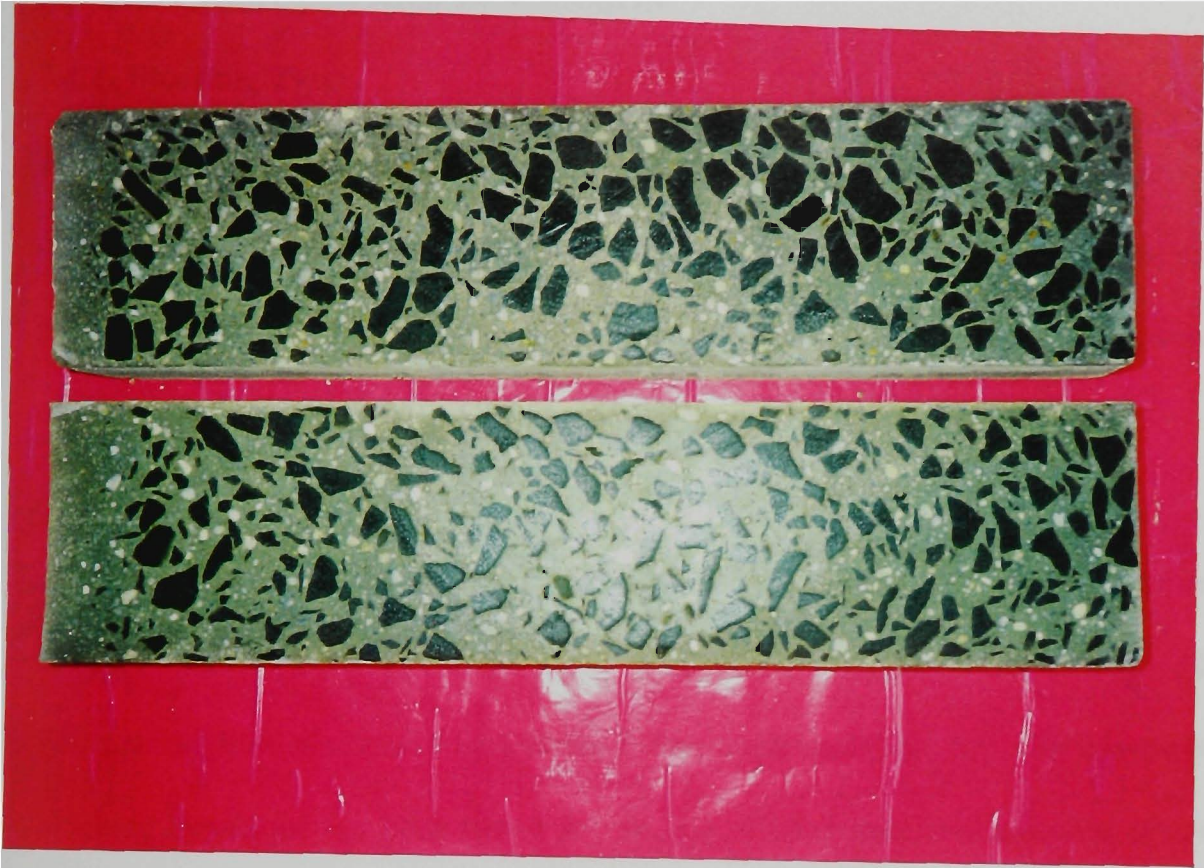


Fig. 7.9: Cut specimens having unsatisfactory segregation resistance

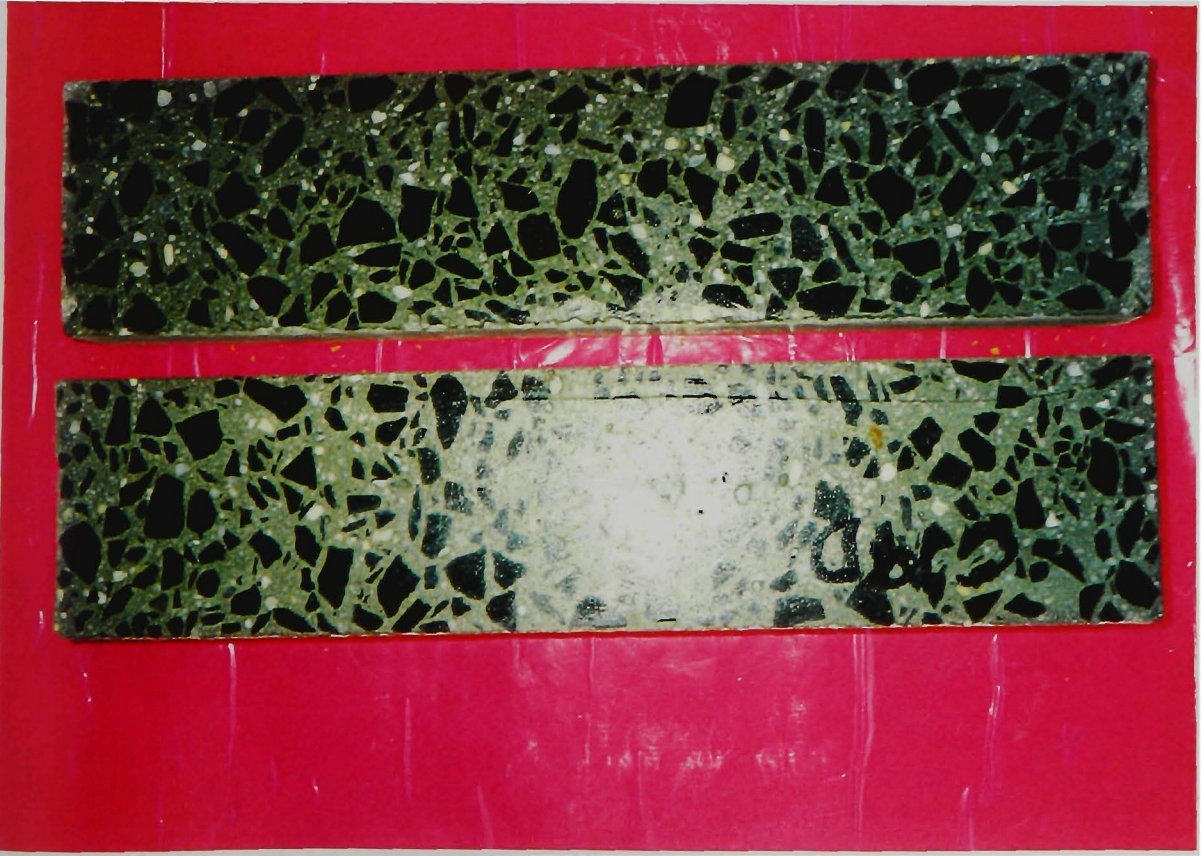


Fig. 7.8: Cut specimens having satisfactory segregation resistance

7.4. TEST RESULTS AND DISCUSSION

7.4.1. Blocking Tests

The main factors that cause blocking around reinforcement bars are: excessive volume of coarse aggregate; too large a maximum size of aggregate compared with clear spacing between reinforcement bars; poor segregation resistance of concrete; poor deformability of concrete.

A previous study (Petersson et al., 1996) showed that concrete is satisfactory from the view of blocking behaviour if the filling head drop is not lower than 490 mm when it flows through reinforcement bars in the L-box apparatus (Fig. 7.2). In this study, the blocking behaviour has been tested for the use of local materials and clear spacing of 40.6mm and 58.3mm between reinforcement bars. Mixture proportions and test results are given in Appendix 7.1. The test results confirmed that the concrete is not blocked if the filling head drop (Hd) is not less than 490mm (Fig. 7.10 and 7.11).

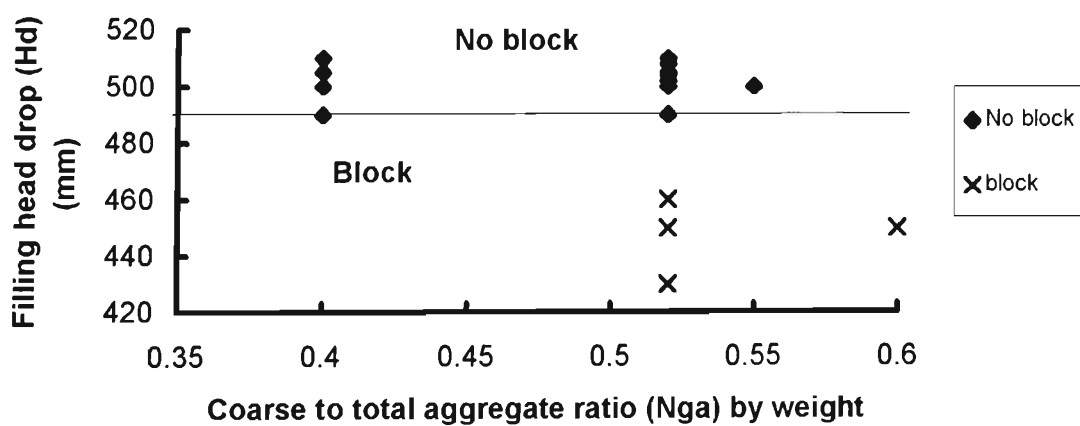


Fig. 7.10: Filling head drop and different coarse to total aggregate ratios



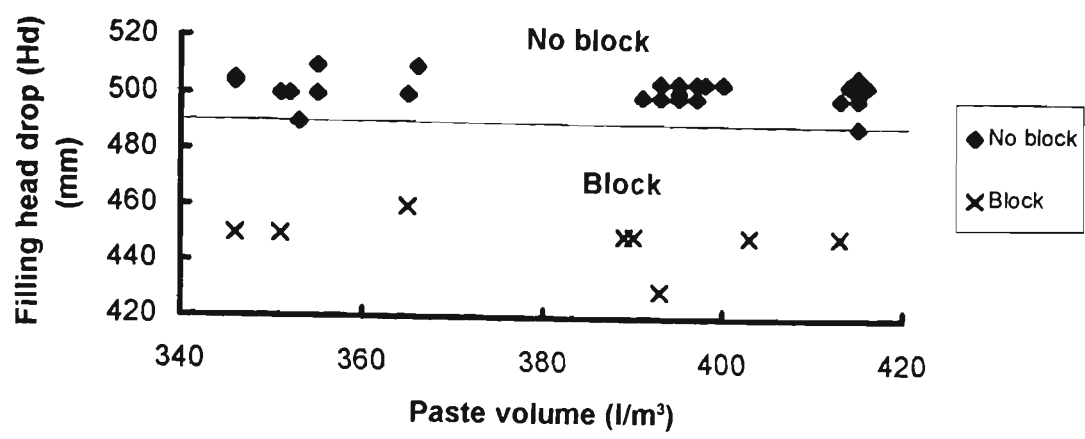


Fig. 7.11: Filling head drop and different paste volumes

7.4.2. Deformability Tests

Self-compacting concrete should have good deformability and flow velocity. Deformability of self-compacting concrete is influenced by mixture proportions (water content, paste volume, fine to coarse aggregate ratio, types and content of cement, fillers, aggregates and admixtures such as superplasticizer) and segregation resistance of concrete. Fresh concrete which is too dry or has poor segregation resistance can have poor deformability.

The deformability of fresh self-compacting concrete has been previously assessed (see section 2.2.5 in chapter 2) by the use of a slump cone and by measuring slump flow diameter (Fig. 7.12A and 7.12B). In addition, in this study, the deformability of fresh concrete was assessed from the use of the L-box apparatus and the final depth  $H_f$  as stated above (Fig. 7.2). The deformability is considered to be satisfactory if concrete can fill all corners of the moulding box without causing honeycombing (casting of specimens was carried out as detailed in step 8 of the testing procedure listed above).



Fig. 12A: Slump cone and plate used in measuring slump flow diameter of SCC



Fig. 12B: Typical slump flow diameter of self-compacting concrete

Test results showed that the deformability of concrete is satisfactory if the height  $H_f$ , measured at the end of the L-box, is less than 83 mm, as specimens with the final depth  $H_f$  smaller than 83 mm did not cause honeycombing (Fig. 7.13 and 7.14). The experiments were carried out with different ratios of coarse to total aggregates, different paste volumes, three types of coarse aggregate and water to binder ratios between 0.30 and 0.37. Typical specimens having satisfactory and unsatisfactory deformability are illustrated in Fig. 7.15, 7.16, 7.17 and 7.18).

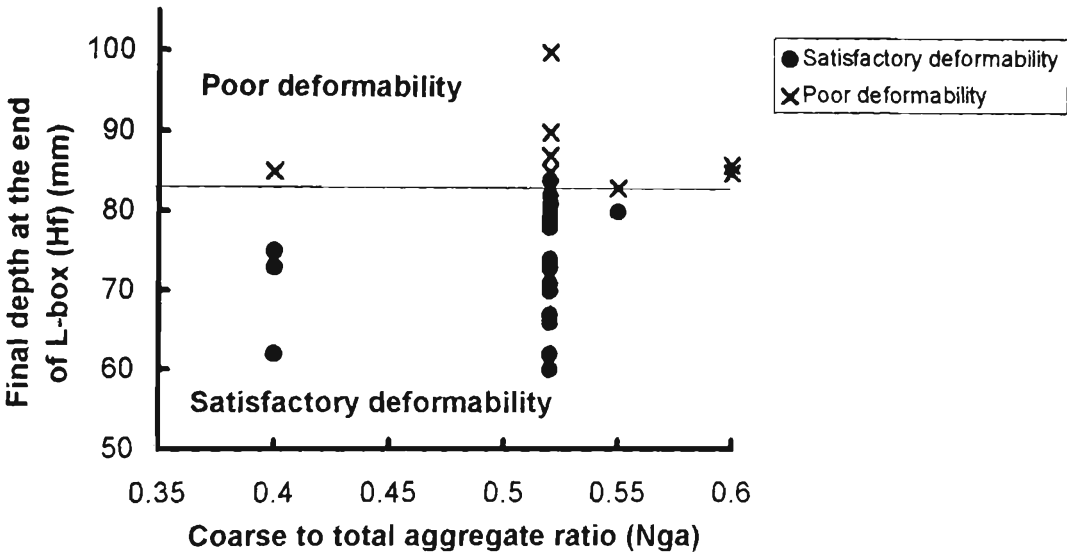


Fig. 7.13: Final depth measured at the end of L-box ( $H_f$ ) and different coarse to total aggregate ratios ( $N_{ga}$ )

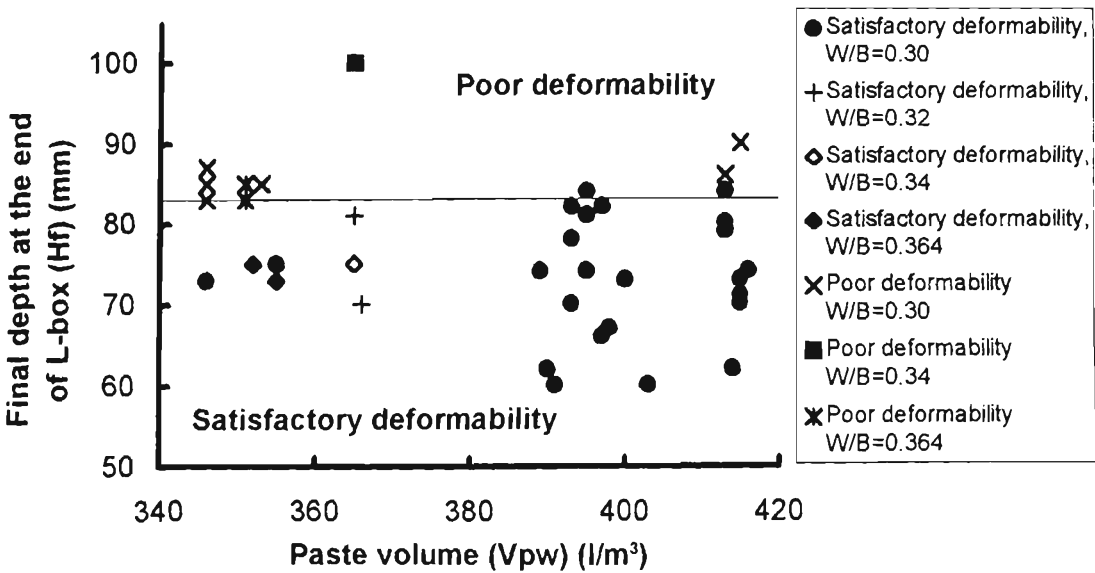






Fig. 7.16: Specimens having unsatisfactory deformability

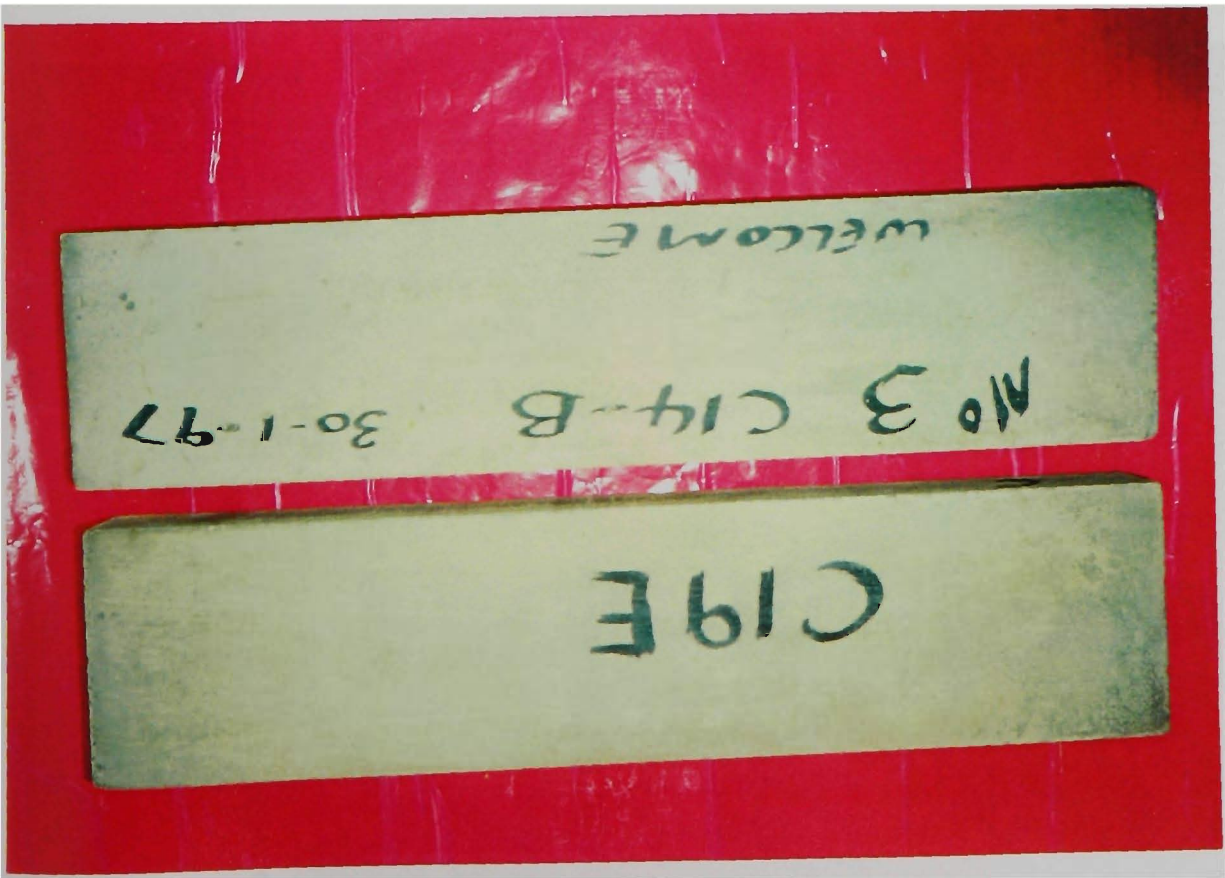


Fig. 7.15: Specimens having satisfactory deformability





Fig. 7.17: Cylinder specimens having satisfactory (middle) and unsatisfactory (left and right) deformability

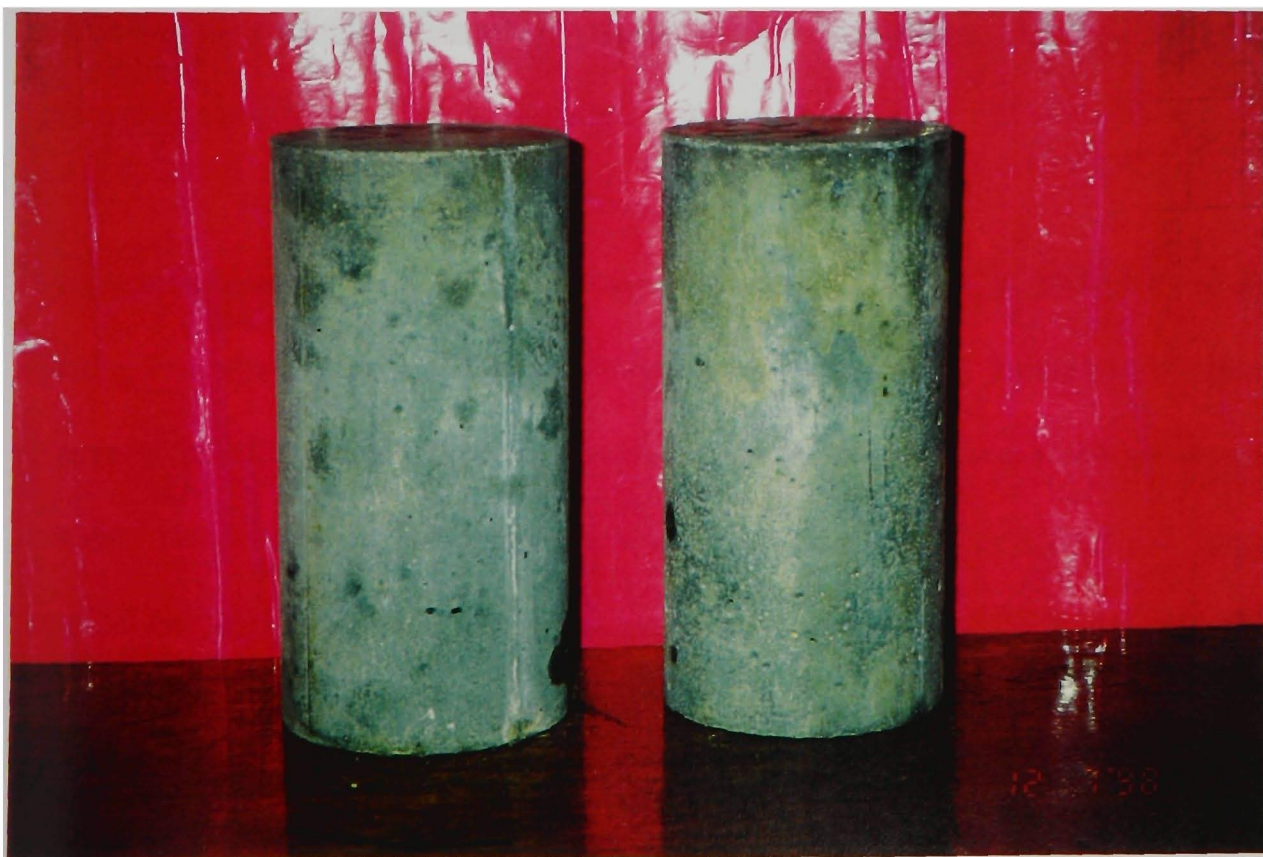


Fig. 7.18: Self-compacting (left) and vibrated cylinder (right) specimens

### **7.4.3. Segregation Tests**

Self-compacting concrete may fill all corners of the formwork without causing blocking around reinforcement bars, but it may be of poor segregation resistance in the vertical and horizontal directions. Good segregation resistance of concrete means that the distribution of aggregate particles in the concrete is relatively equivalent at all locations and at all levels; therefore the concrete should not segregate in vertical and horizontal directions. Segregation resistance plays an important role for self-compacting concrete because poor segregation resistance can cause poor deformability, blocking around reinforcement and high drying shrinkage as well as non-uniform compressive strength of concrete. Therefore, it is required that an appropriate method to assess segregation resistance of this new type of concrete be developed. This section presents the testing method for rapid assessment of segregation resistance of self-compacting concrete in both the vertical and horizontal directions. Laboratory test results on segregation resistance of concrete containing various mineral admixtures, different types of aggregates and different kinds of cements are discussed.

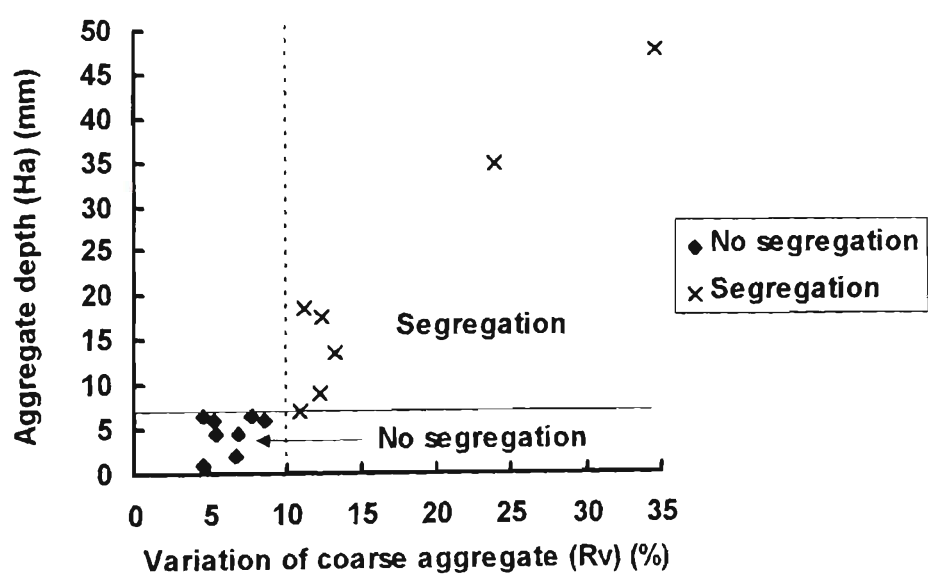
Segregation tests were carried out as detailed in steps 2, 6, 7, 8, 9, 10 and 11 of the Testing Procedure. Two experimental programs were carried out. In the first program, concretes containing pure shrinkage limited portland cements and shrinkage limited cements blended with milled limestone were tested in order to develop rapid testing method for segregation resistance of self-compacting concrete. The second program, forming part of the final year thesis programs of undergraduate students (Wilton, 1998, and Mourad, 1998) was carried out under the guidance of the author in order to check if the developed method can be applied for SCC containing other materials such as fly ash

and blast furnace slag. Mixture proportions and test results of SCC containing milled limestone, fly ash and blast furnace slag are given in Appendices 7.2 and 7.3.

7.4.3.1. Segregation resistance in vertical direction

Aggregate depth (Ha) of coarse aggregate and segregation resistance in vertical direction

Fig. 7.19, Appendices 7.2 and 7.3 show that specimens having aggregate depths (Ha) smaller than 7 mm had variations Rv of coarse aggregate in the vertical direction less than 10%; and specimens with aggregate depths (Ha) equal to and larger than 7 mm had variations Rv larger than 10%.



Test results with different paste volumes showed that the zones of poor segregation resistance and satisfactory segregation resistance were clearly divided by the line representing the proposed acceptable values of  $H_a$  (Fig. 7.20, Appendices 7.2 and 7.3). Typical specimens having satisfactory and unsatisfactory segregation can be seen in Fig. 7.8 and 7.9.

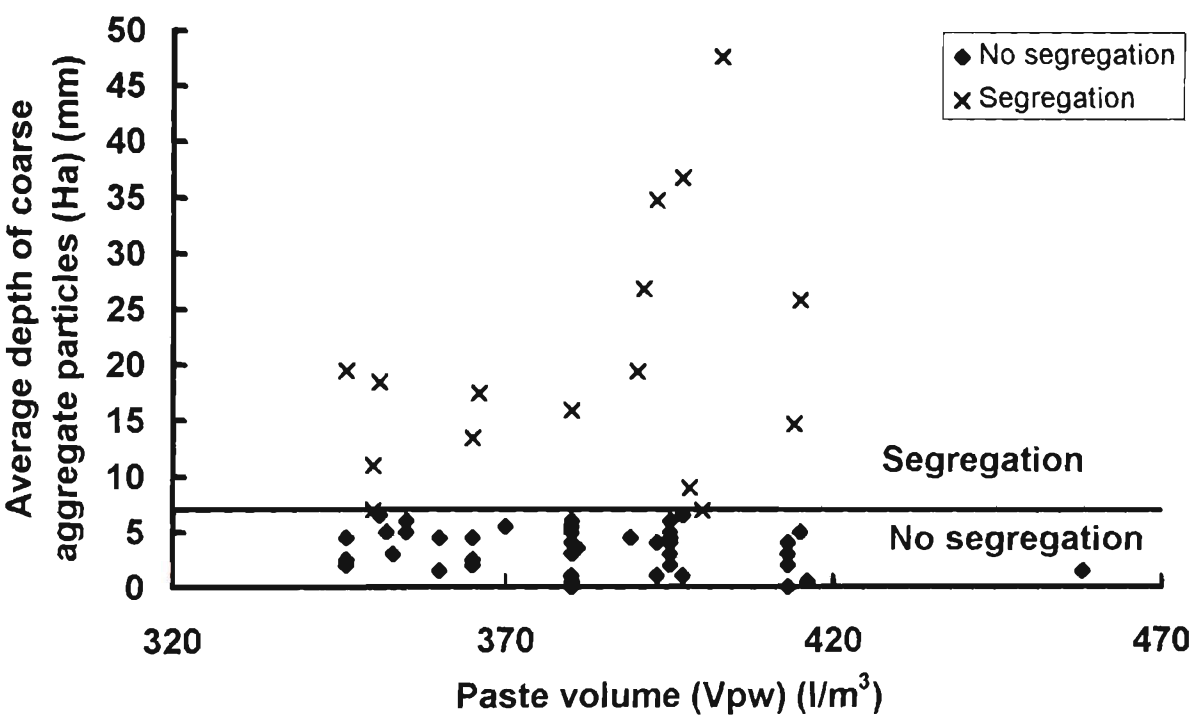


Fig. 7.20: Average aggregate depth ( $H_a$ ) and different paste volumes ( $V_{pw}$ )

Penetration depth ( $P_d$ ) and segregation resistance in vertical direction

As discussed above, the testing method using the moulding box is a good method to evaluate segregation resistance of self-compacting concrete. However, it is quite laborious and slow, therefore, a penetration apparatus (PA) was developed in order to carry out the test more quickly and with less labour. The structure of the apparatus has been described previously in section 7.3.1 entitled Apparatus for Rapid Testing of Blocking Characteristics, Deformability and Segregation Resistance of SCC and



illustrated in Fig. 7.3. Testing was implemented as detailed in step 2 of the Testing Procedure. Results using the penetration apparatus (PA) were compared with test results using the moulding box (type M), where the specimens with variation Rv smaller than 10% and aggregate depth smaller than 7 mm exhibited satisfactory segregation resistance.

Fig. 7.21, Appendices 7.2 and 7.3 show that specimens with penetration depths (Pd) smaller than, or equal to 8 mm were of satisfactory segregation resistance, as they exhibited mass variation Rv (of coarse aggregate in vertical direction) smaller than 10%; while specimens with penetration depths (Pd) larger than 8 mm exhibited unsatisfactory segregation resistance, because those specimens had mass variation Rv larger than 10%.

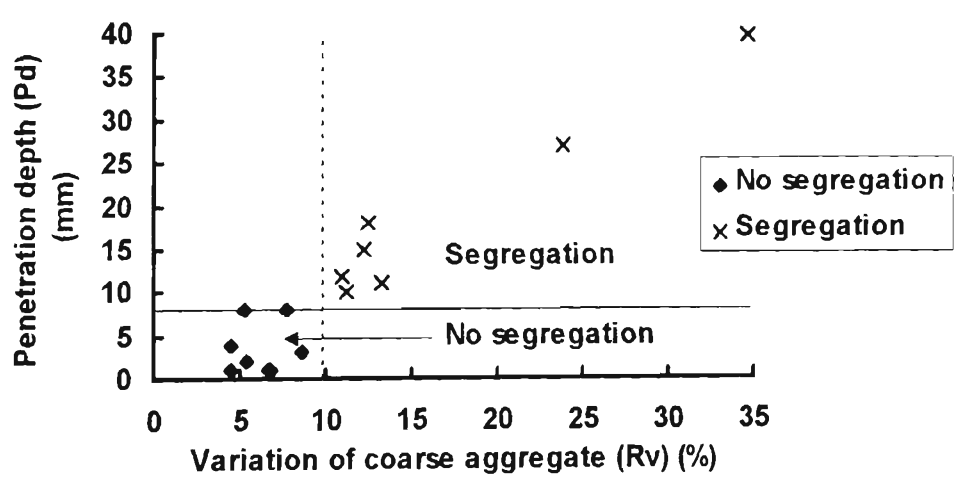


Fig. 7.21: Penetration depth (Pd) and different variations (Rv) of coarse aggregate by mass in vertical direction

As can be seen from Fig. 7.22, Appendices 7.2 and 7.3, for different water to binder ratios, different paste volumes and different materials, namely different types of cement, mineral admixtures and aggregates, the specimens with penetration depths (Pd) smaller than, or equal to, 8 mm had aggregate depths (Ha) smaller than 7 mm which can be

considered as the maximum allowable value for specimens having good segregation resistance. Fig. 7.22 also shows that specimens having penetration depths (Pd) larger than 8 mm had aggregate depths equal to and larger than 7 mm. Therefore, segregation resistance of self-compacting concrete can be assessed as follows:

- Concrete has satisfactory segregation resistance in vertical direction if  $Pd \leq 8$  mm;
- Concrete has poor segregation resistance in vertical direction if  $Pd > 8$  mm.

where Pd is the penetration depth measured by use of the penetration apparatus.

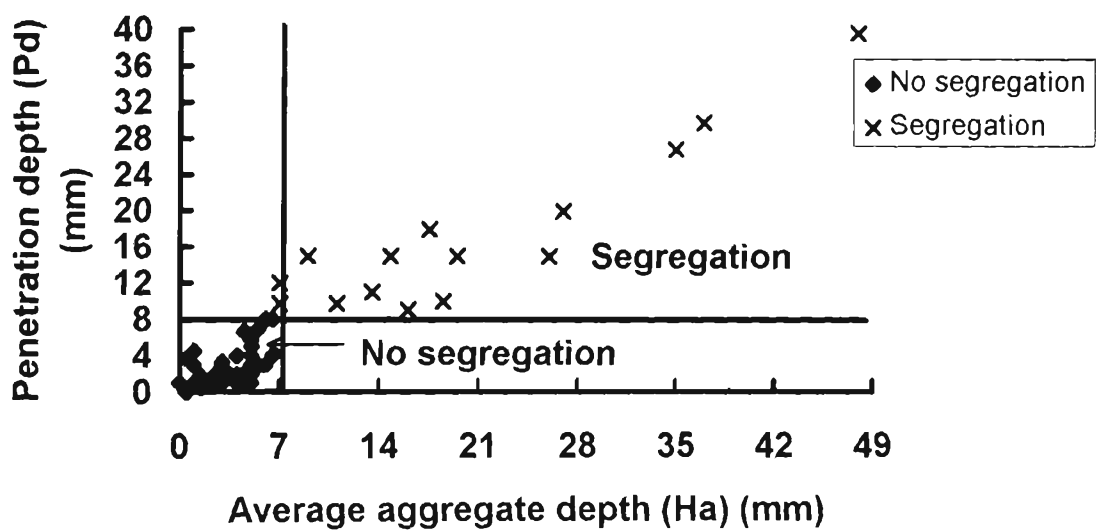


Fig. 7.22: Penetration depth (Pd) and average aggregate depth (Ha)

Fig. 7.23, 7.24, 7.25, Appendices 7.2 and 7.3 show laboratory test results with different coarse to total aggregate ratios, different water to binder ratios and different paste volumes with different cement types, different mineral admixtures and different aggregate combinations consisting of different aggregate types. The results indicated that the zones of satisfactory segregation resistance and poor segregation resistance were clearly divided by the lines representing the proposed values stated above.



7.4.3.2. Segregation Resistance in Horizontal Direction

Non-uniform distribution of coarse aggregate particles in concrete structures is caused not only by blocking around reinforcements, but also by poor segregation resistance of concrete. As can be seen from Fig 7.26, 7.27, 7.28, 7.29, Appendices 7.2 and 7.3, for different water to binder ratios, different paste volumes and different materials, namely different types of cement, mineral admixtures and aggregates, the specimens with penetration depths (Pd) smaller than or equal to, 9 mm had mass difference (Rh) of coarse aggregate smaller than 10%; while the specimens with penetration depths (Pd) larger than 9 mm had mass difference (Rh) of coarse aggregate larger than 10%. Therefore, segregation resistance of self-compacting concrete can be assessed as follows:

- Concrete has satisfactory segregation resistance in horizontal direction if  $Pd \leq 9\text{mm}$ ;
- Concrete has poor segregation resistance in horizontal direction if  $Pd > 9\text{mm}$ .

where Pd is the penetration depth measured by use of the penetration apparatus.

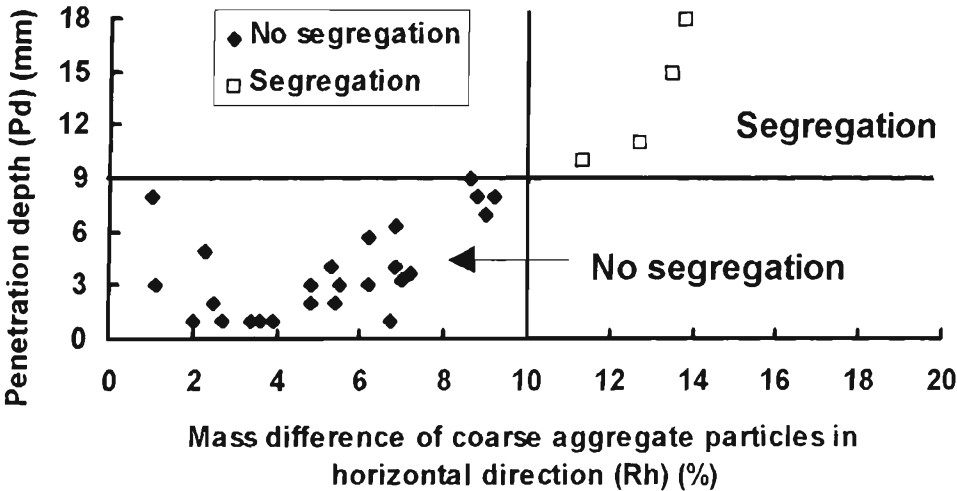


Fig. 7.26: Penetration depth (Pd) and mass difference (Rh) of coarse aggregate particles in horizontal direction

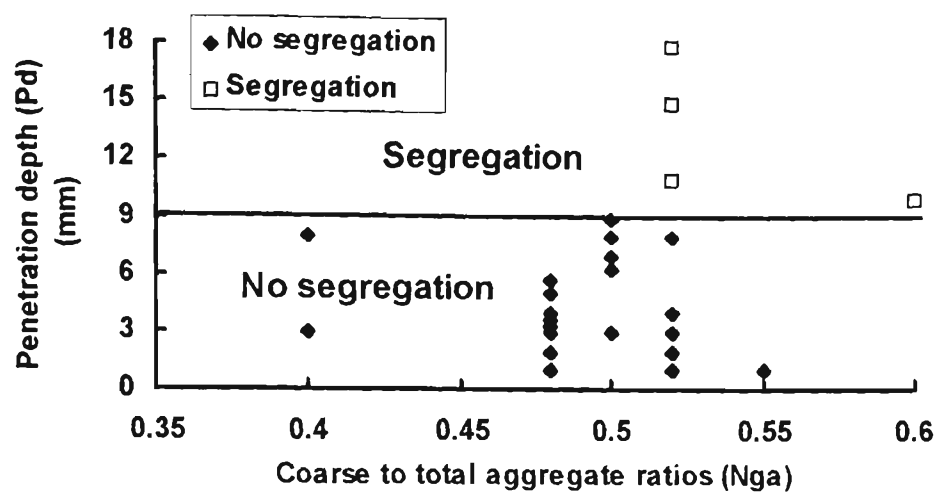


Fig. 7.27: Penetration depth (Pd) with different coarse to total aggregate ratios (Nga) and concrete segregation resistance in horizontal direction

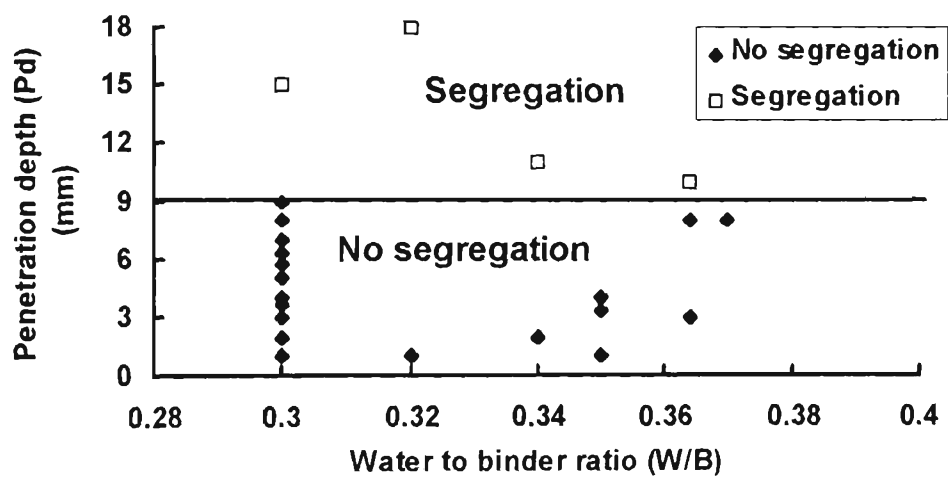


Fig. 7.28: Penetration depth (Pd) with different water to binder ratios (W/B) and concrete segregation resistance in horizontal direction

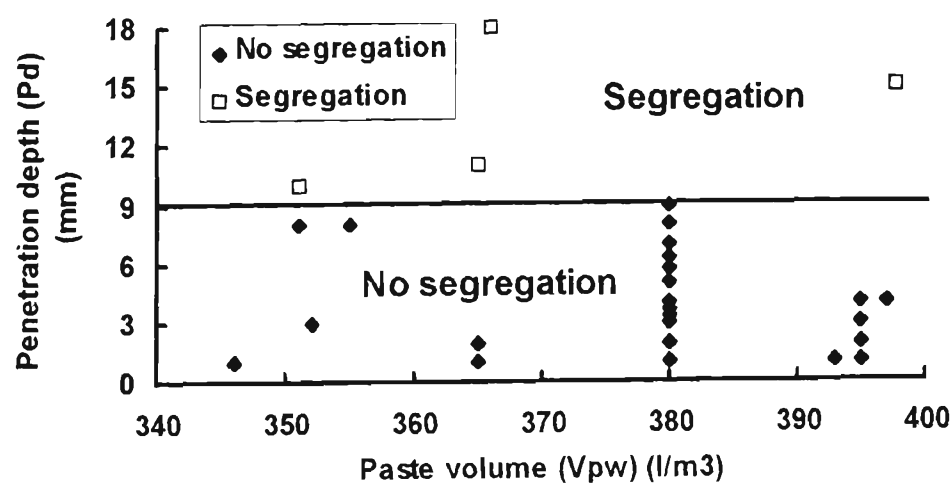


Fig. 7.29: Penetration depth (Pd) with different paste volumes (Vpw) and concrete segregation resistance in horizontal direction

#### ***7.4.3.3. Criteria for Penetration Depth (Pd) in Considering Segregation Resistance of Self-Compacting Concrete in Both Vertical and Horizontal Directions***

As stated above, self-compacting concrete should have good segregation resistance in both the vertical and horizontal directions. From test results and discussions in sections 7.4.3.1 and 7.4.3.2, the following criteria for penetration depth (Pd) for segregation resistance of self-compacting concrete are proposed:

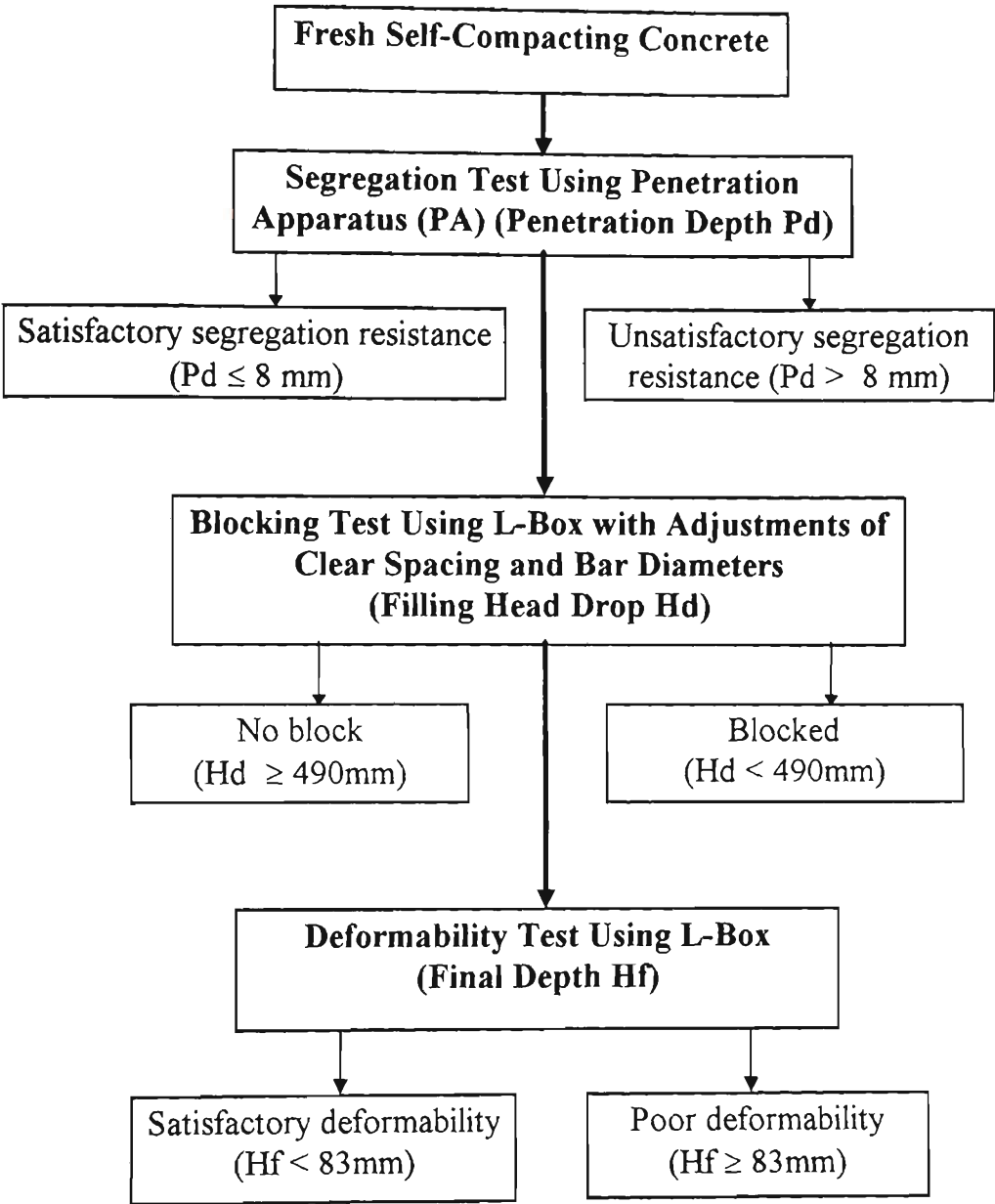
- Concrete has satisfactory segregation resistance if  $Pd \leq 8 \text{ mm}$ ;
- Concrete has poor segregation resistance if  $Pd > 8 \text{ mm}$ .

where Pd is the penetration depth measured by use of the penetration apparatus.

In summary, extensive testing for segregation resistance of self-compacting concrete was carried out. A simple penetration apparatus and rapid testing method were developed. The test results showed that the proposed method and developed apparatus are useful in rapidly evaluating segregation resistance of concrete in both vertical and horizontal directions. The method can reduce testing time and laboratory work necessary. The proposed method is applicable for different coarse to total aggregate ratios, different water to binder ratios and different materials.

### **7.5. FLOW CHART FOR RAPID EVALUATION OF SEGREGATION RESISTANCE, DEFORMABILITY AND BLOCKING BEHAVIOUR OF SELF-COMPACTING CONCRETE**

The evaluation of segregation resistance and filling ability of self-compacting concrete can be illustrated schematically as follows:



7.6. SUMMARY

A simple apparatus for segregation resistance testing is proposed. This apparatus and modified L-box apparatus are considered useful for rapid testing of segregation resistance, deformability and blocking behaviour of fresh self-compacting concrete.

Extensive testing for segregation resistance of self-compacting concrete was carried out. The test results showed that the proposed method and developed apparatus are useful in

rapidly evaluating segregation resistance of concrete in both vertical and horizontal directions.

The proposed rapid testing methods can reduce testing time and laboratory work necessary. The proposed method is applicable for different coarse to total aggregate ratios, different water to binder ratios and different materials.



## CHAPTER 8

### PROPOSED MIX DESIGN METHOD FOR SELF-COMPACTING HIGH PERFORMANCE CONCRETE

#### 8.1. BACKGROUND AND NEW CONCEPT

##### 8.1.1. Background

Self-compacting concrete (SCC) is a relatively new type of concrete that has been developed in recent years. The main properties of interest in its fresh state are deformability, segregation resistance and blocking property when the concrete flows through clear spacing between reinforcement bars. Good deformability or flowability is necessary to ensure adequate flow under self-weight of SCC. Adequate segregation resistance is required to ensure that components, especially coarse aggregate, are uniformly distributed in SCC when it is in a static or flowing condition, particularly through and around reinforcement. In addition, SCC should not block around reinforcements. It is therefore necessary to apply appropriate mix design procedures for SCC in order to achieve these properties. Several procedures have been proposed in recent years, being identified as: a) General Purpose Mix Design, b) Further Modifications and Additions to the General Purpose Mix Design, c) LCPC Approach and d) Optimisation of Aggregate Quantity and Composition Mix Design. These have been described in Chapter Two. The first three mix designs, a), b) and c), are largely based on experience on binder type, aggregates, admixtures, etc. and trial mixes. However, they all pose unanswered questions related to:

- How to evaluate segregation resistance of SCC;
- How to design SCC to have high durability with attributes such as low drying shrinkage and high degree of self-compaction;

- How to design SCC to be economically efficient (less required paste volume and less superplasticizer dosage);
- How to address the effect of clear spacing between reinforcement bars and effect of water to binder ratio on filling ability of SCC, including deformability and segregation resistance; and
- Possibility of applying mix design approach to different raw materials.

The mix design based on Optimisation of Aggregate Quantity and Composition has been developed by the author and co-workers (Bui, 1994; Tangtermsirikul et al., 1995 and Petersson et al., 1996) from 1993, and prior research has been focused on the aggregate phase in self-compacting concrete. A summary of the methodology used in investigating the aggregate phase follows.

In this approach concerning the Optimisation of Aggregate Quantity and Composition, concrete is considered as two-phase material, namely solid and liquid phases. The solid phase consists of fine and coarse aggregates. The liquid phase includes powder (cement, fillers), water, admixtures and air. The paste fills the voids in the aggregate matrix and provides a lubricating layer around each aggregate particle. The author and co-workers have focused on the solid phase (the aggregate phase), and the blocking criteria for the aggregate phase in SCC was developed based on the condition that the concrete does not segregate and has sufficient deformability. From the blocking criteria, a minimum required paste volume (or maximum allowable aggregate volume) can be calculated in order to obtain self-compaction of concrete without causing blocking around the reinforcement. It was found that the minimum required paste volumes with regard to different coarse to total aggregate ratios (Nga) depend on the following factors:

- Clear spacing between reinforcement bars;
- Ratio between particle size and diameters of reinforcement bars;
- Particle size distributions of fine and coarse aggregates; and
- Types (or shapes) of aggregate (e.g. crushed aggregate or river gravels).

The blocking criteria relates the aggregate blocking volume ratio to the ratio between reinforcement clear spacing and diameter of aggregate fraction and ratio between reinforcement diameter and maximum aggregate size. Fig. 8.1 shows a model for deriving the blocking volume of various single-size aggregates. The model was derived from the filling ability test of concrete using the L-shape apparatus (see Fig. 6.2). The model relates the blocking volume ratio ( $N_{bi}$ ) of aggregate to the ratio between reinforcement clear spacing and the three-quarter dimension of each aggregate fraction (specified as the clear spacing to particle size ratio,  $D_{ca}$ ) and the ratio ( $K$ ) between reinforcement diameter and maximum size of aggregate. The parameters  $N_{bi}$ ,  $D_{ca}$  and  $K$  are defined as follows:

$$N_{bi} = \frac{V_{bi}}{V_t} \quad (\text{Eq. 8.1})$$

$$D_{ca} = \frac{c}{D_{af}} \quad (\text{Eq. 8.2})$$

$$K = \frac{\Phi}{D_{max}} \quad (\text{Eq. 8.3})$$

Where

$N_{bi}$ : blocking volume ratio of aggregate group  $i$ ,

$V_{bi}$ : blocking volume of aggregate group  $i$  ( $V_{bi}$  is the volume of aggregate from group  $i$  that retains in front of the reinforcement set in the L-box

apparatus),

$V_t$ : total volume of the concrete mixture,

$D_{ca}$ : ratio between reinforcement clear spacing ( $c$ ) and the three-quarter dimension of each aggregate fraction ( $D_{af}$ )

$$D_{af} = M_{i-1} + 3/4 * (M_i - M_{i-1})$$

$M_i$  and  $M_{i-1}$  are upper and lower sieve dimensions of aggregate group  $i$ , respectively

$K$ : ratio between reinforcement diameter ( $\Phi$ ) and maximum size ( $D_{max}$ ) of aggregate

Fig. 8.1 shows that a larger ratio ( $K$ ) between reinforcement diameter and maximum size of aggregate gives smaller aggregate blocking volume ratio ( $N_{abi}$ ). Fig. 8.1 also indicates that, for the same value of  $K$ , the river coarse aggregate has a higher aggregate blocking volume ratio ( $N_{abi}$ ) than that of crushed coarse limestone aggregate. This can be explained by the effect of friction between aggregate particles being more rounded and smooth surfaced, (the river coarse aggregates have a smaller inter-particle friction than that of crushed coarse limestone aggregate).

Ozawa et al. (1992b) proposed an equation for computing the risk of blocking risk for a multi-size sand as

$$\text{Risk of blocking} = \sum (n_{si}/n_{sbi}) \quad (\text{Eq. 8.4})$$

where  $n_{si}$  is the volume ratio of an aggregate of single-size group  $i$  and  $n_{sbi}$  represents the blocking volume ratio (i.e. the volume ratio which causes blocking) of the aggregate of single-size group  $i$ . The volume ratio of aggregate is defined as the ratio between

volume of the aggregate and the total volume of the concrete.

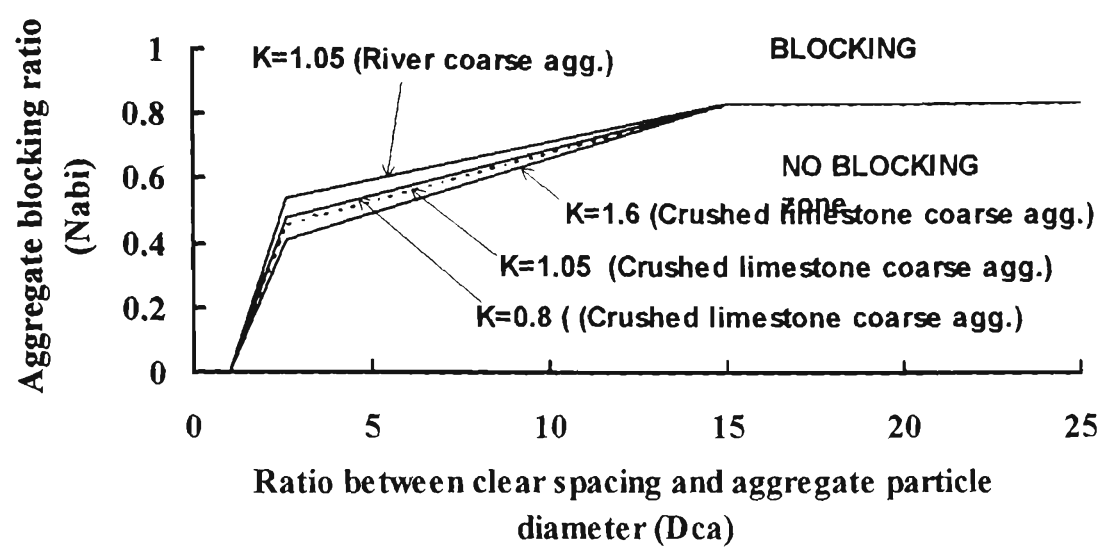


Fig. 8.1: Relationship between blocking volume ratio and clear spacing to particle size ratio

The equation for computing the maximum aggregate volume corresponding to each gravel-total aggregate ratio of each aggregate type can be derived from Eq. 8.1 and 8.4 as

$$\text{Risk of blocking} = \sum_{i=1}^n \left( \frac{N_{ai}}{N_{abi}} \right) = \sum_{i=1}^n \left( \frac{V_{ai} / V_t}{V_{abi} / V_t} \right) = \sum_{i=1}^n \left( \frac{V_{ai}}{V_{abi}} \right) \quad (\text{Eq. 8.5})$$

where V<sub>ai</sub> is volume of aggregate group i, V<sub>abi</sub> is the blocking volume of aggregate group i, V<sub>t</sub> is total volume of the concrete mixture and n is number of aggregate size groups. The maximum total aggregate volume is the volume at which the blocking risk equals to 1, so

$$\sum_{i=1}^n \left( \frac{V_{ai}}{V_{abi}} \right) = 1.0 \quad (\text{Eq. 8.6})$$

$$\text{Risk of blocking} = \sum_{i=1}^n \left( \frac{V_{ai}}{V_{abi}} \right) = \sum \left( \frac{V_{am}}{V_{abm}} \right) + \sum \left( \frac{V_{an}}{V_{abn}} \right) \quad (\text{Eq. 8.7})$$

where

$$\sum \left( \frac{V_{am}}{V_{abm}} \right) : \text{Contribution of coarse aggregate,}$$

$$\sum \left( \frac{V_{an}}{V_{abn}} \right) : \text{Contribution of fine aggregate (sand),}$$

$V_{am}$ : Volume of coarse aggregate group m,

$V_{abm}$ : Blocking volume of coarse aggregate group m,

$V_{an}$ : Volume of fine aggregate group n,

$V_{abn}$ : Blocking volume of fine aggregate group n.

On the other hand, we have:

$$N_{ga} = \frac{G}{G + S} \quad (8.8)$$

where

G: Total coarse aggregate content by weight

S: Total fine aggregate content by weight

$N_{ga}$ : Coarse to total aggregate ratio by weight

From Eq. 8.8:

$$V_g = \frac{V_a * N_{ga} * \rho_s}{\rho_g + (\rho_s - \rho_g) * N_{ga}} \quad (\text{Eq. 8.9})$$

$$V_s = V_a - V_g \quad (\text{Eq. 8.10})$$

where

$V_g$ : Total coarse aggregate volume

$V_s$ : Total fine aggregate volume

$\rho_g$ : Bulk specific gravity of coarse aggregate

$\rho_s$ : Bulk specific gravity of fine aggregate

$V_a$ : Total aggregate volume

Then  $V_{gm}$  and  $V_{sn}$  are calculated as follows:

$$V_{gm} = P_{vgm} * V_g \quad (\text{Eq. 8.11})$$

$$V_{sn} = P_{vsn} * V_s \quad (\text{Eq. 8.12})$$

where

$P_{vgm}$ : Ratio of volume of coarse aggregate group m to total coarse aggregate volume,

$P_{vsn}$ : Ratio of volume of fine aggregate group n to total fine aggregate volume,

Substituting Eq. 8.9 and 8.10 into Eq. 8.11 and 8.12 leads to:

$$V_{gm} = \frac{V_a * P_{vgm} * N_{ga} * \rho_s}{\rho_g + (\rho_s - \rho_g) * N_{ga}} \quad (\text{Eq. 8.13})$$

$$V_{sn} = \frac{V_a * P_{vsn} * (1 - N_{ga}) * \rho_g}{\rho_g + (\rho_s - \rho_g) * N_{ga}} \quad (\text{Eq. 8.14})$$

Then the total maximum allowable aggregate volume ( $V_{abmax}$ ) is the volume for which the blocking risk is equal to 1:

$$V_{abmax} = \sum_{i=1}^n V_{ai} = V_a \quad (\text{Eq. 8.15})$$

where  $V_{abmax}$  is total maximum allowable aggregate volume for which the blocking risk equals to 1,

Then from Eq. 8.7, we get:

$$\text{Risk of blocking} = \sum \left( \frac{V_{gm}}{V_{bgm}} \right) + \sum \left( \frac{V_{sn}}{V_{bsn}} \right) = 1 \quad (\text{Eq. 8.16})$$

From Eq. 8.13, 8.14, 8.15 and 8.16, we obtain:

$$V_{abmax} = \frac{\rho_g + (\rho_s - \rho_g) * N_{ga}}{\sum \frac{P_{vgm} * N_{ga} * \rho_s}{V_{abm}} + \sum \frac{P_{vsn} * (1 - N_{ga}) * \rho_g}{V_{abn}}} \quad (\text{Eq. 8.17})$$

where

$V_{abm}$  and  $V_{abn}$  can be calculated of the Eq. 8.1:

$$V_{abi} = N_{abi} * V_t \quad (\text{Eq. 8.18})$$

$$\text{or } V_{abm} = N_{abm} * V_t \quad (\text{Eq. 8.19})$$

$$V_{abn} = N_{abn} * V_t \quad (\text{Eq. 8.20})$$

and from test results, for crushed coarse aggregate, the values of  $N_{abi}$  can be calculated as follows:

a) For  $1 \leq D_{ca} \leq 2.6$

$$N_{abm} \equiv N_{abi} = \frac{C_k}{1.6} D_{ca} - \frac{C_k}{1.6} \quad (\text{Eq. 8.21})$$

$$N_{abn} \equiv N_{abi} = \frac{C_k}{1.6} D_{ca} - \frac{C_k}{1.6} \quad (\text{Eq. 8.22})$$

b) For  $2.6 \leq D_{ca} \leq 15$

$$N_{abm} \equiv N_{abi} = \frac{0.84 - C_k}{12.4} D_{ca} + 1.2097 C_k - 0.1761 \quad (\text{Eq. 8.23})$$



$$N_{abn} \equiv N_{abi} = \frac{0.84 - C_k}{12.4} D_{ca} + 1.2097 C_k - 0.1761 \quad (\text{Eq. 8.24})$$

c) For  $D_{ca} > 15$

$$N_{abm} \equiv N_{abi} = 0.84 \quad (\text{Eq. 8.25})$$

$$N_{abn} \equiv N_{abi} = 0.84 \quad (\text{Eq. 8.26})$$

where  $C_k$  is a coefficient dependent on ratio ( $K$ ) between reinforcement diameter and maximum aggregate size (see Eq. 8.3):

$$C_k = -0.0875 K + 0.55 \quad (\text{Eq. 8.27})$$

For different values of  $K$ , the values of  $N_{abi}$  were computed from Eq. 8.21 to Eq. 8.26 and illustrated in Fig. 8.1. Using Eq. 8.17, for certain coarse to total aggregate ratio ( $N_{ga}$ ), maximum allowable total aggregate volume ( $V_{abmax}$ ) (or minimum required paste volume ( $V_{pwmin}$ )) can be calculated.

The test results that were reported in a number of publications (Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al., 1996; Montgomery et al., 1998) showed that the blocking criteria is useful in predicting the minimum required paste volume and can be applied for different materials.

In a previous study (Bui, 1994), the author also proposed formule to calculate the average spacing ( $D_{ss}$ ) between particle surfaces in concrete as follows:

$$D_{ss} = D_{av} \left\{ \sqrt[3]{1 + \frac{V_{pw} - V_{oid}}{V_t - V_{pw}}} - 1 \right\} \quad (\text{Eq. 8.28})$$

where

$D_{ss}$ : Average spacing between particle surfaces (particles are assumed to be spherical) (Fig. 8.2);

$V_{pw}$ : Paste volume;

Void: Volume of voids in the densely compacted aggregate;

$V_t$ : Total concrete volume; and

$D_{av}$ : The average particle diameter, which is given by:

$$D_{av} = \frac{\sum D_i * M_i}{\sum M_i} \quad (\text{Eq. 8.29})$$

where

$D_i$ : Average size of aggregate fraction  $i$

$M_i$ : Percentage of aggregate mass retained between upper and lower sieve sizes  
(obtained from sieve analysis) in fraction  $i$

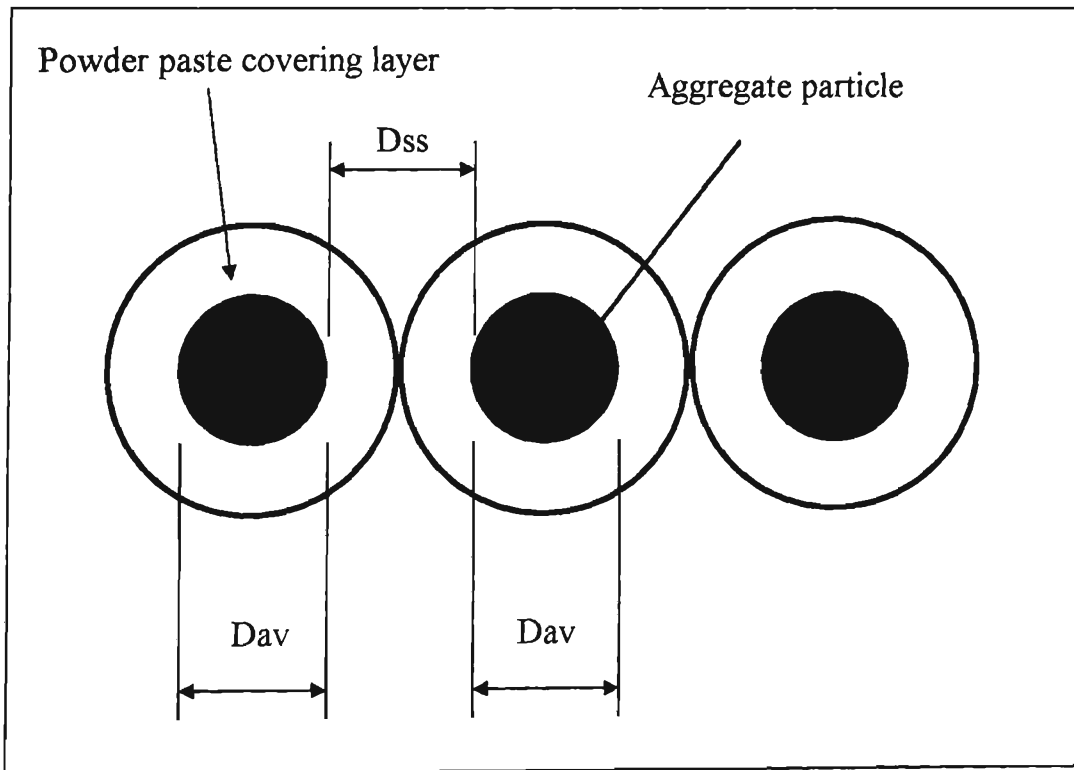


Fig. 8.2: Spherical aggregate particles, powder paste covering layer and average spacing  $D_{ss}$

As can be seen from Eq. 8.28 and 8.29, the average aggregate spacing ( $D_{ss}$ ) can be calculated from:

- the average particle size, calculated from grading curves,
- the measured volume of voids in the compacted aggregate, and
- the volume of paste in concrete.

### **8.1.2. New Concept**

As stated above, the previous studies by the author and co-workers (Bui, 1994; Tangtermsirikul and Bui, 1995; Petersson et al., 1996) focused mainly on the solid phase, e.g. the aggregate phase when considering blocking behaviour, based on the condition that concrete does not segregate and has sufficient deformability. In this study, a major emphasis has concentrated on the liquid phase, e.g. the paste phase that includes water, cement, mineral powder, admixtures and air in concrete. Also, a comprehensive mix proportioning method was developed. The method is based on the concept of:

- high durability (control of strength and drying shrinkage),
- economic efficiency (as low paste volume and superplasticizer dosage as possible),
- capacity to be applied for many kinds of materials,
- enhancing quality control (as little sensitivity as possible to quality control), and
- reducing laboratory testing (less trial mixes, use of computing program and rapid tests for deformability, blocking behaviour and segregation resistance of self-compacting concrete).

Based on these concepts, the study has investigated the following:

- Minimum required paste volumes with different coarse to total aggregate ratios, in considering blocking behaviour with the use of materials available in Australia;

- Minimum required paste volume with different coarse to total aggregate ratios with regard to producing:
  - sufficient deformability,
  - satisfactory segregation resistance,
  - satisfactory flowing velocity,
  - as low drying shrinkage as possible, and
  - as low superplasticizer dosage as possible;
- Optimum coarse to total aggregate ratio in order to enhance:
  - as low paste volume as possible,
  - as low drying shrinkage as possible,
  - as little sensitivity as possible to quality control, and
  - as low superplasticizer dosage as possible;

The final mix design procedure consists of a series of individual steps to be carried out in sequence in order to specify required proportions of materials to produce self-compacting high performance concrete of appropriate quality.

## **8.2. MATERIALS AND EXPERIMENTAL PROGRAM**

### **8.2.1. Materials**

Materials used for testing self-compacting high performance concrete (SC-HPC) containing milled limestone were described in chapters 4, 5 and 6. In addition, fly ash and blast furnace slag cements (Appendix 3.1) were also used in further studies (Wilton, 1998 and Mourad, 1998) in order to verify application of the proposed mix design methods. Total materials used include:

- five types of cement, comprising two types of shrinkage limited portland cements (SPC1 and SPC2), one type of ordinary portland cement (OPC) and two types of blast furnace slag cement (BFC1 and BFC2) (Appendix 3.1);
- four types of mineral admixtures, namely three sources of milled limestone (LS1, LS2 and LS3) and one type of fly ash (FA) (Appendix 3.1);
- six types of coarse aggregate (T1, T2, T3, T4, T5 and T6) blended from two sources of 20-mm basalt coarse aggregate (A, B), two sources of 14-mm coarse aggregate (C, D) and two sources of 10-mm coarse aggregate (E, F) (Appendix 3.2);
- two sources of river sand (RS1 and RS2) (Appendix 3.2); and
- one type of naphthalene sulphonate superplasticizer (SP) in dry form.

### **8.2.2. Experimental Program**

Two experimental programs were carried out. In the first program, concretes containing pure shrinkage limited portland cements and milled limestone were tested in order to develop models for determining minimum required paste volumes with relation to blocking behaviour, deformability, segregation resistance, superplasticizer requirement, flow velocity, compressive strength and drying shrinkage of self-compacting concrete. The second program, forming part of final year thesis programs of undergraduate students (Wilton, 1998, and Mourad, 1998) were carried out under the guidance of the author in order to check if the developed models can be applied for SCC containing other materials such as fly ash and blast furnace slag. Testing parameters and measurements included slump flow diameter (Fd), penetration depth (Pd), filling head drop (Hd), flow time (T50), superplasticizer dosage (SP), compressive strength and drying shrinkage.

Four combinations of coarse aggregate (T1, T2, T3 and T4) and river sand RS1 were used in mixes containing milled limestone and shrinkage limited portland cements (SPC1 and SPC2),. The combinations of coarse aggregate are indicated in Appendix 8.1. Concretes containing different paste volumes with coarse to total aggregate ratios between 0.40 and 0.60, and water to binder ratios from 0.30 to 0.37 were tested. Experimental data are presented in Appendix 8.1.

In the second program, ordinary portland cement (OPC), two combinations (T5 and T6) of coarse aggregate and river sand RS2 were used in concretes containing fly ash and blast furnace slag cements. The combinations of coarse aggregate, T5 and T6, are indicated in Appendix 8.2. Concretes containing different paste volumes with coarse to total aggregate ratios between 0.40 and 0.60, and water to binder ratios of 0.30, 0.32, 0.35 were tested. Test data can be seen in Appendix 8.2.

### **8.3. MINIMUM PASTE VOLUMES IN CONSIDERING BLOCKING BEHAVIOUR**

The test results relating to minimum paste volume required in order to investigate the blocking behaviour of SCC containing limestone modified cements were reported in section 6.2.1 of Chapter Six. As stated in Chapter Six, the results of this study confirmed that blocking criteria developed from previous studies (Bui, 1994, Tangtermsirikul and Bui, 1995) are useful in predicting the minimum paste volume required for SCC when it flows through clear spacing between reinforcement bars without blocking. The blocking criteria together with other criteria will be used in mix design of self-compacting concrete.

#### **8.4. MINIMUM PASTE VOLUMES IN CONSIDERING LIQUID-PHASE CRITERIA OF SCC**

The paste volume should be sufficient to fill all voids between aggregates in the matrix and provide lubricating layers around aggregate particles. According to Ozawa et al. (1992a, 1992b), SCC in the fresh state must have good deformability and segregation resistance in order to have satisfactory filling ability. The authors also concluded that the blocking and segregation of flowing concrete around obstructions are closely aligned with particle to particle interactions and that the liquid phase, such as paste between particles can control this interaction. It was found that larger spacing ( $D_{ss}$ ) between aggregate particle surfaces, (calculated by using Eq. 8.28 and 8.29), can lead to better deformability and filling ability of SCC (Bui K. Van, 1994). However, to date, no recommendations have been put forward to predict a required value of  $D_{ss}$  for self-compacting concrete. Thus, in this study, a model for predicting the required value of  $D_{ss}$  for self-compacting high performance concrete (SC-HPC) was developed.

In order to have SC-HPC with sufficient deformability and segregation resistance from the view point of high durability and less cost, the concrete should have the following characteristics:

- Slump flow diameter ( $F_d$ ) should be larger than 650 mm in order to have good flow or deformability and good surface appearance, as Shiba et al. (1998) has reported that SCC with slump flow diameter larger than 650 mm is of better surface appearance;
- Penetration depth ( $P_d$ ) should not be larger than 8 mm in order to ensure that concrete has satisfactory segregation resistance as indicated in Chapter Seven.
- The flow time  $T_{50}$  should not be greater than 12 seconds ( $T_{50}$  is the time for

concrete to flow to a diameter of 50 cm, when it is tested for slump flow) because flow time affects speed of construction;

- Superplasticizer dosage should be less than 15 kg per m<sup>3</sup> in dry form to reduce the cost of concrete, and also to limit any unwanted repercussion due to concrete containing excessive amounts of certain type of superplasticizer (compressive strength of mix OFA1 containing pure cement was lower than that of mix OFA2 containing 30% of fly ash, because mix OFA1 contained excessively high superplasticizer dosage (29.83 kg/m<sup>3</sup>) (Appendix 8.2);
- As low paste volume as possible in order to control drying shrinkage (as low paste volume usually leads to lower drying shrinkage), and to lower the cost of SCC.

#### ***8.4.1. Minimum Required Value of Average Aggregate Spacing ( $D_{ssmin}$ )***

Minimum required value of  $D_{ss}$  is dependent on a number of factors, namely:

- Properties of cement (chemical composition and fineness);
- Properties of aggregates (particle size distribution, specific gravity, surface texture and shape);
- Properties and content of supplementary materials and admixtures (chemical compositions, fineness, particle shape and size distribution);
- Properties of superplasticizer
- Water to binder ratio
- Characteristics of binary mixture of fine and coarse aggregate (void content);
- Interaction between components such as reaction between cement and superplasticizer, or between cement and mineral admixtures.



Test results given in Fig. 8.3 to Fig. 8.10, inclusive, show higher values of average aggregate particle diameter ( $D_{av}$ ) generally require higher average spacing ( $D_{ss}$ ) between particle surfaces in order to achieve a sufficient slump flow diameter greater than 650 mm without producing segregation. However, for certain mixes when the average diameter,  $D_{av}$  was low, the superplasticizer requirement and flow time of the respective concrete was high. The superplasticizer requirement and flow time can be reduced by increasing the paste volume (e.g. increase average spacing  $D_{ss}$ ) for mixes with the same average aggregate diameter ( $D_{av}$ ). Also, for concrete containing similar superplasticizer dosage, lower water to binder ratio requires higher paste volume ( $V_{pw}$ ) (e.g. higher  $D_{ss}$ ) in order to achieve similar slump flow diameters without causing segregation. In addition, different coarse aggregates with different maximum sizes can have an affect on flow velocity, tendency for segregation and required paste volume (i.e. average spacing  $D_{ss}$ ). Concretes containing coarse aggregate of higher maximum size tends to have higher flow velocity and higher risk of segregation.

As discussed above, the minimum required values of  $D_{ss}$  depend on a number factors, and there is no formula that can calculate exactly the minimum required value of  $D_{ss}$  for all materials. Therefore, in this study, effort was made to propose a model that can be used to estimate the approximate minimum required value of  $D_{ss}$ . The model can be used to estimate an initial value to be used in trial mix designs. The proposed model is based on consideration of :

- Water to binder ratio (W/B) (or water to powder ratio, in the case of large proportion of very fine particles in aggregates);
- Particle size distribution and particle shape of aggregate binary mixtures by incorporating average aggregate diameter ( $D_{av}$ ) and void content in formula

estimating the minimum required value of  $D_{ss}$ ;

- Aggregate maximum sizes of 20 mm and 14 mm (for the same coarse to total aggregate ratio, 20-mm aggregate can lead to higher risk of segregation and higher flow velocity of SCC in comparison with 14-mm aggregate); and
- Different coarse to total aggregate ratios ( $N_{ga}$ ) that relate to average aggregate diameter,  $D_{av}$  and void content.

Average aggregate diameter ( $D_{av}$ ) and average aggregate spacing ( $D_{ss}$ ) of all mixes were calculated according to Eq. 8.28 and 8.29, these being indicated in Appendix 8.1 and 8.2. These values of  $D_{ss}$  with respect to different values of  $D_{av}$  for concretes containing 20-mm and 14-mm aggregates and water to binder ratios of 0.30, 0.32 and 0.35 are plotted in Fig. 8.3 to 8.10, inclusive. The analytical lines for  $D_{ssmin}$  in SCC containing 20-mm and 14-mm coarse aggregates with different water to binder ratios are generated based on experimental results by considering pairs of points (having corresponding values of  $D_{av}$  and  $D_{ss}$ ) where the values of  $D_{av}$  are divided into three ranges ( $D_{av} \leq 5.0$  mm,  $5.0$  mm  $< D_{av} \leq 6.5$  mm and  $D_{av} > 6.5$  mm) for SCC containing 20-mm coarse aggregate and two ranges ( $D_{av} \leq 6.5$  mm and  $D_{av} > 6.5$  mm) for SCC containing 14-mm coarse aggregates, respectively. Linear relationships are considered to exist in the respective ranges for  $D_{av}$ . For SCC containing mineral admixture and portland cements (ordinary portland cement, shrinkage limited portland cement, portland cement containing blast furnace slag) with fineness between 300 m<sup>2</sup>/kg and 450 m<sup>2</sup>/kg, the formule that can be used to predict the minimum value of required average spacing ( $D_{ssmin}$ ) between aggregate particle surfaces are proposed as follows:

a) For aggregate with maximum size of 20 mm

- For  $W/B = 0.30$

$$D_{ssmin} = 0.422 \text{ mm if } D_{av} \leq 5.0 \text{ mm} \quad (\text{Eq. 8.30})$$

$$D_{ssmin} = 0.0540 D_{av} + 0.1520 \text{ if } 5.0 \text{ mm} < D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.31})$$

$$D_{ssmin} = 0.2913 D_{av} - 1.3904 \text{ if } D_{av} \geq 6.5 \text{ mm} \quad (\text{Eq. 8.32})$$

- For  $W/B = 0.32$

$$D_{ssmin} = 0.369 \text{ mm if } D_{av} \leq 5.0 \text{ mm} \quad (\text{Eq. 8.33})$$

$$D_{ssmin} = 0.0233 D_{av} + 0.2523 \text{ if } 5.0 \text{ mm} < D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.34})$$

$$D_{ssmin} = 0.1081 D_{av} - 0.2987 \text{ if } D_{av} \geq 6.5 \text{ mm} \quad (\text{Eq. 8.35})$$

- For  $W/B = 0.35$

$$D_{ssmin} = 0.289 \text{ mm if } D_{av} \leq 5.0 \text{ mm} \quad (\text{Eq. 8.36})$$

$$D_{ssmin} = 0.0407 D_{av} + 0.0857 \text{ if } 5.0 \text{ mm} < D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.37})$$

$$D_{ssmin} = 0.0931 D_{av} - 0.2551 \text{ if } D_{av} \geq 6.5 \text{ mm} \quad (\text{Eq. 8.38})$$

b) For aggregate with maximum size of 14 mm

- For  $W/B = 0.30$

$$D_{ssmin} = 0.437 \text{ mm if } D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.39})$$

$$D_{ssmin} = 0.0463 D_{av} + 0.1361 \text{ if } D_{av} > 6.5 \text{ mm} \quad (\text{Eq. 8.40})$$

- For  $W/B = 0.32$

$$D_{ssmin} = 0.400 \text{ mm if } D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.41})$$

$$D_{ssmin} = 0.0463 D_{av} + 0.0991 \text{ if } D_{av} > 6.5 \text{ mm} \quad (\text{Eq. 8.42})$$

- For  $W/B = 0.35$

$$D_{ssmin} = 0.350 \text{ mm if } D_{av} \leq 6.5 \text{ mm} \quad (\text{Eq. 8.43})$$

$$D_{ssmin} = 0.0463 D_{av} + 0.0491 \text{ if } D_{av} > 6.5 \text{ mm} \quad (\text{Eq. 8.44})$$

where

W/B: Water to binder ratio

Dssmin: Minimum required average spacing between aggregate particle surfaces

Dav: Average aggregate diameter that can be calculated from Eq. 8.29

As can be seen from Fig. 8.6 and 8.10, the required value of Dssmin depends on water to binder ratio (W/B) and average aggregate diameter (Dav). Lower water to binder ratio requires higher value of Dssmin, and generally, higher average aggregate diameter Dav requires higher value of Dssmin. Fig. 8.6 and 8.10 also show that the required value of Dssmin is remarkably increased when the average aggregate diameter is larger than 6.5 mm. This is due to the fact that too large a value of Dav, i.e. too large proportion of coarse aggregate, causes high sensitivity to segregation control for SCC. The high value of Dssmin is necessary to reduce the sensitivity and increase the deformability of SCC without causing segregation. For certain types of fine and coarse aggregates, the average aggregate diameter, Dav, depends on the coarse to total aggregate ratio (Nga). Therefore, it is better to choose a coarse to total aggregate ratio (Nga) with an average aggregate diameter smaller than or equal to 6.5 mm.

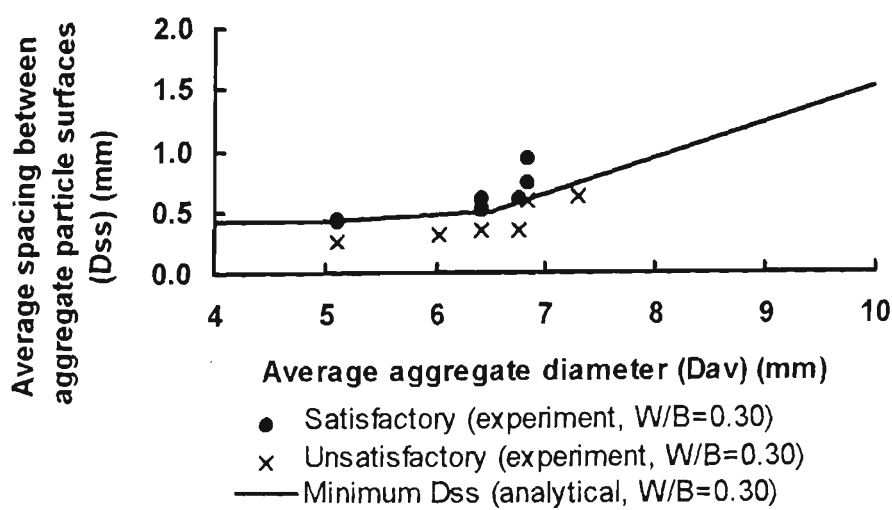


Fig. 8.3: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 20-mm coarse aggregate with water to binder ratio of 0.30

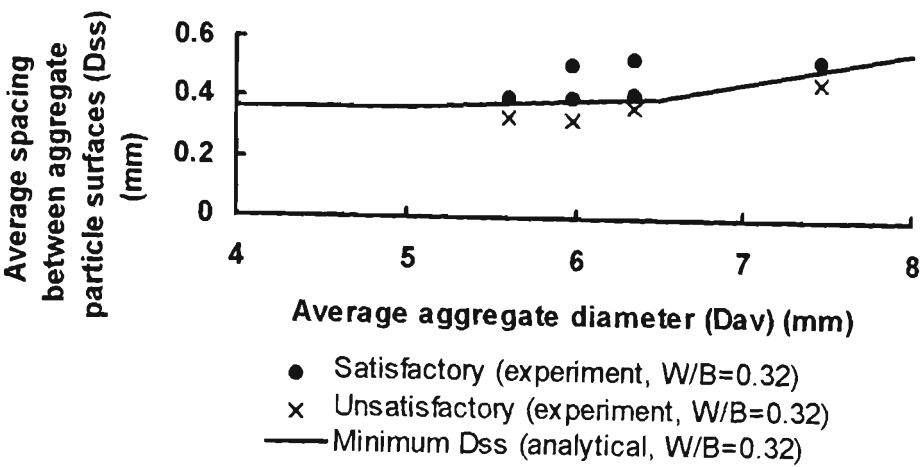


Fig. 8.4: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 20-mm coarse aggregate with water to binder ratio of 0.32

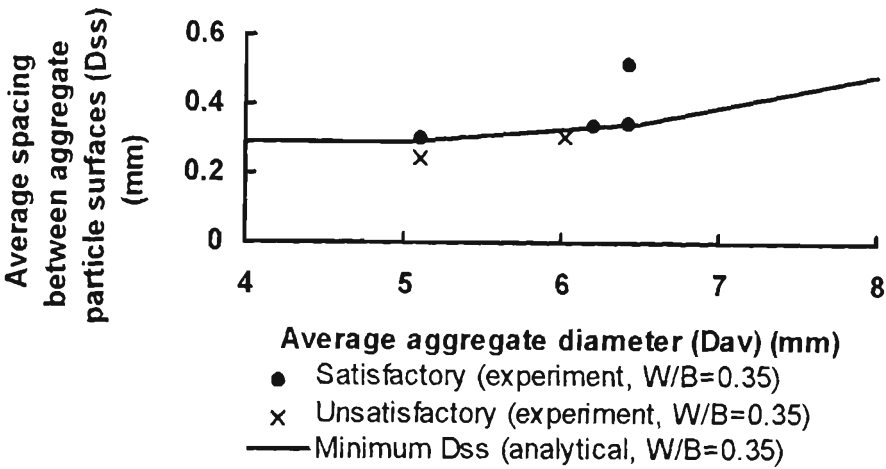


Fig. 8.5: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 20-mm coarse aggregate with water to binder ratio of 0.35

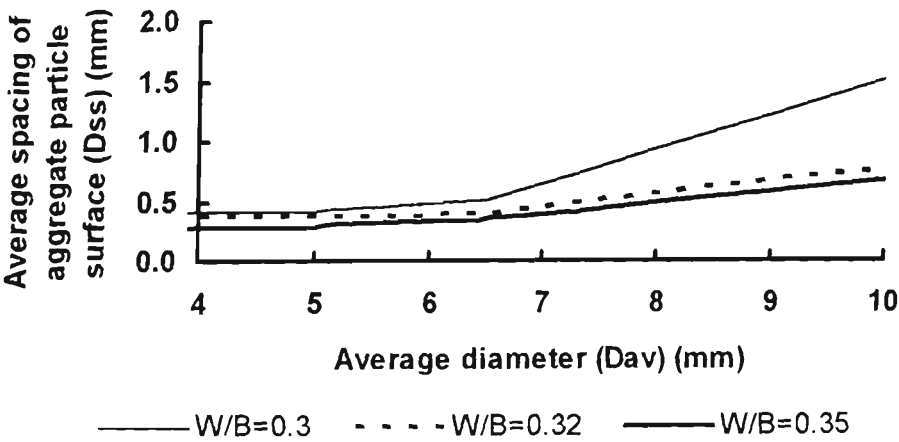


Fig. 8.6: Analytical values of minimum required average spacing (Dssmin) and average aggregate diameter (Dav) for SCC containing 20-mm coarse aggregate with water to binder ratios of 0.30, 0.32 and 0.35

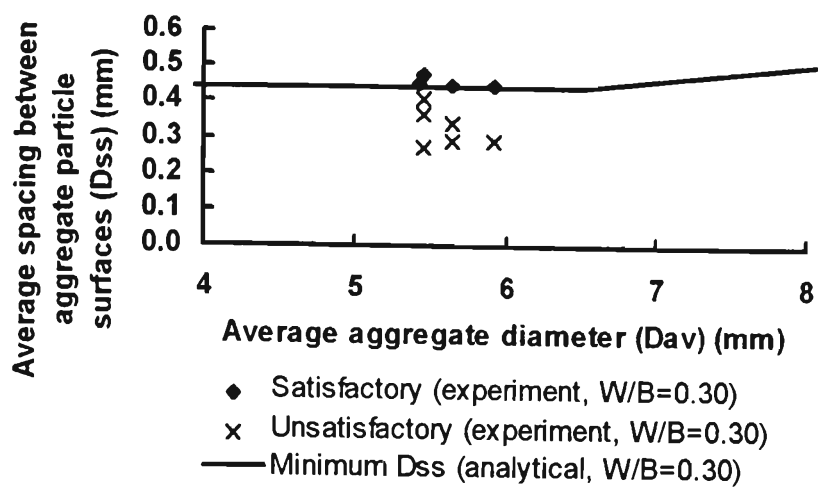


Fig. 8.7: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 14-mm coarse aggregate with water to binder ratio of 0.30

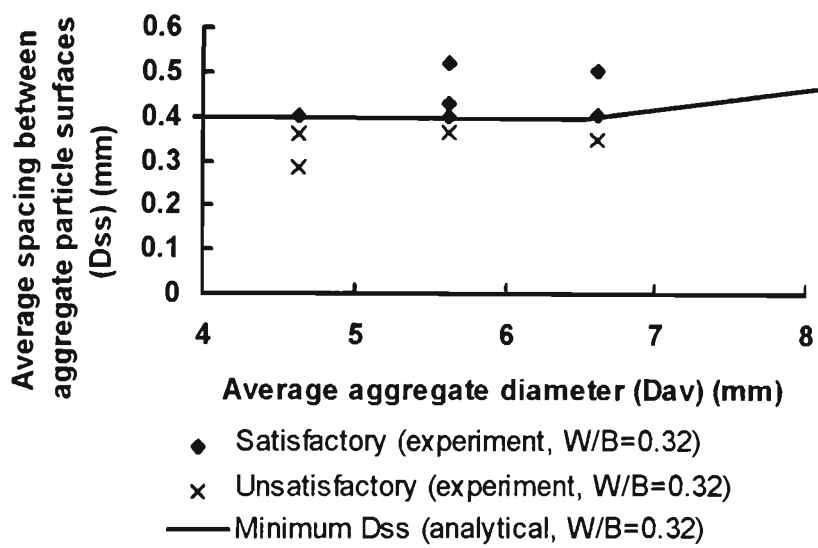


Fig. 8.8: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 14-mm coarse aggregate with water to binder ratio of 0.32

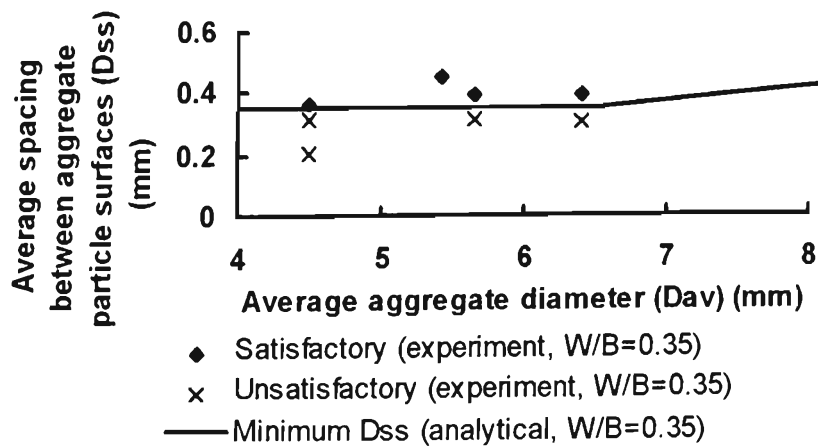


Fig. 8.9: Average spacing (Dss) and average aggregate diameter (Dav) for SCC containing 14-mm coarse aggregate with water to binder ratio of 0.35

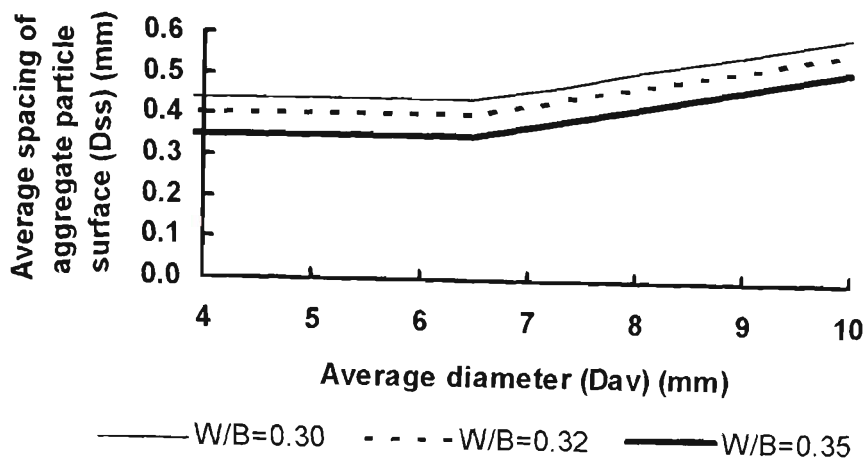


Fig. 8.10: Analytical values of minimum required average spacing ( $D_{ssmin}$ ) and average aggeragte diameter ( $D_{av}$ ) for SCC containing 14-mm coarse aggregate with water to binder ratios of 0.30, 0.32 and 0.35

Test results from Appendices 8.1 and 8.2 indicate that, for certain combination of aggregate, lower values of  $D_{av}$  (i.e., lower coarse to total aggregate ratio) permit lower values of  $D_{ssmin}$  if the specified requirements of superplasticizer dosage and flow velocity are excluded from the criteria on liquid phase. However, if these requirements are included in the criteria, the value of  $D_{ssmin}$  must be increased in order to achieve good deformability, satisfactory segregation resistance and flow velocity without the need for too high a superplasticizer dosage. For low average aggregate diameter,  $D_{av}$  (i.e. low coarse to total aggregate ratio), the required values of  $D_{ssmin}$  for SCC containing 14-mm coarse aggregate are generally higher than those for SCC containing 20-mm coarse aggregate. This is due to the fact that, for low value of  $D_{av}$ , low flow velocity and high requirement of superplasticizer dosage are generally problematic; therefore, the increase in paste volume (e.i. increase of  $D_{ssmin}$ ) is necessary in order to achieve satisfactory flow velocity for SCC containing 14-mm coarse aggregate. On the other hand, when average aggregate diameter ( $D_{av}$ ) is high (larger than 6.5 mm), SCC containing 20-mm coarse aggregate has higher risk of segregation than that containing 14-mm coarse

aggregate; thus, in order to reduce the risk of segregation, the value of  $D_{ssmin}$  in SCC containing 20-mm coarse aggregate needs to be larger than for SCC containing 14-mm coarse aggregate. Fig. 8.11, 8.12 and 8.13 illustrate the comparison between the analytical lines for  $D_{ssmin}$  (computed from Eq. 8.30 to 8.44), for SCC containing 20-mm and 14-mm coarse aggregates with water to binder ratios of 0.30, 0.32 and 0.35.

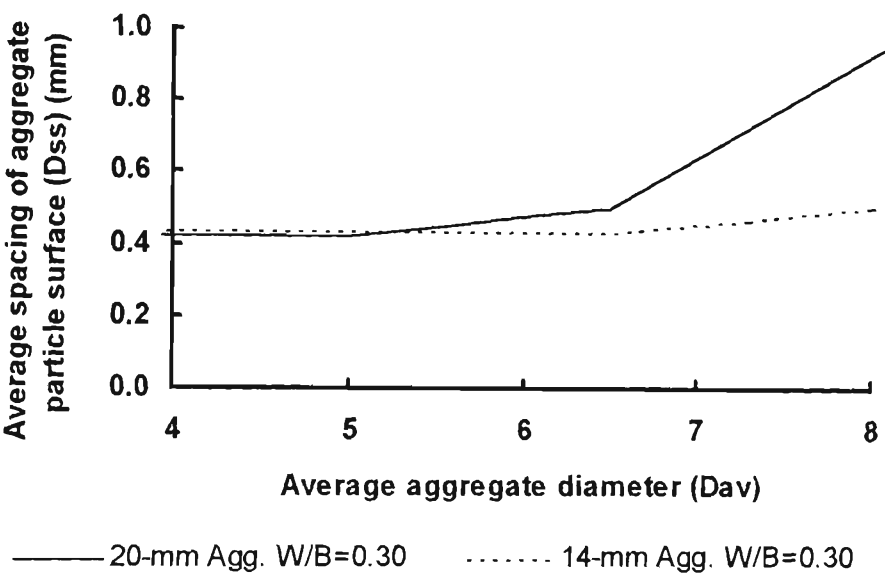


Fig. 8.11: Minimum average spacing ( $D_{ssmin}$ ) for SCC containing 14-mm and 20-mm coarse aggregates with constant water to binder ratio of 0.30

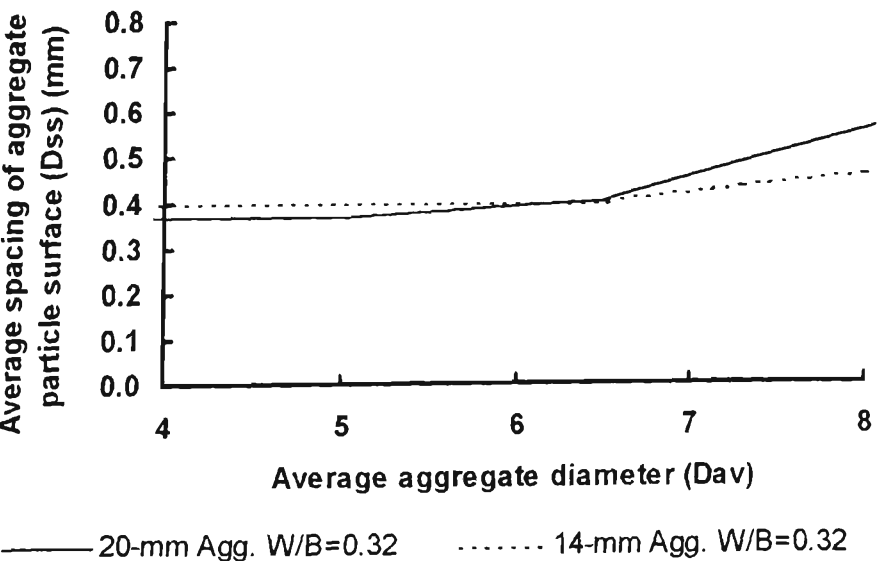


Fig. 8.12: Minimum average spacing ( $D_{ssmin}$ ) for SCC containing 14-mm and 20-mm coarse aggregates with constant water to binder ratio of 0.32



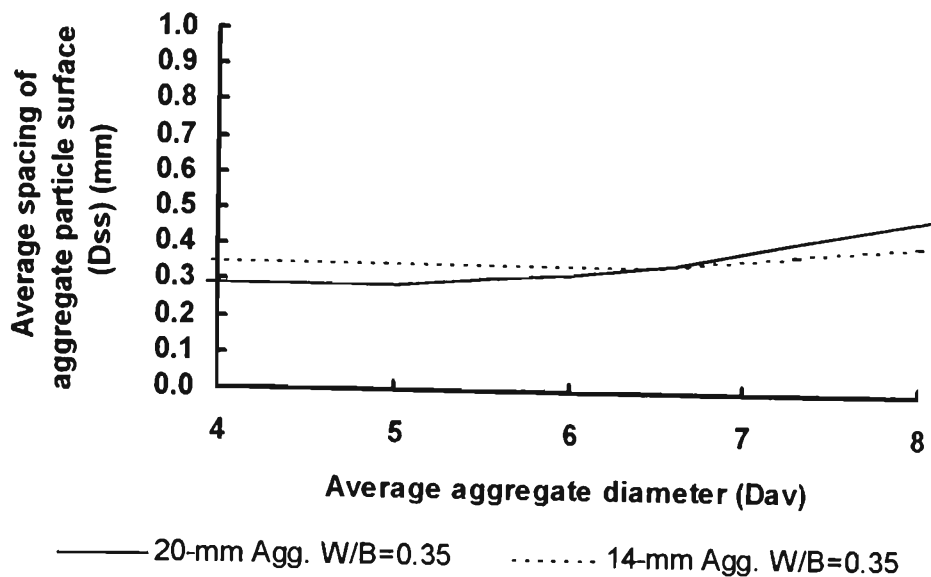


Fig. 8.13: Minimum average spacing ( $D_{ssmin}$ ) for SCC containing 14-mm and 20-mm coarse aggregates with constant water to binder ratio of 0.35

Fig. 8.3, 8.4 and 8.5 show that, for 20-mm coarse aggregate and water to binder ratios of 0.30, 0.32 and 0.35, the analytical lines, depicting the values of  $D_{ssmin}$  computed from Eq. 8.30 to Eq. 8.38, inclusive, divide the zones of satisfactory and unsatisfactory values of  $D_{ss}$ . Similarly, for 14-mm coarse aggregate and water to binder ratios of 0.30, 0.32 and 0.35, the analytical lines, relating to the values of  $D_{ssmin}$  computed from Eq. 8.39 to Eq. 8. 44, inclusive, divide the zones of satisfactory and unsatisfactory values of  $D_{ss}$  (Fig. 8.7, 8.8 and 8.9). Therefore, the equations from Eq. 8.30 to Eq. 8.44, inclusive, can be used to estimate the minimum required values of aggregate spacing ( $D_{ssmin}$ ) for specified aggregate types, varying coarse to total aggregate ratio and specified water to binder ratio. (For corresponding aggregate types and coarse to total aggregate ratios, the average aggregate diameter  $D_{av}$  can be computed from Eq. 8.29). The minimum required value of average aggregate spacing ( $D_{ssmin}$ ) can then be used to calculate the minimum paste volume ( $V_{pdmin}$ ) of SCC, as derived in the section 8.4.2.

### 8.4.2. Minimum Required Paste Volume ( $V_{pdmin}$ ) of SCC Considering Liquid-Phase Criteria

From Eq. 8.28, paste volume ( $V_{pw}$ ) of SCC can be obtained:

$$V_{pw} = V_t - \frac{V_t - \text{Void}}{\left[ \frac{D_{ss}}{D_{av}} + 1 \right]^3} \quad (\text{Eq. 8.45})$$

Substitute  $D_{ss}$  by  $D_{ssmin}$  into Eq. 8.45, we can calculate minimum required paste volume ( $V_{pdmin}$ ) of SCC considering liquid phase as follows:

$$V_{pdmin} = V_t - \frac{V_t - \text{Void}}{\left[ \frac{D_{ssmin}}{D_{av}} + 1 \right]^3} \quad (\text{Eq. 8.46})$$

For 1 m<sup>3</sup> of concrete ( $V_t = 1000$  l), then

$$V_{pdmin} = 1000 - \frac{1000 - \text{Void}}{\left[ \frac{D_{ssmin}}{D_{av}} + 1 \right]^3} \quad (\text{Eq. 8.47})$$

where

$V_{pdmin}$ : Minimum required paste volume (l/m<sup>3</sup>) for certain coarse to total aggregate ratio ( $N_{ga}$ );

Void: Aggregate void content of compacted aggregate matrix, measured according to ASTM C29/C29M

$D_{ssmin}$ : Minimum required average spacing (mm) between aggregate particle surfaces calculated by using the appropriate equation from Eq. 8.30 to 8.44, inclusive; and

$D_{av}$ : Average aggregate particle diameter (mm) that is calculated from Eq. 8.29.

The minimum paste volumes ( $V_{pdmin}$ ) required for different coarse to total aggregate ratios with specified water to binder ratio can be calculated from Eq. 8.47. The analytical values of  $V_{pdmin}$  for different coarse to total aggregate ratios are determined as follows:

- a) Average aggregate diameters ( $D_{av}$ ) are computed from sieve analysis and Eq. 8.29;
- b) Aggregate void contents (Void) of compacted aggregate matrix are measured according to ASTM C29/C29M;
- c) Minimum required average spacing ( $D_{ssmin}$ ) between aggregate particle surfaces is calculated by using the appropriate equation from Eq. 8.30 to 8.44, inclusive; and
- d) Minimum required paste volumes ( $V_{pdmin}$ ) are calculated from Eq. 8.47.

Test results and analytical values of paste volumes for SCC containing milled limestone with different coarse aggregate combinations (T1, T2, T4) and water to binder ratios of 0.30, 0.32 and 0.35 are given in Appendices 8.1, 8.3, 8.4, 8.5, Fig. 8.14, 8.15, 8.16, 8.17 and 8.18. Test results and analytical values of paste volume for SCC containing fly ash (FA) and blast furnace slag cements (BFC1 and BFC2) with different coarse aggregate combinations (T5 and T6) and water to binder ratios of 0.30, 0.32 and 0.35 are shown in Appendices 8.2, 8.6, 8.7, Fig. 8.19 and 8.20.

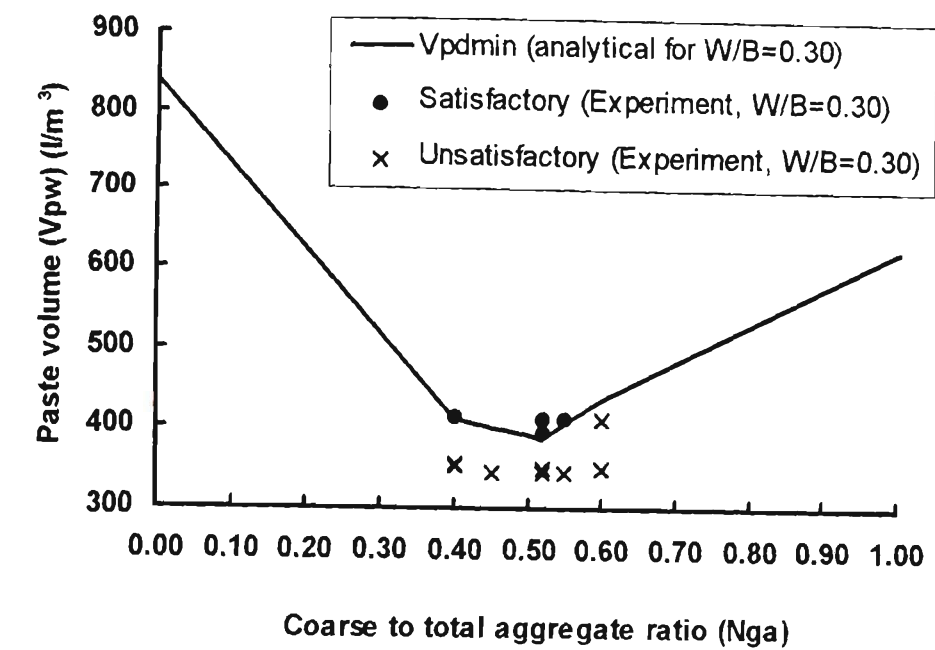


Fig. 8.14: Minimum required paste volume ( $V_{pmin}$ ) (analytical) and experimental results for SCC containing limestones with constant water to binder ratio of 0.30 and aggregate combination T1

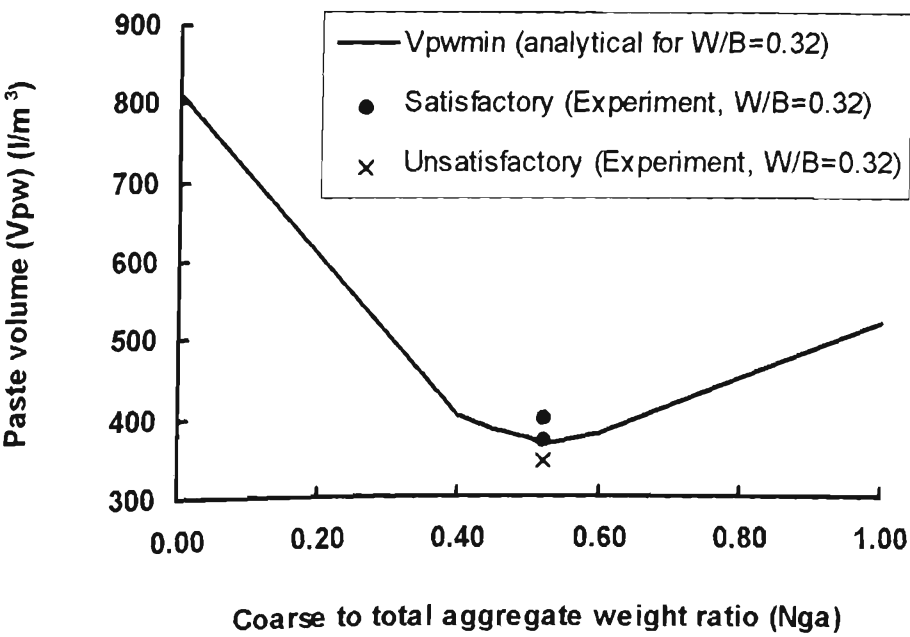


Fig. 8.15: Minimum required paste volume ( $V_{pmin}$ ) (analytical) and experimental results for SCC containing limestones with constant water to binder ratio of 0.32 and aggregate combination T2

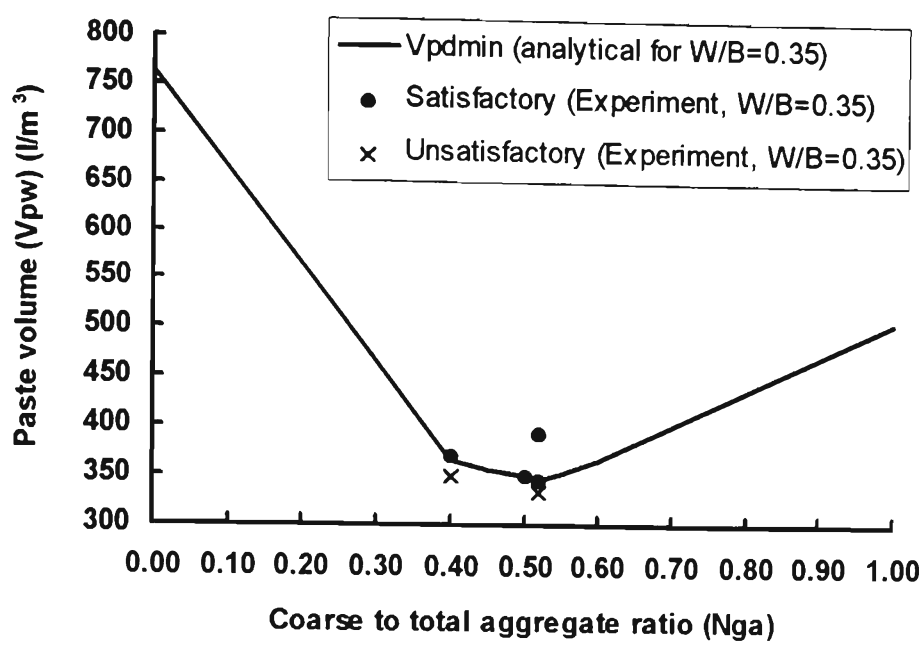


Fig. 8.16: Minimum required paste volume ( $V_{pdmin}$ ) (analytical) and experimental results for SCC containing limestones with constant water to binder ratio of 0.35 and aggregate combination T1

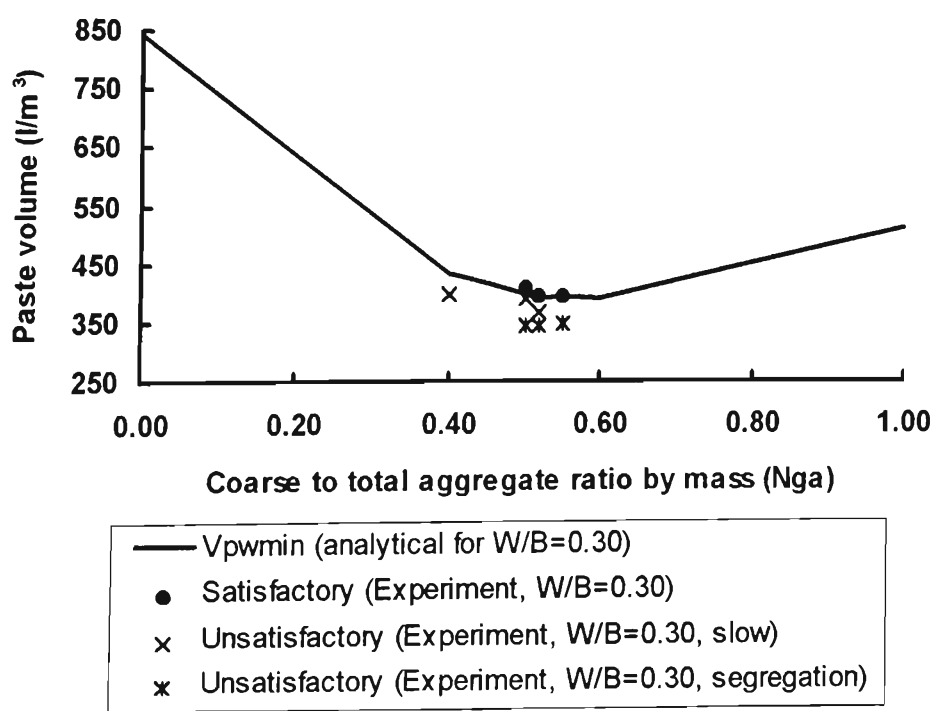


Fig. 8.17: Minimum required paste volume ( $V_{pdmin}$ ) (analytical) and experimental results for SCC containing limestones with constant water to binder ratio of 0.30 and aggregate combination T4

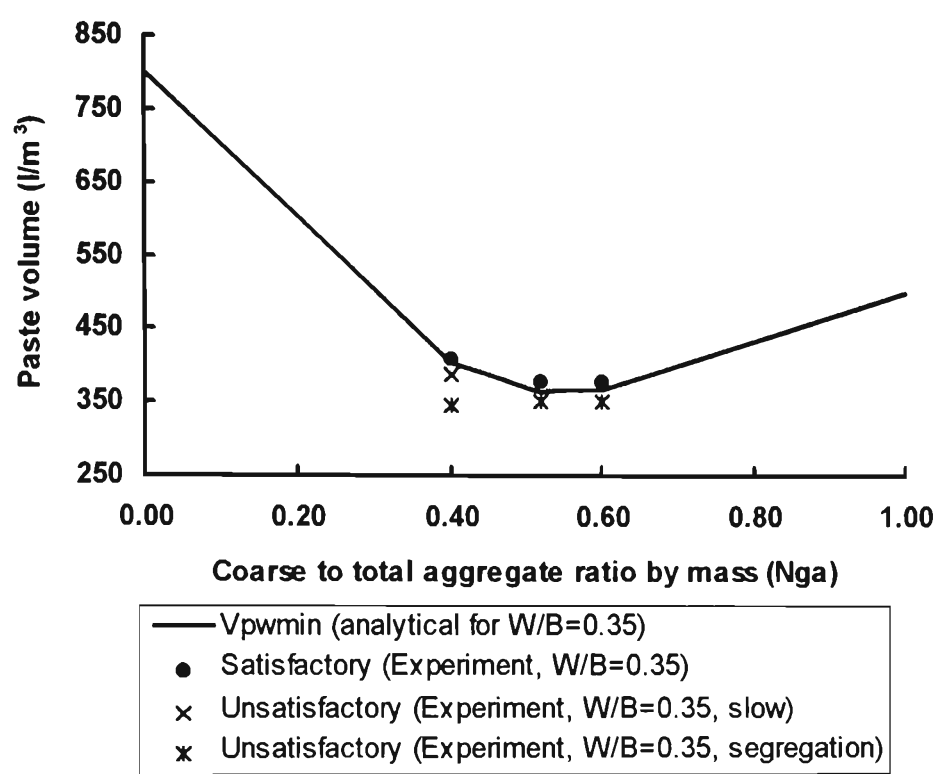


Fig. 8.18: Minimum required paste volume ( $V_{pdmin}$ ) (analytical) and experimental results for SCC containing limestones with constant water to binder ratio of 0.35 and aggregate combination T4

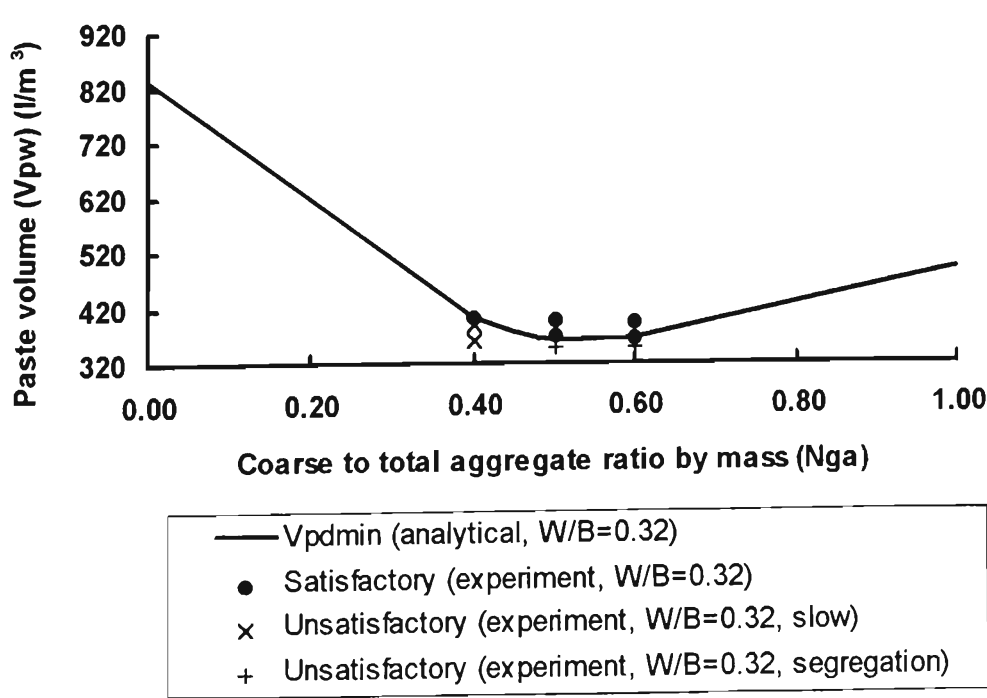


Fig. 8.19: Minimum required paste volume ( $V_{pdmin}$ ) (analytical) and experimental results for SCC containing blast furnace slag cements with constant water to binder ratio of 0.32 and aggregate combination T5

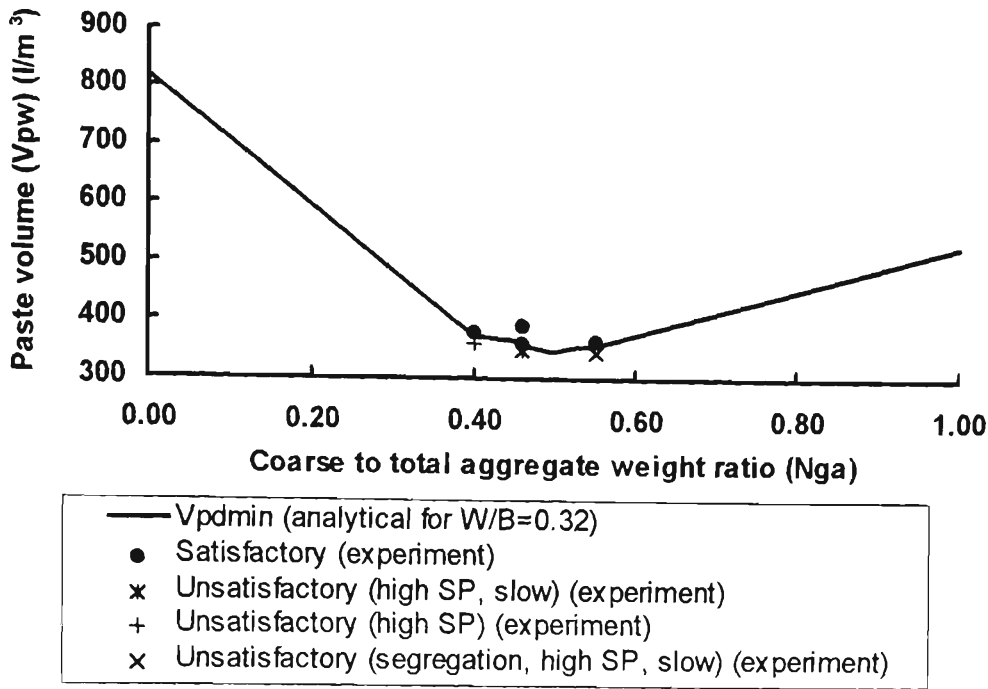


Fig. 8.20: Minimum required paste volume ( $V_{pdmin}$ ) (analytical) and experimental results for SCC containing fly ash with constant water to binder ratio of 0.32 and aggregate combination T6

If deformability and segregation resistance of SCC only are considered, then for low coarse to total aggregate ratio and/or low maximum size of coarse aggregate, SCC sometimes requires less paste volume ( $V_{pw}$ ) than that computed from the proposed criteria of liquid phase. However, other parameters are considered, namely flow velocity and superplasticizer dosage, it is necessary to increase paste volume to a level which is not less than that computed from the criteria. For example, mixes SN1B, OFA12, OFA15, BFC14, BFC15 with  $V_{pw}$  of 353 l, 350 l, 360 l, 390 l and 361 l, respectively, which had paste volumes lower than their respective minimum paste volume computed from liquid-phase criteria, exhibited satisfactory deformability and segregation resistance (Appendix 8.1, 8.2, Fig. 8.14, 8.19 and 8.20). However, those mixes did not meet the requirements for all parameters of liquid-phase criteria.

As can be seen from Fig. 8.14 to Fig. 8.20, inclusive, the analytical lines, which illustrated the values computed from Eq. 8.47, divide the zones of satisfactory and unsatisfactory experimental results. Therefore, Eq. 8.47 can be used to predict the minimum required paste volume ( $V_{pdmin}$ ) for SCC to have satisfactory deformability, segregation resistance and flow velocity, and to require less superplasticizer. (Hereafter,  $V_{pdmin}$  will be specified as the minimum required paste volume of liquid-phase criteria).

## **8.5. OPTIMUM COARSE TO TOTAL AGGREGATE RATIO**

As discussed in Chapter 6, for similar paste volumes of about  $346 \text{ l/m}^3$  and constant water to binder ratio of 0.30, mix SN5 with  $N_{ga}$  of 0.52 required superplasticizer dosage similar to, and lower than, respectively, mixes SN6 and SN27 with  $N_{ga}$  of 0.55 and 0.485 (Appendix 6.2 and Fig. 6.5). In addition, mix SN5 exhibited the lowest drying shrinkage, at all ages, in comparison with mixes SN6 and SN27 (Appendix 6.3 and Fig. 6.9). This is due to the fact that mix SN5 had average aggregate spacing ( $D_{ss}$ ) similar to and higher, respectively, than mixes SN5 and SN27 (Appendix 8.1 and Fig. 8.21), and the higher value of  $D_{ss}$  promotes better compaction for SCC, which results in lower drying shrinkage. Also, less superplasticizer is required for higher value of  $D_{ss}$  (Bui, 1994).

For similar paste volumes of about  $413 \text{ l/m}^3$  and constant water to binder ratio of 0.30, mixes with  $N_{ga}$  of 0.52 and 0.55 (mixes SN2 and SN3) had similar superplasticizer requirement, being lower and higher, respectively, than those with  $N_{ga}$  of 0.40 and 0.60 (mixes SN1 and SN4) (Appendix 6.2 and Fig. 6.4). This is again due to the fact that mixes SN2 and SN3 had similar average aggregate spacing, being larger and lower,



respectively, than mixes SN1 and SN4 (Appendix 8.1 and Fig. 8.22). In addition, mix SN2 (Nga of 0.52) had 168-day drying shrinkage lower than those with Nga of 0.40, 0.55 and 0.60 (mixes SN1, SN3 and SN4) (Appendix 6.3 and Fig. 6.8). The results showed that larger values of Dss do not always result in lower drying shrinkage. This may be explained by the fact that too high average diameter of aggregates ( $D_{av} > 6.5\text{mm}$ ) (e.g. too high coarse to total aggregate ratio) causes high risk of segregation and low degree of compaction of SCC. Therefore, the average aggregate diameter ( $D_{av}$ ) should not be larger than 6.5 mm.

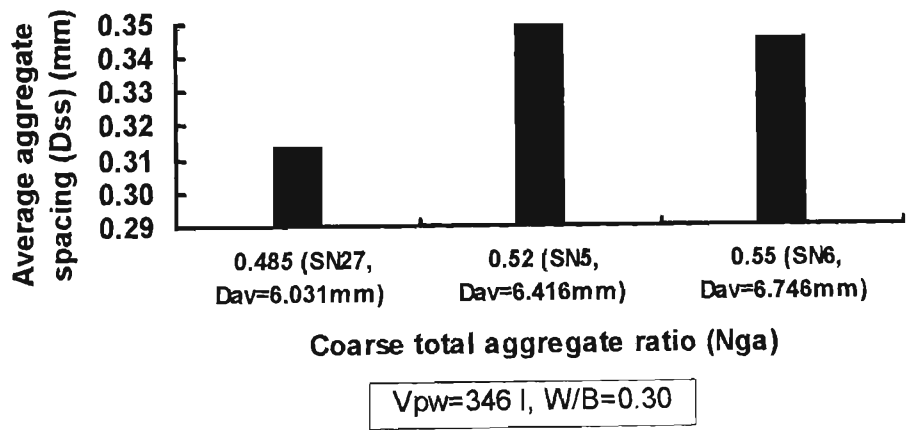


Fig. 8.21: Average aggregate spacing (Dss) of SCC with different coarse to total aggregate ratios and similar paste volumes of about 346 l/m<sup>3</sup>

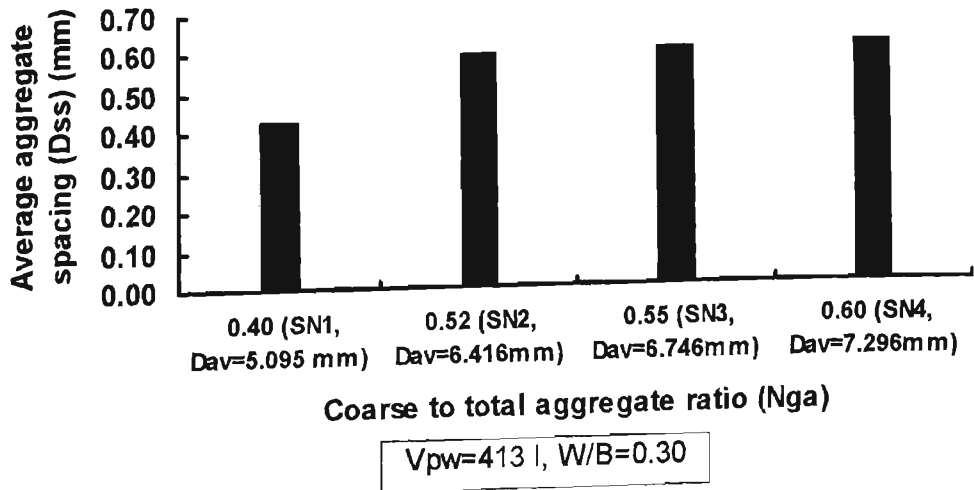


Fig. 8.22: Average aggregate spacing (Dss) of SCC with different coarse to total aggregate ratios and similar paste volumes of about 413 l/m<sup>3</sup>

As stated in Chapter 6, for aggregate combination T1, the optimum coarse to total aggregate ratio was 0.52. The analytical results computed from Eq. 8.26 indicate that, for a given combination of aggregates, there is an optimum coarse to aggregate ratio (Nga), which results in the lowest paste volume (Fig. 8.14 to Fig. 20, inclusive). For aggregate combination T1, SCC with Nga of 0.52 ( $D_{av} = 6.416 \text{ mm} < 6.5 \text{ mm}$ ) requires the lowest paste volume (Fig. 8.14, 8.15 and 8.16). For aggregate combination T6, SCC with Nga of 0.50 ( $D_{av} = 6.833 \text{ mm} > 6.5 \text{ mm}$ ) requires the lowest paste volume (Appendix 8.1 and Fig. 8.20), however, in practice, Nga of 0.46 should be chosen because it had average aggregate diameter of 6.341 mm, which is lower than 6.5 mm. For aggregate combination T5, Nga of 0.50 ( $D_{av} = 5.619 \text{ mm} < 6.5 \text{ mm}$ ) should be selected, as it requires the lowest paste volume (Appendix 8.1 and Fig. 8.19).

Based on the above analysis, it is therefore recommended that the coarse to total aggregate ratio (Nga) which requires the lowest paste volume computed from Eq. 8.47 be selected, provided that the respective average aggregate diameter ( $D_{av}$ ) is not larger than 6.5 mm. However, if the value of  $D_{av}$  is larger than 6.5 mm, the coarse to total aggregate ratio (Nga) which has  $D_{av}$  equal to 6.5 mm should be chosen.

## 8.6. MIXTURE PROPORTIONING STEPS

Fig. 8.24 presents a flow diagram for mix design of SCC. The steps in the mix design procedure are as follows:

- a) Construction criteria such as minimum clear spacing ( $D_c$ ) between reinforcement bars, diameter of reinforcement bars and requirement of compressive strength are specified;

b) Determine material characteristics for:

- mineral admixtures and cement such as fineness and 28-day compressive strength of standard mortar;
- fine and coarse aggregates, namely specific gravity, particle size distribution, maximum size, average diameters ( $D_{av}$ ) of different coarse to total aggregate ratios ( $N_{ga}$ ) (values of  $N_{ga}$  between 0.40 and 0.60 are recommended), void contents corresponding to different  $N_{ga}$  that have  $D_{av} \leq 6.5$  mm; and
- superplasticizer such as percentage of solids, specific gravity and recommended dosage.

c) Calculate maximum allowable aggregate volumes ( $V_{abmax}$ ) for different  $N_{ga}$ , according to blocking criteria (Eq. 8.17), then the corresponding minimum paste volumes ( $V_{pwmin}$ ) per  $m^3$  concrete are determined as follows:

$$V_{pwmin} = 1000 - V_{abmax} \quad (\text{Eq. 8.48})$$

d) Determine water to binder ratio and mineral admixture to total binder ratio in considering the required compressive strength (the use of the modified Feret's formula described in Chapter 6 is recommended);

e) Calculate minimum required values of  $D_{ssmin}$  for different  $D_{av}$  with respective value of  $N_{ga}$  (use one of the equations from Eq. 8.10 to Eq. 8.24, dependent on the water to binder ratio and maximum size of coarse aggregate);

f) Calculate minimum required paste volumes ( $V_{pdmin}$ ) (considering liquid-phase criteria) corresponding to different coarse to total aggregate ratios ( $N_{ga}$ ), using

Eq. 8.47; (sand particles lower than 0.063 mm should be considered as fillers which are parts of paste)

- g) Select the optimum  $N_{ga}$  that requires the lowest paste volume, provided that respective  $D_{av}$  is not larger than 6.5 mm; otherwise, choose the  $N_{ga}$  which has  $D_{av}$  of 6.5 mm;
- h) The paste volume ( $V_{opt}$ ) at optimum coarse to total aggregate ratio ( $N_{opt}$ ), which satisfies both blocking criteria (solid phase) and liquid-phase criteria, is selected as follows (see Fig. 8.23):
- (h1)  $V_{opt} \geq V_{pdmin}$ , if  $V_{pdmin} > V_{pwmin}$ ; or
  - (h2)  $V_{opt} \geq V_{pwmin}$ , if  $V_{pdmin} < V_{pwmin}$ , and  $V_{pwmin}$  is not too high from the view point of economic efficiency ( $V_{opt} \leq 420 \text{ l/m}^3$  is recommended);
  - (h3) In the case of very narrow clear spacing between reinforcement bars and  $V_{pwmin}$  is too high ( $V_{pwmin} > 420 \text{ l/m}^3$ ), the use of the coarse aggregate with smaller maximum size should be considered; or  $N_{ga}$  with respective  $V_{opt}$  of  $420 \text{ l/m}^3$  that satisfies both criteria for solid phase (aggregate blocking) and liquid phase, otherwise  $N_{ga}$  with respective paste volume ( $V_{opt}$ ) that equals to both  $V_{pdmin}$  and  $V_{pwmin}$  are chosen. In both alternatives, a special attention should be paid to control of drying shrinkage of SCC.

(As can be seen from Fig. 8.23, alternative (h1) and (h2) should be selected if clear spacing between reinforcement bars is 58.3 mm and 40.6 mm,

- respectively; and alternative (h3) should be selected if paste volume relating to alternative (h2) is too high).
- i) Estimate superplasticizer dosage, and carry out trial mixing and testing; during the trial mixing, superplasticizer is increasingly added into mixer in order to achieve satisfactory properties of SCC in its fresh state, namely good deformability (measurement of slump flow diameter ( $F_d \geq 650$  mm) or final height ( $H_f < 83$  mm) as discussed in Chapter 7), satisfactory segregation resistance (penetration depth,  $F_d \leq 8$  mm) and reasonable flow time ( $T_{50} \leq 12$ s).
- j) If required superplasticizer dosage is very high ( $SP \geq 15$  kg per  $m^3$  concrete) or if the mix is unsatisfactory, it is necessary to increase paste volume ( $V_{pw}$ ) or adjust water to binder ratio and admixture, accordingly.
- k) If the trial mix is satisfactory, the final mixture proportions are calculated and recorded.

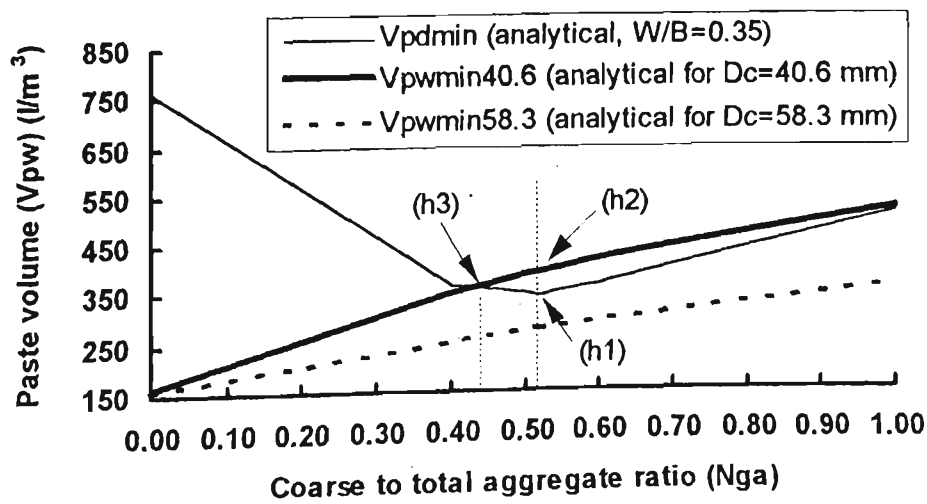


Fig. 8.23: Selection of optimum coarse to total aggregate ratio ( $N_{opt}$ ) and respective paste volume ( $V_{opt}$ )

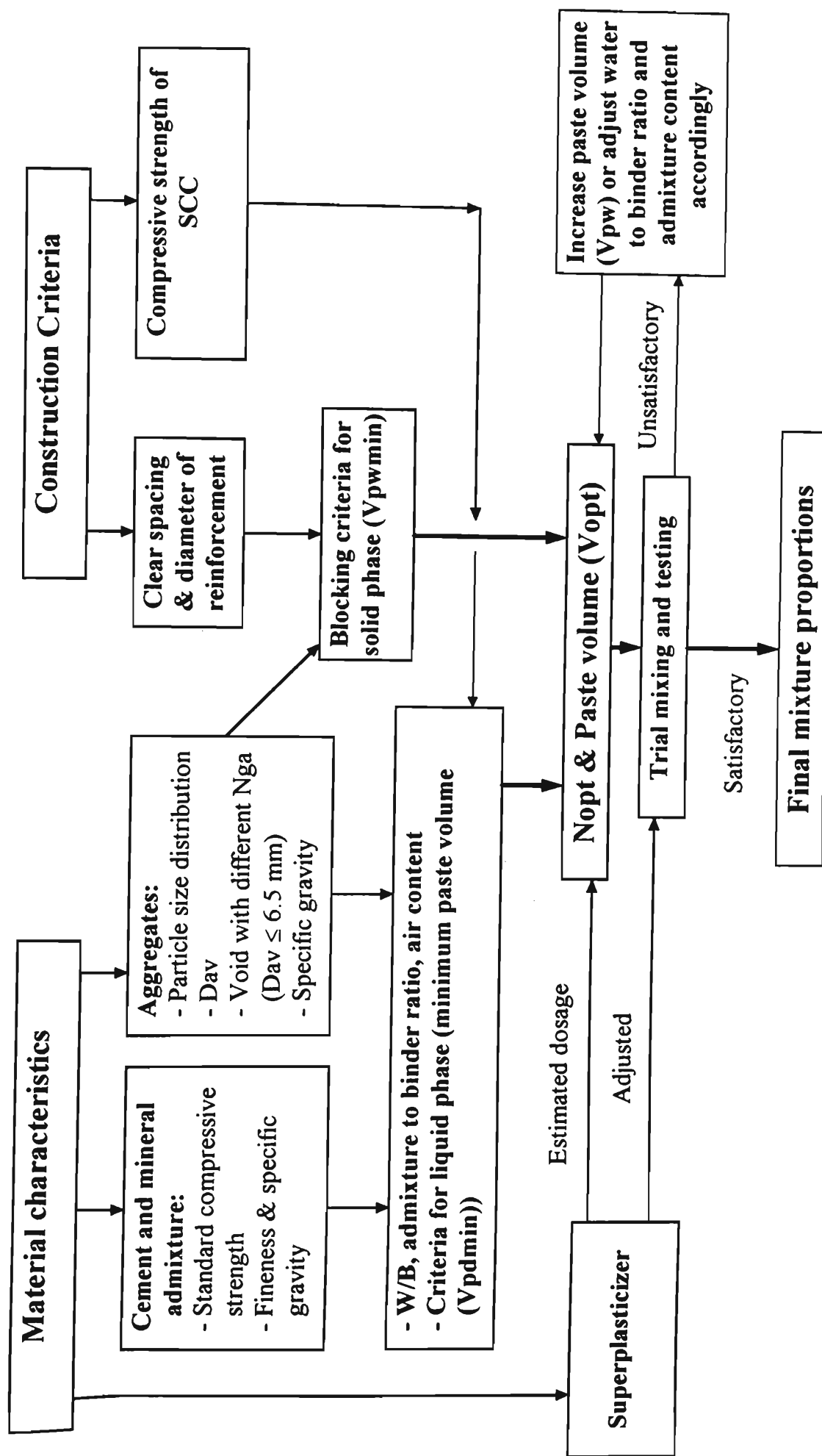


Fig. 8.24: Flow diagram for mix design

## 8.7. SUMMARY

Test results with SCC containing materials available in Australia verified that the blocking criteria for aggregate phase was previously developed by the author and co-workers is useful in predicting the minimum required paste volume ( $V_{pwmin}$ ) necessary for SCC to flow without blocking through clear spacing between reinforcement bars.

Criteria for liquid phase that include minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum paste volume ( $V_{pdmin}$ ) were developed. The minimum average aggregate spacing ( $D_{ssmin}$ ) depends on water to binder ratio, maximum size of coarse aggregate and average aggregate diameter ( $D_{av}$ ) (i.e., coarse to total aggregate ratio ( $N_{ga}$ )). The minimum required paste volume ( $V_{pdmin}$ ) can be calculated from a formula that relates to  $D_{ssmin}$ ,  $D_{av}$  and void content of aggregates. Test results have shown that an analytical line, which corresponds to the computed minimum required paste volume, divides zones of satisfactory and unsatisfactory experimental results. Therefore, the proposed criteria for liquid phase can be useful in estimating the required minimum paste volume in order to achieve SCC having satisfactory deformability, segregation resistance and flow velocity, and requiring reasonable dosage of superplasticizer.

Criteria for selection of optimum coarse to total aggregate ratio were also developed. For a certain combination of aggregates, there is an optimum coarse to total aggregate ratio which results in the lowest paste volume required for SCC to have satisfactory deformability, segregation resistance and flow velocity as well as requiring reasonable superplasticizer dosage.

A flow diagram and associated steps for mix design for SCC were presented. The proposed mix design method combines the criteria for aggregate blocking and liquid phase (deformability, segregation resistance and flow velocity as well as superplasticizer requirement), criteria for selection of optimum coarse to total aggregate ratio ( $N_{opt}$ ) and construction criteria. The method can be used to design SCC having high durability, economic efficiency and application for different materials. The developed criteria should also reduce the need for repeated mixing trials, the times and extent of laboratory procedures and practices.



## CHAPTER 9

### CONCLUSIONS

Limestone modified cements to be used for self-compacting and vibrated high performance concretes (SC-HPC and V-HPC) have been developed. Emphasis has been placed on the development of rapid testing methods for determining quality of self-compacting concrete. In addition, a mix design method, which is applicable for different materials, was proposed to ensure high durability and economic efficiency for self-compacting high performance concrete. The conclusions of this study are summarised below.

#### 9.1. PASTES AND MORTARS CONTAINING LIMESTONE MODIFIED CEMENTS

- Pastes containing milled limestones of different fineness and replacement contents required different amounts of mixing water in order to achieve normal consistence of the binder pastes. Suitable content of milled limestone with average particle size about three to six times smaller than mean particle size of cement can reduce the required amount of mixing water for normal consistence. There is an optimum content of limestone of each fineness which can enhance the lowest amount of mixing water for normal consistence. Setting times of binders containing milled limestone were shorter than those of pure cement, however they all meet the requirement of Australian Standard AS2350.4 (1988).
- For constant water content, mortars containing milled limestones exhibited 28-day compressive strength lower than those with pure cement. The use of fine and very

fine limestones improved compressive strength of mortars in comparison with those containing coarse limestone. For similar flow values, mortars containing fine and very fine limestone required less water content than those with coarse limestone and pure cements. This led to the improvement of compressive strength of the mortars containing fine and very fine milled limestone. Superplasticizer had the greatest effect when combined with very fine limestone.

- The use of fine and very fine milled limestones significantly reduced the drying shrinkage of mortars at ages greater than 7 days in comparison with those of mortars containing coarse limestone or pure cements. However, at age of 7 days, drying shrinkages of mortars containing milled limestones were generally higher than those of mortars containing pure cements. This can be explained by the fact that the high content of free water in mortars with milled limestones resulted in high evaporation of water during the first seven days and thus led to high drying shrinkage at this age.
- The use of milled limestones with suitable fineness and replacement content can improve workability and drying shrinkage of binder paste and mortar. Microstructure of pastes containing fine and very fine milled limestones was more uniform than those containing pure cement and coarse milled limestone.  $\text{CaCO}_3$  in milled limestones reacts mainly with minerals containing  $\text{C}_3\text{A}$  in portland cements to form compounds such as calcium aluminium oxide carbonate hydrate  $\text{C}_3\text{A} \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$ ,  $\text{C}_3\text{A} \cdot 3\text{CaCO}_3 \cdot 11\text{H}_2\text{O}$  and calcium aluminium oxide carbonate sulfide hydrate,  $\text{C}_3\text{A} \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3 \cdot 11\text{H}_2\text{O}$ .

- The use of milled limestones can significantly reduce the heat of hydration of the binder. Higher content of limestone resulted in larger reduction of heat of hydration. A model has been proposed and can be used to predict the reduction of the heat of hydration for mortars containing milled limestone, at ages of 48 h, 72 h, 96 h and 120 h, in comparison with those containing pure cements.

## **9.2. SELF-COMPACTING AND VIBRATED HIGH PERFORMANCE CONCRETES CONTAINING LIMESTONE MODIFIED CEMENTS**

- Fineness of milled limestone has an effect on water demand and drying shrinkage of SC-HPC and V-HPC. Limestones with mean particle sizes about 3 and 6 times, respectively, smaller than pure cements, reduced drying shrinkage and water demand of high performance concretes in comparison with HPC containing coarse milled limestone and pure cement. The reduction of superplasticizer requirement and drying shrinkage of concrete containing limestones with suitable fineness can be explained by the fact that the fine and very fine limestones can fill pores and voids in cement paste and concrete, and this leads to more freely moving water in the concrete.
- Different contents of limestone with suitable fineness resulted in different performance of concrete, and the use of limestone modified cements consisting of up to 20% of the limestone can produce high performance concretes with low drying shrinkage, high compressive strength and less superplasticizer dosage in comparison with that containing pure cement. Also, the use of limestone modified cements consisting of 30% and 40% of limestone with suitable fineness can be beneficial for HPC with 28-day compressive strength between 50 MPa and 70 MPa, because these concretes exhibited reduced superplasticizer requirement, drying shrinkage and cement content.

- Coarse aggregates with different maximum sizes affect mainly superplasticizer requirement and drying shrinkage of HPC, and higher maximum size coarse aggregate results in lower superplasticizer requirement and drying shrinkage of high performance concretes.
- The use of 10% and 20% of fine limestone is beneficial for normal concrete with high water to binder ratio only if it is combined together with a small amount of superplasticizer, and if the combination proves to be of economic efficiency.
- Proposed formulae, which were modified from the classical Feret's equation, can be used to predict 28-day compressive strength of self-compacting and vibrated high performance concrete. The formulae involve not only classic factors, such as aggregate types, cement strength, water content, air volume in concrete and content of limestone and cement, but also include water to binder ratio and the dimensions of test specimens.
- Coarse to total aggregate ratio affects considerably not only the blocking characteristics, but also superplasticizer requirement and drying shrinkage of SC-HPC; and there is an optimum coarse to total aggregate ratio that enhances low superplasticizer requirement, low drying shrinkage of SC-HPC and satisfactory compressive strength.

- With regard to superplasticizer requirement, compressive strength and drying shrinkage, the use of limestone with suitable fineness in SC-HPC and V-HPC with low water to binder ratio was more beneficial than with high water to binder ratio. However, lower water to binder ratio requires higher minimum required paste volume in order to achieve good compaction and satisfactory performance of SC-HPC.
- The use of suitable limestone in SC-HPC with low paste volumes resulted in higher percentage reduction of superplasticizer dosage, lower reduction in compressive strength and lower drying shrinkage, than for those with high paste volume.

Generally, the use of limestone modified cements containing milled limestone with suitable fineness and content can improve workability, compressive strength and reduce drying shrinkage and heat of hydration of self-compacting and vibrated high-performance concrete. Concretes incorporating limestone modified cements can also require reduced superplasticizer dosage and cement content; thereby enabling high-performance concrete to be produced more economically.

### **9.3. RAPID TESTING METHODS FOR DETERMINING THE QUALITY OF SELF-COMPACTING PERFORMANCE CONCRETE**

- A simple apparatus for segregation resistance testing is proposed. This apparatus and the modified L-box apparatus are considered useful for rapid testing of segregation resistance, deformability and blocking behaviour of fresh self-compacting concrete.

- Extensive testing for segregation resistance of self-compacting concrete was carried out. The test results showed that the proposed method and developed apparatus are useful in rapidly evaluating segregation resistance of concrete in both vertical and horizontal directions.
- The proposed rapid testing methods can reduce testing time and laboratory work necessary.

#### 9.4. PROPOSED MIX DESIGN METHOD FOR SELF-COMPACTING HIGH PERFORMANCE CONCRETE

- Criteria for liquid phase that include minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum paste volume ( $V_{pdmin}$ ) were developed. The minimum average aggregate spacing ( $D_{ssmin}$ ) depends on water to binder ratio, maximum size of coarse aggregate and average aggregate diameter ( $D_{av}$ ) (i.e., coarse to total aggregate ratio ( $N_{ga}$ )). The minimum required paste volume ( $V_{pdmin}$ ) can be calculated from a formula that relates to  $D_{ssmin}$ ,  $D_{av}$  and void content of aggregates. The proposed criteria for liquid phase can be useful in estimating the required minimum paste volume in order to achieve SCC having satisfactory deformability, segregation resistance and flow velocity, and requiring reasonable dosage of superplasticizer.
- Criteria for selection of optimum coarse to total aggregate ratio were also developed. For a certain combination of aggregates, there is an optimum coarse to total aggregate ratio which results in the lowest paste volume required for SCC to have satisfactory deformability, segregation resistance and flow velocity as well as requiring reasonable superplasticizer dosage.

- A flow diagram and associated steps for mix design for SCC were presented. The proposed mix design method combines the criteria for aggregate blocking and liquid phase (deformability, segregation resistance and flow velocity as well as superplasticizer requirement), criteria for selection of optimum coarse to total aggregate ratio ( $N_{opt}$ ) and construction criteria. The method, which is applicable for different materials, can be used to design SCC having high durability and economic efficiency. The developed criteria should also reduce the need for repeated mixing trials, the times and extent of laboratory procedures and practices.

## **RECOMMENDATIONS FOR FUTURE STUDY**

Limestone modified cements consisting of portland cements and milled limestones were developed in this study. An investigation into the properties of pastes, mortars, self-compacting and vibrated high performance concretes containing limestone modified cements was carried out. The main properties investigated include consistency and setting times of the paste, superplasticizer requirement, compressive strength and drying shrinkage of the concretes. The study has also developed rapid testing methods for determining quality and a mix design method for self-compacting high performance concrete. However, there are several areas in which future research could be conducted:

- An investigation on water tightness of normal and high performance concretes containing limestone modified cements;
- Blending techniques for limestone modified cements at a cement works or a concrete batching plant;
- Development of blended cements consisting of portland cement, milled limestone, blast furnace slag and/or fly ash;
- Study on the use of the developed penetration apparatus to determine segregation resistance of self-compacting concrete containing viscosity agent with water to binder ratio greater than 0.35;
- Applicability of the proposed mix design method for SCC containing viscosity agent with water to binder ratio greater than 0.35;
- Development of a suitable truck mounted quality control system for self-compacting concrete; and
- Characteristics of structural components filled with self-compacting concrete.



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**Appendix 3.1: Chemical analysis of cement and limestone**

	SPC1	SPC2	OPC	BFC1	BFC2	LS1	LS2	LS3	FA
Specific gravity	3.14	3.18	3.15	3.03	2.97	2.65	2.69	2.69	1.9
Fineness index (Blaine) (m <sup>2</sup> /kg)	336	357	370	405	410	380	870	1680	-
Mean particle size (μm)	18.2	17.5	-	-	-	27.4	6.3	3.8	-
Passing 45μm (%)	-	-	-	-	-	-	-	-	91
Chemical compositions:									
SiO <sub>2</sub>	20.5	20.4	20.0	25.3	28.3	10.0	1.9	1.3	68.0
Al <sub>2</sub> O <sub>3</sub>	4.4	4.7	4.7	8.1	10.4	2.1	0.8	0.2	23.0
Fe <sub>2</sub> O <sub>3</sub>	5.5	4.7	4.7	2.3	1.8	2.8	0.3	0.1	3.0
CaO	64.5	65.0	65.0	55.4	48.4	45.7	53.2	53.6	1.0
SO <sub>3</sub>	2.1	2.6	2.6	2.80	2.6	0.09	0.03	0.0	-
MgO	1.5	1.0	0.8	3.05	4.7	0.98	0.55	1.5	0.7
K <sub>2</sub> O	0.36	0.57	0.56	0.46	0	0.3	0.1	0.0	1.4
LOI	0.8	0.8	1.0	-	0.5	35.83	40.9	41.1	1.4

**Appendix 3.2: Particle size distribution, maximum size and density of coarse aggregates and river sands**

Screen size	A	B	C	D	E	F	Screen size	RS1	RS2
(mm)	(%p)	(%p)	(%p)	(%p)	(%p)	(%p)	(mm)	(%p)	(%p)
19.0	99.0	93.5	100.0	100.0	100.0	100.0	2.36	99.0	99.4
13.2	34.0	4.9	90.0	84.2	100.0	99.9	1.18	90.0	84.2
9.5	4.0	0.0	10.0	11.1	90.0	86.7	0.600	60.0	62.2
4.75	1.0	0.0	0.0	0.0	3.0	0.5	0.300	16.0	34.5
2.36	-	-	-	-	-	-	0.150	1.0	8.2
Maximum size (mm)	20	20	14	14	10	10		4.75	4.75
Specific gravity	2.88	2.67	2.87	2.66	2.82	2.69		2.62	2.57

Appendix 3.3A: Particle size distribution of shrinkage limited portland cement  
SPC1 (analysis report)

**MAIVERN** M A S T E R S I Z E R

Result: Analysis Report

Sample Details		
Sample ID: VIC-CEMENT	Run Number: 1	Measured: Tue, Oct 15, 1996 3:59PM
Sample File: VAN	Record Number: 17	Analysed: Tue, Oct 15, 1996 3:59PM
Sample Path: C:\SIZERS\DATA\		Result Source: Analysed
Sample Notes: VIC CEMENT, P5-S5-U5		

System Details			
Range Lens: 300RF mm	Beam Length: 2.40 mm	Sampler: None	Obscuration: 14.3 %
Presentation: 3OHD	[Particle R.I. = ( 1.5295, 0.1000);	Dispersant R.I. = 1.3300]	Residual: 3.442 %
Analysis Model: Polydisperse			
Modifications: None			

Result Statistics			
Distribution Type: Volume	Concentration = 0.0213 %Vol	Density = 1.000 g / cub. cm	Specific S.A. = 0.5585 sq. m / g
Mean Diameters:	D (v, 0.1) = 5.22 um	D (v, 0.5) = 16.18 um	D (v, 0.9) = 34.06 um
D (4, 3) = 18.17 um	D [3, 2] = 10.74 um	Span = 1.782E+00	Uniformity = 5.568E-01

Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.00	0.06	0.00	6.63	4.19	7.72	19.50
0.06	0.00	0.07	0.00	7.72	4.87	9.00	24.37
0.07	0.00	0.08	0.00	9.00	5.57	10.48	29.94
0.08	0.00	0.09	0.00	10.48	6.33	12.21	36.27
0.09	0.00	0.11	0.00	12.21	7.12	14.22	43.39
0.11	0.00	0.13	0.00	14.22	7.89	16.57	51.27
0.13	0.00	0.15	0.00	16.57	8.52	19.31	59.79
0.15	0.00	0.17	0.00	19.31	8.91	22.49	68.71
0.17	0.00	0.20	0.00	22.49	9.00	26.20	77.71
0.20	0.00	0.23	0.00	26.20	7.84	30.53	85.54
0.23	0.00	0.27	0.00	30.53	5.97	35.56	91.51
0.27	0.00	0.31	0.00	35.56	4.27	41.43	95.78
0.31	0.00	0.36	0.00	41.43	2.75	48.27	98.54
0.36	0.00	0.42	0.00	48.27	1.46	56.23	100.00
0.42	0.00	0.49	0.00	56.23	0.00	65.51	100.00
0.49	0.00	0.58	0.00	65.51	0.00	76.32	100.00
0.58	0.00	0.67	0.00	76.32	0.00	88.91	100.00
0.67	0.00	0.78	0.00	88.91	0.00	103.58	100.00
0.78	0.00	0.91	0.00	103.58	0.00	120.67	100.00
0.91	0.00	1.06	0.00	120.67	0.00	140.58	100.00
1.06	0.00	1.24	0.00	140.58	0.00	163.77	100.00
1.24	0.00	1.44	0.00	163.77	0.00	190.80	100.00
1.44	0.47	1.68	0.47	190.80	0.00	222.28	100.00
1.68	0.44	1.95	0.91	222.28	0.00	258.95	100.00
1.95	0.36	2.28	1.47	258.95	0.00	301.68	100.00
2.28	0.75	2.65	2.22	301.68	0.00	351.46	100.00
2.65	1.04	3.09	3.26	351.46	0.00	409.45	100.00
3.09	1.38	3.60	4.64	409.45	0.00	477.01	100.00
3.60	1.83	4.19	6.47	477.01	0.00	555.71	100.00
4.19	2.34	4.88	8.81	555.71	0.00	647.41	100.00
4.88	2.94	5.69	11.75	647.41	0.00	754.23	100.00
5.69	3.56	6.63	15.30	754.23	0.00	878.67	100.00

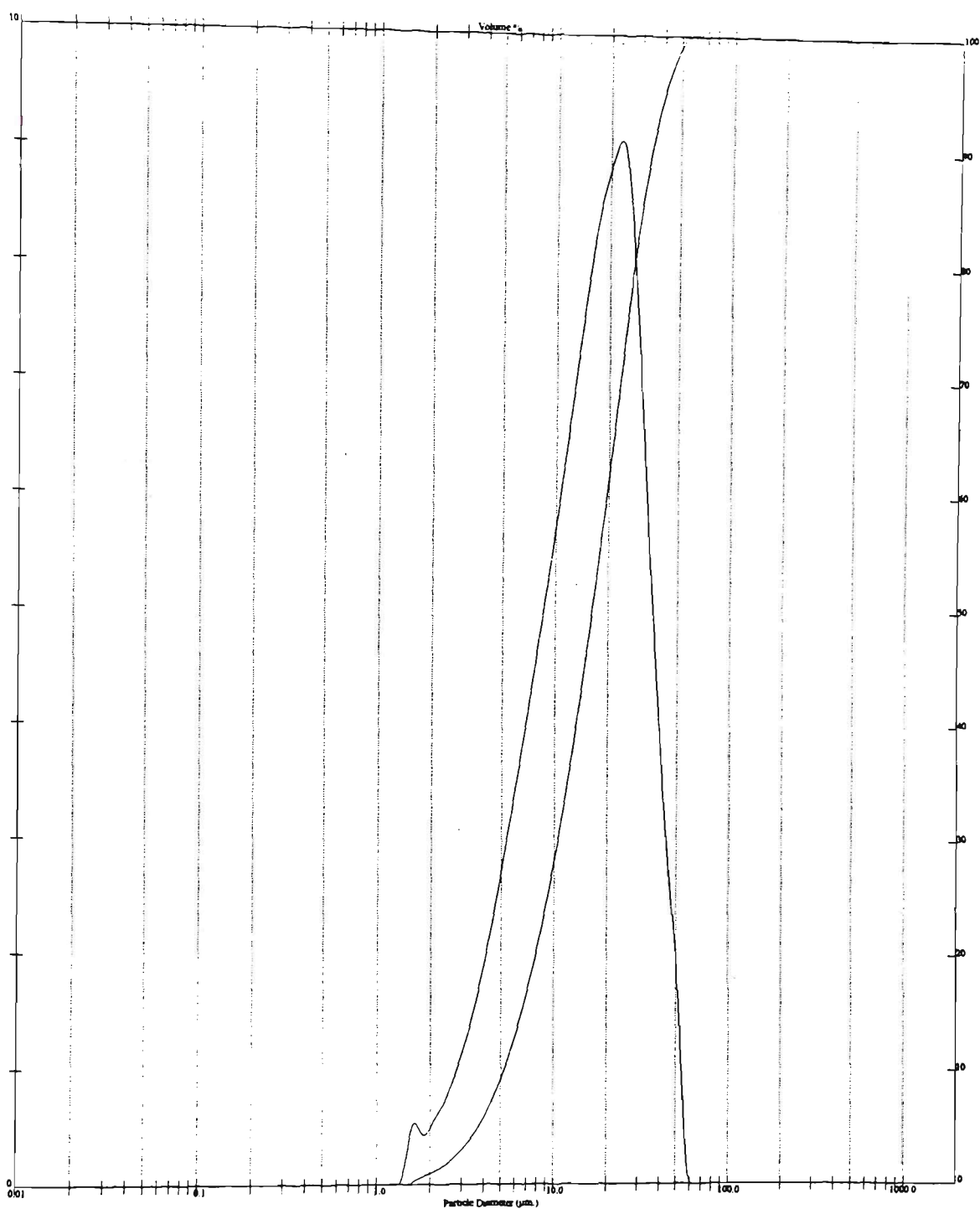
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### Appendix 3.3B: Particle size distribution of shrinkage limited portland cement SPC1 (analysis graph)



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# Appendix 3.4A: Particle size distribution of shrinkage limited portland cement SPC2 (analysis report)



## MASTERSIZER

### Result: Analysis Report

Sample Details		
Sample ID: NSW-CEMENT	Run Number: 1	Measured: Tue, Oct 15, 1996 3:28PM
Sample File: VAN	Record Number: 14	Analysed: Tue, Oct 15, 1996 3:28PM
Sample Path: CASIZERS\DATA\		Result Source: Analysed
Sample Notes: NSW CEMENT, P5-S5-U5		

System Details			
Range Lens: 300RF mm	Beam Length: 2.40 mm	Sampler: None	Obscuration: 15.4 %
Presentation: 30HD	[Particle R.I. = (1.5295, 0.1000);	Dispersant R.I. = 1.3300]	Residual: 1.739 %
Analysis Model: Polydisperse			
Modifications: None			

Result Statistics			
Distribution Type: Volume	Concentration = 0.0119 %Vol	Density = 1.000 g / cub. cm	Specific S.A. = 3.0254 sq. m / g
Mean Diameters:	D (v, 0.1) = 0.56 um	D (v, 0.5) = 14.75 um	D (v, 0.9) = 37.22 um
D [4, 3] = 17.51 um	D [3, 2] = 1.98 um	Span = 2.485E+00	Uniformity = 7.429E-01

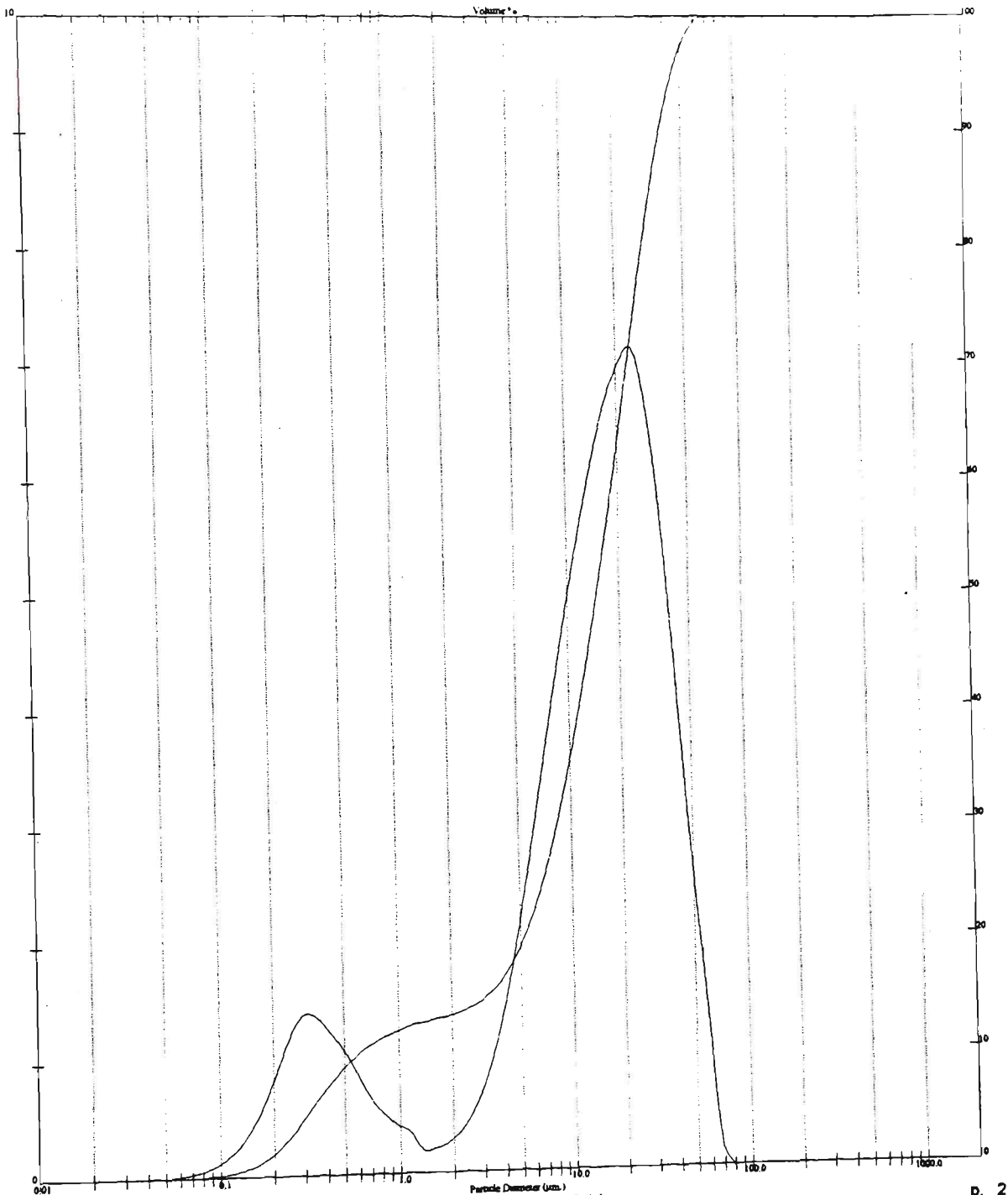
Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.01	0.06	0.01	6.63	3.62	7.72	28.05
0.06	0.02	0.07	0.03	7.72	4.25	9.00	32.30
0.07	0.04	0.08	0.08	9.00	4.86	10.48	37.15
0.08	0.07	0.09	0.15	10.48	5.42	12.21	42.57
0.09	0.12	0.11	0.27	12.21	5.94	14.22	48.51
0.11	0.20	0.13	0.47	14.22	6.39	16.57	54.91
0.13	0.31	0.15	0.78	16.57	6.76	19.31	61.66
0.15	0.47	0.17	1.24	19.31	7.00	22.49	68.66
0.17	0.68	0.20	1.92	22.49	7.12	26.20	75.78
0.20	0.93	0.23	2.85	26.20	6.73	30.53	82.51
0.23	1.19	0.27	4.05	30.53	5.93	35.56	88.44
0.27	1.37	0.31	5.41	35.56	4.79	41.43	93.23
0.31	1.38	0.36	6.79	41.43	3.45	48.27	96.67
0.36	1.28	0.42	8.07	48.27	2.19	56.23	98.86
0.42	1.15	0.49	9.22	56.23	1.04	65.51	99.90
0.49	0.99	0.58	10.21	65.51	0.10	76.32	100.00
0.58	0.79	0.67	10.99	76.32	0.00	88.91	100.00
0.67	0.61	0.78	11.60	88.91	0.00	103.58	100.00
0.78	0.50	0.91	12.10	103.58	0.00	120.67	100.00
0.91	0.41	1.06	12.52	120.67	0.00	140.58	100.00
1.06	0.36	1.24	12.88	140.58	0.00	163.77	100.00
1.24	0.20	1.44	13.08	163.77	0.00	190.80	100.00
1.44	0.21	1.68	13.29	190.80	0.00	222.28	100.00
1.68	0.25	1.95	13.54	222.28	0.00	258.95	100.00
1.95	0.33	2.28	13.87	258.95	0.00	301.68	100.00
2.28	0.46	2.65	14.32	301.68	0.00	351.46	100.00
2.65	0.66	3.09	14.99	351.46	0.00	409.45	100.00
3.09	0.95	3.60	15.93	409.45	0.00	477.01	100.00
3.60	1.33	4.19	17.26	477.01	0.00	555.71	100.00
4.19	1.81	4.88	19.07	555.71	0.00	647.41	100.00
4.88	2.37	5.69	21.44	647.41	0.00	754.23	100.00
5.69	2.99	6.63	24.42	754.23	0.00	878.67	100.00

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Appendix 3.4B: Particle size distribution of shrinkage limited portland cement  
SPC2 (analysis graph)



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Appendix 3.5A: Particle size distribution of milled limestone LS1 (analysis report)

MAIVERN MASTERSIZER

Result: Analysis Report

Sample Details		
Sample ID: VIC-LIME	Run Number: 9	Measured: Tue, Oct 15, 1996 12:08PM
Sample File: HELEN	Record Number: 5	Analysed: Tue, Oct 15, 1996 12:08PM
Sample Path: C:\SIZERS\DATA\		Result Source: Analysed
Sample Notes: VICTORIAN LIMESTONE, P5-U5-S5		

System Details			
Range Lens: 300RF mm	Beam Length: 2.40 mm	Sampler: None	Obscuration: 14.5 %
Presentation: 30HD	[Particle R.I. = ( 1.5295, 0.1000);	Dispersant R.I. = 1.3300]	Residual: 1.097 %
Analysis Model: Polydisperse			
Modifications: None			

Result Statistics			
Distribution Type: Volume	Concentration = 0.0074 %Vol	Density = 1.000 g / cub. cm	Specific S.A. = 3.4878 sq. m / g
Mean Diameters:	D (v, 0.1) = 0.56 um	D (v, 0.5) = 8.53 um	D (v, 0.9) = 83.05 um
D [4, 3] = 27.44 um	D [3, 2] = 1.72 um	Span = 9.675E+00	Uniformity = 2.864E+00

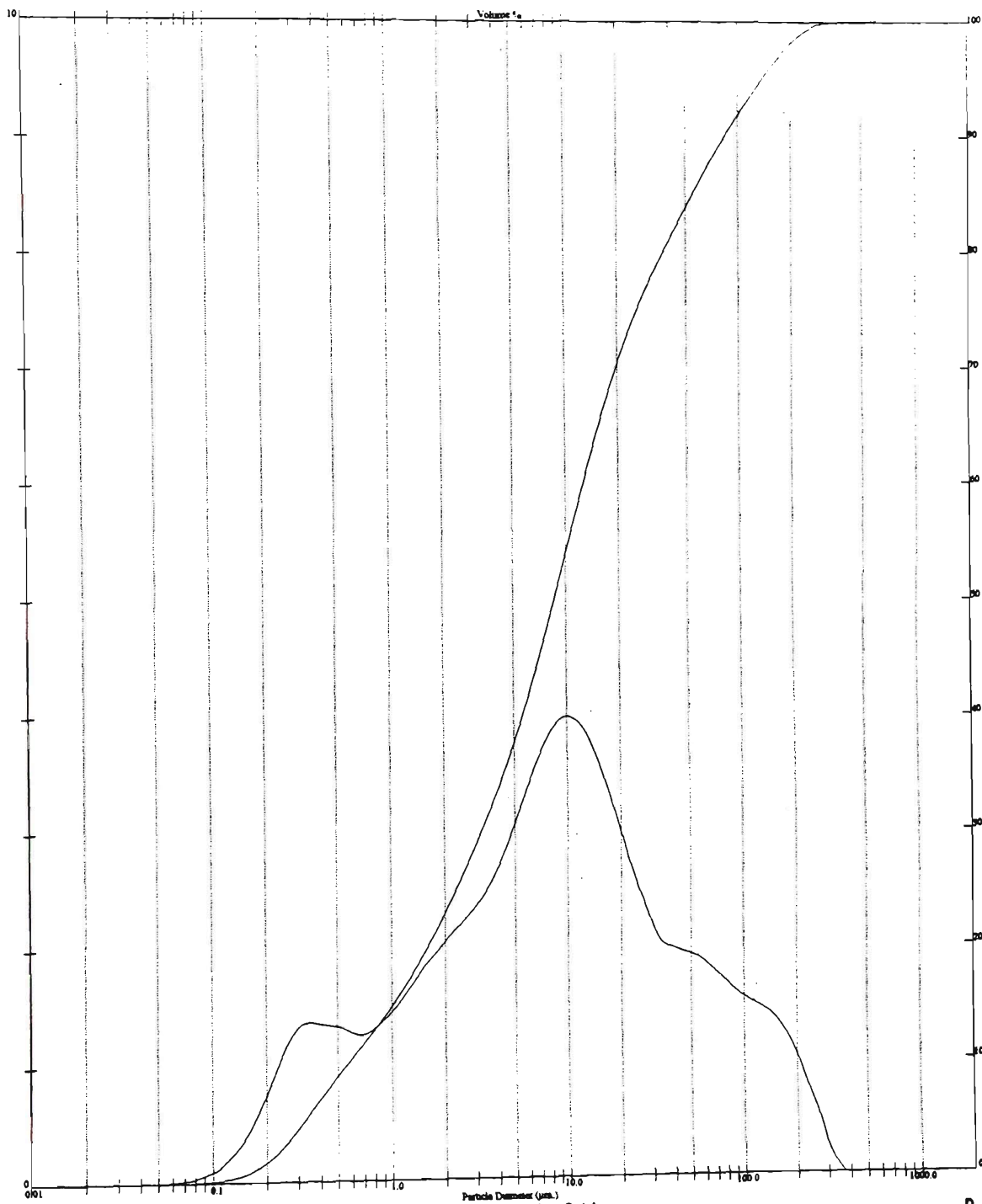
Size Low (um)	ln %	Size High (um)	Under%	Size Low (um)	ln %	Size High (um)	Under%
0.05	0.01	0.06	0.01	6.63	3.70	7.72	47.49
0.06	0.01	0.07	0.02	7.72	3.89	9.00	51.38
0.07	0.03	0.08	0.05	9.00	3.98	10.48	55.36
0.08	0.05	0.09	0.10	10.48	3.95	12.21	59.31
0.09	0.09	0.11	0.19	12.21	3.80	14.22	63.10
0.11	0.16	0.13	0.36	14.22	3.54	16.57	66.65
0.13	0.27	0.15	0.62	16.57	3.23	19.31	69.87
0.15	0.42	0.17	1.04	19.31	2.88	22.49	72.76
0.17	0.61	0.20	1.65	22.49	2.56	26.20	75.31
0.20	0.85	0.23	2.50	26.20	2.28	30.53	77.60
0.23	1.10	0.27	3.60	30.53	2.05	35.56	79.65
0.27	1.29	0.31	4.89	35.56	1.98	41.43	81.63
0.31	1.36	0.36	6.25	41.43	1.94	48.27	83.57
0.36	1.36	0.42	7.61	48.27	1.91	56.23	85.48
0.42	1.34	0.49	8.94	56.23	1.84	65.51	87.32
0.49	1.32	0.58	10.26	65.51	1.75	76.32	89.07
0.58	1.27	0.67	11.53	76.32	1.65	88.91	90.73
0.67	1.26	0.78	12.79	88.91	1.56	103.58	92.29
0.78	1.34	0.91	14.13	103.58	1.50	120.67	93.79
0.91	1.44	1.06	15.57	120.67	1.44	140.58	95.23
1.06	1.56	1.24	17.13	140.58	1.35	163.77	96.59
1.24	1.71	1.44	18.84	163.77	1.20	190.80	97.79
1.44	1.85	1.68	20.68	190.80	0.98	222.28	98.77
1.68	1.97	1.95	22.65	222.28	0.70	258.95	99.47
1.95	2.09	2.28	24.74	258.95	0.41	301.68	99.88
2.28	2.20	2.65	26.94	301.68	0.12	351.46	100.00
2.65	2.31	3.09	29.25	351.46	0.00	409.45	100.00
3.09	2.45	3.60	31.70	409.45	0.00	477.01	100.00
3.60	2.63	4.19	34.33	477.01	0.00	555.71	100.00
4.19	2.87	4.88	37.20	555.71	0.00	647.41	100.00
4.88	3.15	5.69	40.36	647.41	0.00	754.23	100.00
5.69	3.44	6.63	43.80	754.23	0.00	878.67	100.00

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Appendix 3.5B: Particle size distribution of milled limestone LS1 (analysis graph)



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## Appendix 3.6A: Particle size distribution of milled limestone LS2 (analysis report)



# MASTERSIZER

## Result: Analysis Report

Sample Details		
Sample ID: NSW-MICR	Run Number: 1	Measured: Tue, Oct 15, 1996 10:49AM
Sample File: VAN	Record Number: 5	Analysed: Tue, Oct 15, 1996 10:49AM
Sample Path: C:\SIZERS\DATA\		Result Source: Analysed
Sample Notes: NSW microfine limestone, 15/10/96, P5-U5-S5		

System Details			
Range Lens: 300RF mm	Beam Length: 2.40 mm	Sampler: None	Obscuration: 17.8 %
Presentation: 3OHD	[Particle R.I. = (1.5295, 0.1000);	Dispersant R.I. = 1.3300]	Residual: 0.584 %
Analysis Model: Polydisperse			
Modifications: None			

Result Statistics			
Distribution Type: Volume	Concentration = 0.0069 %Vol	Density = 1.000 g / cub. cm	Specific S.A. = 4.4020 sq. m / g
Mean Diameters:	D (v, 0.1) = 0.44 um	D (v, 0.5) = 4.55 um	D (v, 0.9) = 14.15 um
D [4, 3] = 6.25 um	D [3, 2] = 1.36 um	Span = 3.016E+00	Uniformity = 9.657E-01

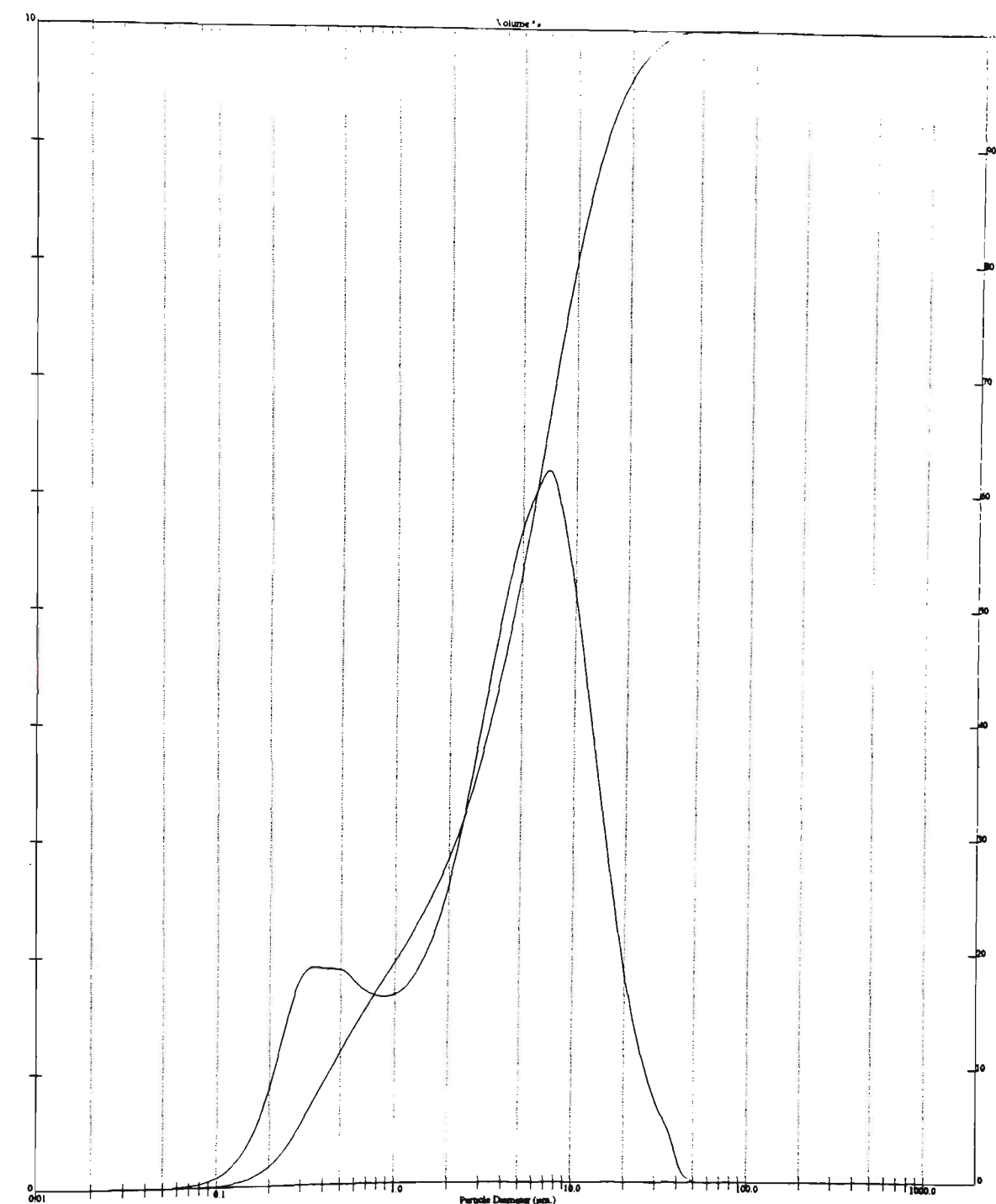
Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.01	0.06	0.01	6.63	6.20	7.72	70.69
0.06	0.01	0.07	0.02	7.72	5.84	9.00	76.53
0.07	0.03	0.08	0.05	9.00	5.27	10.48	81.80
0.08	0.05	0.09	0.09	10.48	4.55	12.21	86.35
0.09	0.09	0.11	0.18	12.21	3.77	14.22	90.12
0.11	0.15	0.13	0.33	14.22	2.98	16.57	93.10
0.13	0.26	0.15	0.58	16.57	2.27	19.31	95.37
0.15	0.42	0.17	1.00	19.31	1.67	22.49	97.04
0.17	0.67	0.20	1.67	22.49	1.19	26.20	98.22
0.20	1.01	0.23	2.68	26.20	0.83	30.53	99.05
0.23	1.40	0.27	4.09	30.53	0.57	35.56	99.63
0.27	1.74	0.31	5.83	35.56	0.32	41.43	99.94
0.31	1.89	0.36	7.71	41.43	0.06	48.27	100.00
0.36	1.89	0.42	9.60	48.27	0.00	56.23	100.00
0.42	1.88	0.49	11.48	56.23	0.00	65.51	100.00
0.49	1.85	0.58	13.33	65.51	0.00	76.32	100.00
0.58	1.74	0.67	15.07	76.32	0.00	88.91	100.00
0.67	1.67	0.78	16.74	88.91	0.00	103.58	100.00
0.78	1.64	0.91	18.38	103.58	0.00	120.67	100.00
0.91	1.65	1.06	20.03	120.67	0.00	140.58	100.00
1.06	1.71	1.24	21.74	140.58	0.00	163.77	100.00
1.24	1.86	1.44	23.60	163.77	0.00	190.80	100.00
1.44	2.07	1.68	25.66	190.80	0.00	222.28	100.00
1.68	2.36	1.95	28.02	222.28	0.00	258.95	100.00
1.95	2.76	2.28	30.78	258.95	0.00	301.68	100.00
2.28	3.25	2.65	34.03	301.68	0.00	351.46	100.00
2.65	3.80	3.09	37.84	351.46	0.00	409.45	100.00
3.09	4.38	3.60	42.22	409.45	0.00	477.01	100.00
3.60	4.95	4.19	47.17	477.01	0.00	555.71	100.00
4.19	5.44	4.88	52.61	555.71	0.00	647.41	100.00
4.88	5.82	5.69	58.43	647.41	0.00	754.23	100.00
5.69	6.06	6.63	64.49	754.23	0.00	878.67	100.00

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## Appendix 3.6B: Particle size distribution of milled limestone LS2 (analysis graph)



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## Appendix 3.7A: Particle size distribution of milled limestone LS3 (analysis report)



# MASTERSIZER

## Result: Analysis Report

Sample Details		
Sample ID: NSW-OMYA	Run Number: 3	Measured: Tue, Oct 15, 1996 11:13AM
Sample File: VAN	Record Number: 9	Analysed: Tue, Oct 15, 1996 11:13AM
Sample Path: C:\SIZERS\DATA\		Result Source: Analysed
Sample Notes: NSW OMYACARB 1, 15/10/96, P5-U5-S5		

System Details			
Range Lens: 300RF mm	Beam Length: 2.40 mm	Sampler: None	Obscuration: 17.1 %
Presentation: 30HD	[Particle R.I. = ( 1.5295, 0.1000); Dispersant R.I. = 1.3300]		Residual: 0.364 %
Analysis Model: Polydisperse			
Modifications: None			

Result Statistics			
Distribution Type: Volume	Concentration = 0.0051 %Vol	Density = 1.000 g / cub. cm	Specific S.A. = 5.3253 sq. m / g
Mean Diameters:	D (v, 0.1) = 0.39 um	D (v, 0.5) = 2.73 um	D (v, 0.9) = 7.81 um
D [4, 3] = 3.76 um	D [3, 2] = 1.13 um	Span = 2.721E+00	Uniformity = 9.523E-01

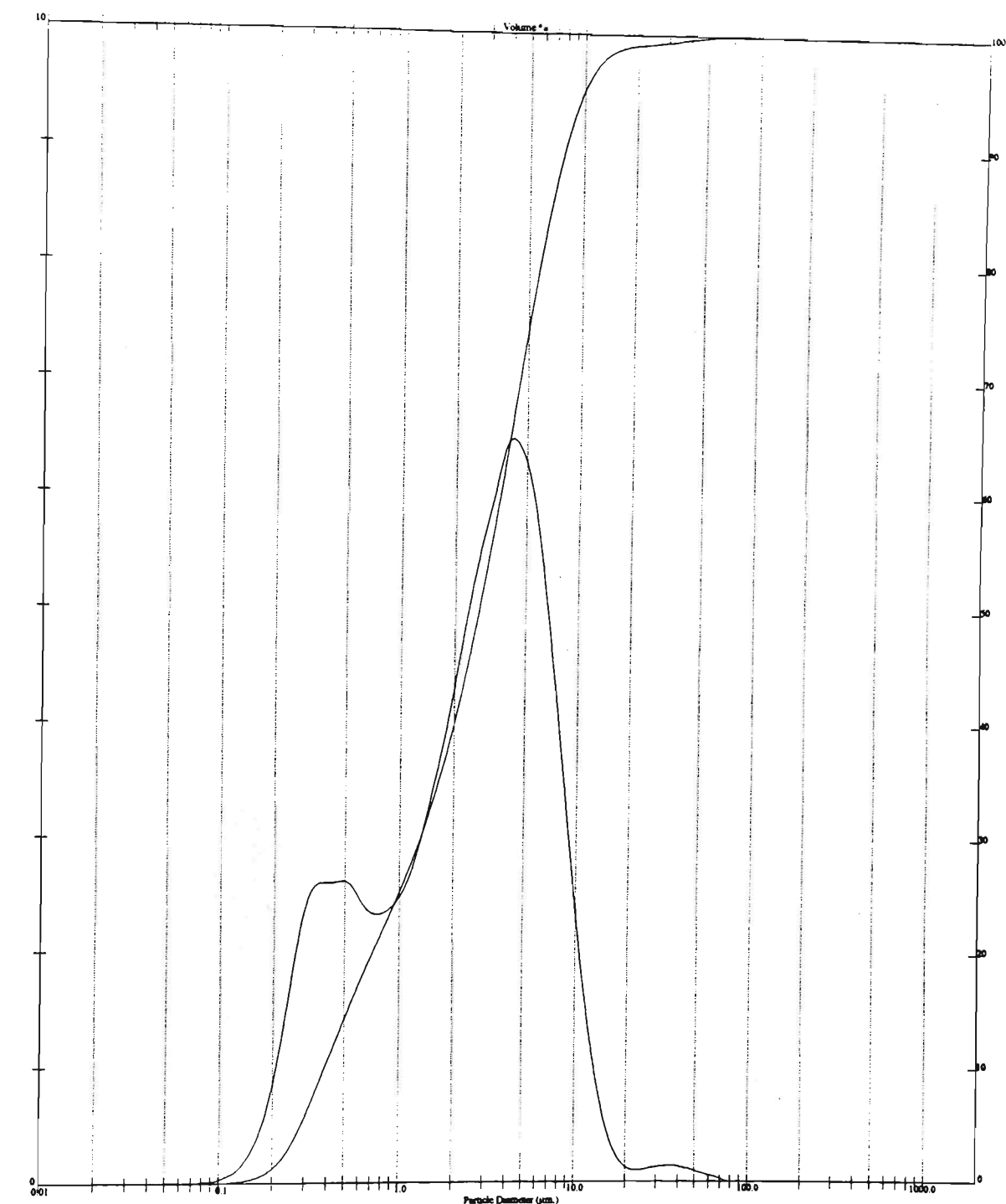
Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.00	0.06	0.00	6.63	4.60	7.72	89.69
0.06	0.00	0.07	0.00	7.72	3.57	9.00	93.26
0.07	0.01	0.08	0.01	9.00	2.54	10.48	95.80
0.08	0.01	0.09	0.02	10.48	1.63	12.21	97.43
0.09	0.03	0.11	0.06	12.21	0.94	14.22	98.37
0.11	0.08	0.13	0.13	14.22	0.47	16.37	98.84
0.13	0.16	0.15	0.29	16.37	0.22	19.31	99.05
0.15	0.33	0.17	0.62	19.31	0.12	22.49	99.17
0.17	0.62	0.20	1.24	22.49	0.11	26.20	99.28
0.20	1.09	0.23	2.33	26.20	0.13	30.53	99.40
0.23	1.70	0.27	4.03	30.53	0.14	35.56	99.55
0.27	2.28	0.31	6.31	35.56	0.14	41.43	99.69
0.31	2.57	0.36	8.88	41.43	0.12	48.27	99.81
0.36	2.60	0.42	11.48	48.27	0.09	56.23	99.91
0.42	2.61	0.49	14.09	56.23	0.06	65.51	99.97
0.49	2.59	0.58	16.68	65.51	0.03	76.32	100.00
0.58	2.42	0.67	19.11	76.32	0.00	88.91	100.00
0.67	2.33	0.78	21.44	88.91	0.00	103.58	100.00
0.78	2.36	0.91	23.80	103.58	0.00	120.67	100.00
0.91	2.46	1.06	26.26	120.67	0.00	140.58	100.00
1.06	2.67	1.24	28.93	140.58	0.00	163.77	100.00
1.24	3.03	1.44	31.96	163.77	0.00	190.80	100.00
1.44	3.47	1.68	35.43	190.80	0.00	222.28	100.00
1.68	3.94	1.95	39.38	222.28	0.00	258.95	100.00
1.95	4.51	2.28	43.89	258.95	0.00	301.68	100.00
2.28	5.09	2.65	48.98	301.68	0.00	351.46	100.00
2.65	5.59	3.09	54.57	351.46	0.00	409.45	100.00
3.09	6.02	3.60	60.59	409.45	0.00	477.01	100.00
3.60	6.43	4.19	67.02	477.01	0.00	555.71	100.00
4.19	6.43	4.88	73.45	555.71	0.00	647.41	100.00
4.88	6.13	5.69	79.58	647.41	0.00	754.23	100.00
5.69	5.51	6.63	85.09	754.23	0.00	878.67	100.00

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**Appendix 3.7B: Particle size distribution of milled limestone LS3 (analysis graph)**

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**Appendix 4.1: Normal consistence and setting times of pastes containing limestone modified cements**

Mix No.	Limestone type	Cement type	Limestone content	Required water <sup>*)</sup>	Setting time (minutes)	
			(%)	(%)	Initial	Final
P1		SPC1	0	28.33	180	270
P2		SPC2	0	26.50	120	180
P3	LS1	SPC1	5	28.33	195	255
P4	LS1	SPC1	10	28.91	165	225
P5	LS1	SPC1	15	29.16	135	210
P6	LS1	SPC1	20	29.25	135	210
P7	LS1	SPC2	5	27.00	120	180
P8	LS1	SPC2	10	27.33	105	195
P9	LS1	SPC2	15	27.33	90	165
P10	LS1	SPC2	20	27.66	90	180
P11	LS2	SPC1	5	27.00	135	240
P12	LS2	SPC1	10	27.33	120	225
P13	LS2	SPC1	15	28.33	120	225
P14	LS2	SPC1	20	28.50	135	210
P15	LS2	SPC2	5	26.16	105	180
P16	LS2	SPC2	10	25.83	90	150
P17	LS2	SPC2	15	26.33	90	150
P18	LS2	SPC2	20	26.16	90	135
P19	LS3	SPC1	5	27.00	135	210
P20	LS3	SPC1	10	27.00	105	180
P21	LS3	SPC1	15	27.33	60	165
P22	LS3	SPC1	20	27.33	90	165
P23	LS3	SPC2	5	26.20	90	135
P24	LS3	SPC2	10	26.07	90	105
P25	LS3	SPC2	15	26.02	75	105
P26	LS3	SPC2	20	28.30	90	105

Note: <sup>\*)</sup> Mixing water required for normal consistence as percentage of total binder by mass

### Appendix 4.2: Compressive strength of mortars containing limestone modified cements

Mix No.	Limestone type	Cement type	Limestone content (%)	Proc. mode (*)	Compressive strength (MPa)					
					3d	7d	28d	90d	362d	724d
M1		SPC1	0	AS	26.1	41.0	56.8	63.7	65.0	63.8
M2		SPC2	0	AS	32.2	43.7	60.4	65.8	65.3	57.7
M3	LS1	SPC1	5	AS	27.2	40.1	52.8	59.2	57.0	61.0
M4	LS1	SPC1	10	AS	25.1	39.4	48.5	57.2	55.0	54.8
M5	LS1	SPC1	15	AS	24.4	38.4	45.5	52.7	50.6	49.9
M6	LS1	SPC1	20	AS	22.1	34.6	38.2	45.6	40.5	42.1
M7	LS1	SPC2	5	AS	31.9	42.0	56.8	60.6	60.2	51.9
M8	LS1	SPC2	10	AS	28.8	39.4	50.6	58.1	52.4	50.8
M9	LS1	SPC2	15	AS	28.3	36.8	45.9	48.0	46.1	40.1
M10	LS1	SPC2	20	AS	25.6	34.7	41.9	49.4	43.4	42.7
M11	LS2	SPC1	5	AS	27.9	44.2	55.0	60.4	58.7	-
M12	LS2	SPC1	10	AS	26.7	41.7	52.9	58.3	55.9	-
M13	LS2	SPC1	20	AS	21.2	32.3	39.8	48.3	44.1	-
M14	LS3	SPC1	5	AS	33.4	47.4	56.7	63.7	62.3	-
M15	LS3	SPC1	10	AS	31.4	44.5	53.2	57.4	54.9	-
M16	LS3	SPC1	15	AS	29.4	41.2	46.5	51.6	52.3	-
M17	LS3	SPC1	20	AS	25.6	36.5	41.3	43.6	46.3	-
M18		SPC2b	0	AS	34.4	44.2	54.8	-	-	-
M19	LS2	SPC2b	10	AS	33.1	41.1	47.7	-	-	-
M20	LS2	SPC2b	20	AS	29.2	34.7	41.6	-	-	-
M21	LS3	SPC2b	10	AS	35.7	43.3	47.5	-	-	-
M22	LS3	SPC2b	20	AS	30.6	33.3	40.9	-	-	-
M23		SPC2	0	F1	37.2	44.6	57.3	-	-	-
M24	LS1	SPC2	10	F1	25.1	39.4	48.5	-	-	-
M25	LS2	SPC2	10	F1	41.3	46.6	56.9	-	-	-
M26	LS3	SPC2	10	F1	38.7	46.5	51.9	-	-	-
M27		SPC2	0	F2	56.8	70.7	81.5	-	-	-
M28	LS2	SPC2	10	F2	58.2	65.8	77.4	-	-	-
M29	LS2	SPC2	20	F2	58.7	60.4	72.1	-	-	-
M30	LS3	SPC2	10	F2	59.9	72.0	81.2	-	-	-
M31	LS3	SPC2	20	F2	53.2	66.0	71.1	-	-	-

Note:

Proc. mode: Procedure mode of limestone addition

Mode AS: Mortars were prepared according to Australian Standard AS2350.12 (constant water amount).

Mode F1: Water amount was adjusted in order to achieve mortar flow value of  $110 \pm 5\%$ .

Mode F2: Mortars with constant superplasticizer dosage and adjusted water amounts were prepared to achieve flow value of  $115 \pm 5\%$ .

SPC2b: The same cement as cement SPC2, but it was tested at time of 6 months later.

**Appendix 4.3: Flexural strength of mortars containing limestone modified cements**

Mix No.	Limestone type	Cement type	Limestone content (%)	Proc. Mode	Flexural strength (MPa)					
					3d	7d	28d	90d	362d	724d
M1		SPC1	0	AS	-	6.84	8.10	8.44	7.83	7.76
M2		SPC2	0	AS	5.70	6.94	8.33	8.63	8.25	7.90
M3	LS1	SPC1	5	AS	-	6.56	7.66	8.55	7.72	7.57
M4	LS1	SPC1	10	AS	-	6.41	7.56	8.05	7.70	7.15
M5	LS1	SPC1	15	AS	-	6.13	7.30	7.54	6.91	6.45
M6	LS1	SPC1	20	AS	-	5.72	6.31	6.87	6.32	5.76
M7	LS1	SPC2	5	AS	6.10	7.07	8.49	8.51	8.47	7.90
M8	LS1	SPC2	10	AS	5.20	6.72	8.03	7.84	7.90	7.30
M9	LS1	SPC2	15	AS	5.40	6.03	7.62	6.90	7.07	6.80
M10	LS1	SPC2	20	AS	4.80	5.68	6.49	6.99	6.52	6.55
M11	LS2	SPC1	5	AS	5.78	7.23	8.37	8.09	8.52	-
M12	LS2	SPC1	10	AS	5.50	7.44	7.60	8.00	7.63	-
M13	LS2	SPC1	20	AS	4.92	6.01	6.56	6.59	7.41	-
M14	LS3	SPC1	5	AS	-	-	-	8.63	7.81	-
M15	LS3	SPC1	10	AS	-	-	-	8.12	7.76	-
M16	LS3	SPC1	15	AS	-	-	-	7.48	7.13	-
M17	LS3	SPC1	20	AS	4.98	-	-	7.10	6.70	-
M18		SPC2b	0	AS	5.69	6.67	8.23	-	-	-
M19	LS2	SPC2b	10	AS	5.89	6.22	6.71	-	-	-
M20	LS2	SPC2b	20	AS	5.07	5.49	6.34	-	-	-
M21	LS3	SPC2b	10	AS	5.91	6.79	7.19	-	-	-
M22	LS3	SPC2b	20	AS	5.45	5.91	6.83	-	-	-

Note:

- Proc. mode: Procedure mode of limestone addition
- Mode AS: Mortars were prepared according to Australian Standard AS2350.12 (constant water amount).
- SPC2b: The same cement as cement SPC2, but it was tested at time of 6 months later.

**Appendix 4.4: Drying shrinkage of mortars containing limestone modified cements**

Mix No.	LS type	Cement type	LS content (%)	Proc. mode	Drying shrinkage (Microstrain)							
					7d	14d	21d	28d	56d	84d	112d	362d
M1		SPC1	0	AS	290	549	633	703	782	831	833	1131
M2		SPC2	0	AS	333	444	500	575	667	674	708	939
M3	LS1	SPC1	5	AS	359	608	685	720	815	869	890	1192
M4	LS1	SPC1	10	AS	265	600	677	708	780	849	823	-
M5	LS1	SPC1	15	AS	443	607	690	741	818	857	854	-
M6	LS1	SPC1	20	AS	613	649	674	733	826	849	861	1041
M7	LS1	SPC2	5	AS	359	477	567	592	682	692	710	886
M8	LS1	SPC2	10	AS	357	456	533	564	636	638	682	833
M9	LS1	SPC2	15	AS	306	428	528	580	679	679	677	844
M10	LS1	SPC2	20	AS	374	494	585	628	672	733	726	869
M11	LS2	SPC1	5	AS	449	608	633	695	713	777	787	1008
M12	LS2	SPC1	10	AS	456	600	636	662	685	728	785	969
M13	LS2	SPC1	20	AS	428	516	555	565	638	697	700	1003
M14	LS3	SPC1	5	AS	425	576	639	679	718	729	756	918
M15	LS3	SPC1	10	AS	429	567	613	653	692	705	723	916
M16	LS3	SPC1	15	AS	316	486	548	579	610	649	659	831
M17	LS3	SPC1	20	AS	387	442	457	559	557	639	667	818
M18		SPC2b	0	AS	232	444	508	554	653	675	679	849
M19	LS2	SPC2b	10	AS	301	444	474	515	588	588	589	790
M20	LS2	SPC2b	20	AS	267	420	454	495	559	564	569	756
M21	LS3	SPC2b	10	AS	308	446	472	477	570	605	664	782
M22	LS3	SPC2b	20	AS	310	438	456	495	543	580	653	764

Note:

Proc. mode: Procedure mode of limestone addition

Mode AS: Mortars were prepared according to Australian Standard AS2350.12 (constant water amount).

SPC2b: The same cement as cement SPC2, but it was tested at time of 6 months later.

### Appendix 4.5: Heat of hydration of mortars containing limestone modified cements

Combination of binder	Heat of hydration (j/g)										
	0.5h	4h	6h	8h	10h	12h	24h	48h	72h	96h	120h
0%LS + 100%SPC1	3	21	50	98	144	169	256	318	328	329	329
10%LS1 + 90%SPC1	7	29	62	111	148	169	249	298	308	310	311
20%LS1 + 80%SPC1	10	30	60	104	136	156	225	266	277	280	281
35%LS1 + 65%SPC1	8	29	57	91	113	128	187	224	234	238	242
10%LS2 + 90%SPC1	6	24	50	92	136	161	249	299	311	315	317
20%LS2 + 80%SPC1	8	28	55	97	129	150	229	272	284	289	292
35%LS2 + 65%SPC1	6	26	50	83	103	118	176	222	234	239	243
40%LS2 + 60%SPC1	10	29	51	82	99	113	166	209	219	224	229
10%LS3 + 90%SPC1	6	17	51	94	135	160	257	307	316	318	319
20%LS3 + 80%SPC1	6	27	56	99	125	145	234	279	288	291	292
35%LS3 + 65%SPC1	1	24	53	84	101	117	188	227	235	239	242
0%LS + 100%SPC2	12	35	78	140	201	231	303	339	341	341	342
10%LS2 + 90%SPC2	4	27	64	116	173	201	272	306	311	313	314
20%LS2 + 80%SPC2	8	39	77	130	169	192	253	280	285	287	288
40%LS2 + 60%SPC2	3	30	59	100	121	136	187	211	217	220	222

Note:

LS: Limestone  
 LS1: Limestone LS1  
 LS2: Limestone LS2

LS3: Limestone LS3  
 SPC1: Cement SPC1  
 SPC2: Cement SPC2

### Appendix 4.6: Compounds in paste containing 10% of limestone LS1 and cement SPC1 at age of 28 days

SS-NNNN	Compound Name Formula	Y-Scale	d x by	Wavelength
31-0301 (*)	Calcium Silicate $\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0003 (*)	Aluminum Silicate ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite $\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al) $\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn $\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate $\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide $\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite $\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn $\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite $\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn $\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn $\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate $\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn $\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn $\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn $\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn $\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn $\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn $\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn $\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside $\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite $\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine $\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite $\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite $\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M $\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite $\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered $\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2 $\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.7: Compounds in paste containing 10% of limestone LS2 and cement SPC1 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540



### Appendix 4.8: Compounds in paste containing 10% of limestone LS3 and cement SPC1 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.9: Compounds in paste containing 10% of limestone LS1 and cement SPC2 at age of 28 days

SS-NNNN	Compound Name, Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5, $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0065 (*)	Calcium Aluminum Sulfate Hydroxide Hydrate, $\text{Ca}_4\text{Al}_2\text{O}_6(\text{SO}_4)0.5(\text{OH}) \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0137 (*)	Chabazite, $\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide, $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al), $\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn, $\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate, $\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite $\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate $\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn $\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite $\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn $\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite $\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)0.67(\text{SO}_3)0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate $\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn $\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate $\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn $\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn $\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn $\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn $\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn $\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn $\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn $\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn $\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn $\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn $\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside $\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite $\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine $\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite $\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate $\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M $\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite $\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered $\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2 $\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.10: Compounds in paste containing 10% of limestone LS2 and cement SPC2 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0484 (*)	Artinite	$\text{Mg}_2\text{CO}_3(\text{OH})_2 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.11: Compounds in paste containing 10% of limestone LS3 and cement SPC2 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_4\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1405 (*)	Cowlesite	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.12: Compounds in paste containing 20% of limestone LS2 and cement SPC1 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0586 (*)	Calcite, syn	$\text{CaCO}_3$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.13: Compounds in paste containing 20% of limestone LS2 and cement SPC2 at age of 28 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0586 (*)	Calcite, syn	$\text{CaCO}_3$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.14: Compounds in paste containing 10% of limestone LS1 and cement SPC1 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength		
56-0003 (*)	Aluminum Silicate	ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540	
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$		50.00	1.000	1.540	
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$		50.00	1.000	1.540	
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$		50.00	1.000	1.540	
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$		50.00	1.000	1.540	
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$		50.00	1.000	1.540	
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$		50.00	1.000	1.540	
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$		50.00	1.000	1.540	
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$		50.00	1.000	1.540	
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$		50.00	1.000	1.540	
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$		50.00	1.000	1.540	
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$		50.00	1.000	1.540	
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$		50.00	1.000	1.540	
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$		50.00	1.000	1.540	
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$		50.00	1.000	1.540	
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$		50.00	1.000	1.540	
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$		50.00	1.000	1.540	
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$		50.00	1.000	1.540	
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$		50.00	1.000	1.540	
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$		50.00	1.000	1.540	
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$		50.00	1.000	1.540	
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$		50.00	1.000	1.540	
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$		50.00	1.000	1.540	
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$		50.00	1.000	1.540	
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$		50.00	1.000	1.540	
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$		50.00	1.000	1.540	
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$		50.00	1.000	1.540	
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$		50.00	1.000	1.540	
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$		50.00	1.000	1.540	
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$		50.00	1.000	1.540	
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$		50.00	1.000	1.540	
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$		50.00	1.000	1.540	
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$		50.00	1.000	1.540	
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$		50.00	1.000	1.540	
56-1475 (*)	Aragonite	$\text{CaCO}_3$		50.00	1.000	1.540	
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$		50.00	1.000	1.540	
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$		50.00	1.000	1.540	

### Appendix 4.15: Compounds in paste containing 10% of limestone LS2 and cement SPC1 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1405 (*)	Cowlesite	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540
6-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
6-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540



### Appendix 4.16: Compounds in paste containing 10% of limestone LS3 and cement SPC1 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.17: Compounds in paste containing 10% of limestone LS1 and cement SPC2 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.18: Compounds in paste containing 10% of limestone LS2 and cement SPC2 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1405 (*)	Cowlesite	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.19: Compounds in paste containing 10% of limestone LS3 and cement SPC2 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.20: Compounds in paste containing 20% of limestone LS2 and cement SPC1 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0586 (*)	Calcite, syn	$\text{CaCO}_3$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.21: Compounds in paste containing 20% of limestone LS2 and cement SPC2 at age of 90 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0586 (*)	Calcite, syn	$\text{CaCO}_3$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0816 (*)	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.22: Compounds in paste containing 10% of limestone LS1 and cement SPC1 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength		
56-0003 (*)	Aluminum Silicate	ZSM-5	Al <sub>2</sub> O <sub>3</sub> ·54SiO <sub>2</sub>	50.00	1.000	1.540	
56-0137 (*)	Chabazite	Ca <sub>2</sub> Al <sub>4</sub> Si <sub>8</sub> O <sub>24</sub> ·12H <sub>2</sub> O	50.00	1.000	1.540		
56-0150 (*)	Calcium Aluminum Oxide	Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	50.00	1.000	1.540		
56-0156 (*)	Pumpellyite-(Al)	Ca <sub>2</sub> MgAl <sub>2</sub> (SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )(OH) <sub>2</sub> ·H <sub>2</sub> O	50.00	1.000	1.540		
56-0189 (*)	Forsterite, syn	Mg <sub>2</sub> SiO <sub>4</sub>	50.00	1.000	1.540		
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	Ca <sub>6</sub> Al <sub>2</sub> O <sub>6</sub> (CO <sub>3</sub> ) <sub>3</sub> ·32H <sub>2</sub> O/3CaO·Al <sub>2</sub> O <sub>3</sub> ·3CaCO <sub>3</sub> ·32H <sub>2</sub> O	50.00	1.000	1.540		
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	Ca <sub>4</sub> Al <sub>2</sub> O <sub>6</sub> CO <sub>3</sub> ·11H <sub>2</sub> O/3CaO·Al <sub>2</sub> O <sub>3</sub> ·CaCO <sub>3</sub> ·11H <sub>2</sub> O	50.00	1.000	1.540		
56-0251 (*)	Calcium Aluminum Oxide	Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	50.00	1.000	1.540		
56-0293 (*)	Indialite, syn	Mg <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	50.00	1.000	1.540		
56-0297 (*)	Calcium Silicate	Ca <sub>2</sub> SiO <sub>4</sub>	50.00	1.000	1.540		
56-0298 (*)	Calcium Silicate	Ca <sub>2</sub> SiO <sub>4</sub>	50.00	1.000	1.540		
56-0299 (*)	Calcium Silicate	Ca <sub>2</sub> SiO <sub>4</sub>	50.00	1.000	1.540		
56-0301 (*)	Calcium Silicate	Ca <sub>3</sub> SiO <sub>5</sub>	50.00	1.000	1.540		
56-0302 (*)	Larnite, syn	Ca <sub>2</sub> SiO <sub>4</sub>	50.00	1.000	1.540		
56-0311 (*)	Gypsum, syn	CaSO <sub>4</sub> ·2H <sub>2</sub> O	50.00	1.000	1.540		
56-0376 (*)	Andalusite	Al <sub>2</sub> (SiO <sub>4</sub> )O	50.00	1.000	1.540		
56-0399 (*)	Bredigite, syn	Ca <sub>14</sub> Mg <sub>2</sub> (SiO <sub>4</sub> ) <sub>8</sub>	50.00	1.000	1.540		
56-0419 (*)	Epsomite, syn	MgSO <sub>4</sub> ·7H <sub>2</sub> O	50.00	1.000	1.540		
56-0471 (*)	Sillimanite	Al <sub>2</sub> SiO <sub>5</sub>	50.00	1.000	1.540		
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	Ca <sub>4</sub> Al <sub>2</sub> O <sub>6</sub> (CO <sub>3</sub> ) <sub>0.67</sub> (SO <sub>3</sub> ) <sub>0.33</sub> ·11H <sub>2</sub> O/3CaO·Al <sub>2</sub> O <sub>3</sub> ·0.33CaSO <sub>3</sub> ·0.67CaCO <sub>3</sub>	50.00	1.000	1.540		
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	Ca <sub>4</sub> Al <sub>2</sub> O <sub>6</sub> SO <sub>3</sub> ·11H <sub>2</sub> O/3CaO·Al <sub>2</sub> O <sub>3</sub> ·CaSO <sub>3</sub> ·11H <sub>2</sub> O	50.00	1.000	1.540		
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	3CaO·Al <sub>2</sub> O <sub>3</sub> ·Ca(OH) <sub>2</sub> ·18H <sub>2</sub> O	50.00	1.000	1.540		
56-0489 (*)	Magnesiocarpholite, syn	MgAl <sub>2</sub> Si <sub>2</sub> O <sub>6</sub> (OH) <sub>4</sub>	50.00	1.000	1.540		
56-0551 (*)	Calcium Silicate	Ca <sub>3</sub> SiO <sub>5</sub>	50.00	1.000	1.540		
56-0590 (*)	Monticellite, syn	CaMgSiO <sub>4</sub>	50.00	1.000	1.540		
56-0591 (*)	Merwinite, syn	Ca <sub>3</sub> Mg(SiO <sub>4</sub> ) <sub>2</sub>	50.00	1.000	1.540		
56-0592 (*)	Akermanite, syn	Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	50.00	1.000	1.540		
56-0610 (*)	Clinoenstatite, syn	MgSiO <sub>3</sub>	50.00	1.000	1.540		
56-0669 (*)	Nesquehonite, syn	MgCO <sub>3</sub> ·3H <sub>2</sub> O	50.00	1.000	1.540		
56-0719 (*)	Hexahydrate, syn	MgSO <sub>4</sub> ·6H <sub>2</sub> O	50.00	1.000	1.540		
56-0720 (*)	Starkeyite, syn	MgSO <sub>4</sub> ·4H <sub>2</sub> O	50.00	1.000	1.540		
56-0725 (*)	Hannebachite, syn	CaSO <sub>3</sub> ·0.5H <sub>2</sub> O	50.00	1.000	1.540		
56-0755 (*)	Gehlenite, syn	Ca <sub>2</sub> Al <sub>2</sub> SiO <sub>7</sub>	50.00	1.000	1.540		
56-0768 (*)	Enstatite, syn	MgSiO <sub>3</sub>	50.00	1.000	1.540		
56-1037 (*)	Grossite, syn	CaAl <sub>4</sub> O <sub>7</sub> /CaO·2Al <sub>2</sub> O <sub>3</sub>	50.00	1.000	1.540		
56-1370 (*)	Diopside	Ca(Mg,Al)(Si,Al) <sub>2</sub> O <sub>6</sub>	50.00	1.000	1.540		
56-1372 (*)	Yugawaralite	Ca(Si <sub>6</sub> Al <sub>2</sub> )O <sub>16</sub> ·4H <sub>2</sub> O	50.00	1.000	1.540		
56-1373 (*)	Gismondine	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub> ·4H <sub>2</sub> O	50.00	1.000	1.540		
56-1381 (*)	Epistilbite	Ca <sub>2</sub> (Si <sub>9</sub> Al <sub>3</sub> )O <sub>24</sub> ·8H <sub>2</sub> O	50.00	1.000	1.540		
56-1400 (*)	Clinozoisite	Ca <sub>2</sub> Al <sub>3</sub> (SiO <sub>4</sub> )(Si <sub>2</sub> O <sub>7</sub> )O(OH)	50.00	1.000	1.540		
56-1405 (*)	Cowlesite	CaAl <sub>2</sub> Si <sub>3</sub> O <sub>10</sub> ·6H <sub>2</sub> O	50.00	1.000	1.540		
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	50.00	1.000	1.540		
56-1451 (*)	Ettringite, syn	Ca <sub>6</sub> Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (OH) <sub>12</sub> ·26H <sub>2</sub> O	50.00	1.000	1.540		
56-1451 (*)	Wairakite	CaAl <sub>2</sub> Si <sub>4</sub> O <sub>12</sub> ·2H <sub>2</sub> O	50.00	1.000	1.540		
56-1460 (*)	Wollastonite-2M	CaSiO <sub>3</sub>	50.00	1.000	1.540		
56-1486 (*)	Anorthite, ordered	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>	50.00	1.000	1.540		
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	SiO <sub>2</sub>	50.00	1.000	1.540		

### Appendix 4.23: Compounds in paste containing 10% of limestone LS2 and cement SPC1 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540



### Appendix 4.24: Compounds in paste containing 10% of limestone LS3 and cement SPC1 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	0.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.25: Compounds in paste containing 10% of limestone LS1 and cement SPC2 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1405 (*)	Cowlesite	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.26: Compounds in paste containing 10% of limestone LS2 and cement SPC2 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540
6-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540

### Appendix 4.27: Compounds in paste containing 10% of limestone LS3 and cement SPC2 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0293 (*)	Indialite, syn	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_{0.67}(\text{SO}_3)_{0.33} \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.28: Compounds in paste containing 20% of limestone LS2 and cement SPC1 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate	ZSM-5 $\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0477 (*)	Calcium Aluminum Oxide Sulfite Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{SO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrite, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1405 (*)	Cowlesite	$\text{CaAl}_2\text{Si}_3\text{O}_{10} \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

### Appendix 4.29: Compounds in paste containing 20% of limestone LS2 and cement SPC2 at age of 180 days

SS-NNNN	Compound Name	Formula	Y-Scale	d x by	Wavelength
56-0003 (*)	Aluminum Silicate ZSM-5	$\text{Al}_2\text{O}_3 \cdot 54\text{SiO}_2$	50.00	1.000	1.540
56-0137 (*)	Chabazite	$\text{Ca}_2\text{Al}_4\text{Si}_8\text{O}_{24} \cdot 12\text{H}_2\text{O}$	50.00	1.000	1.540
56-0150 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0156 (*)	Pumpellyite-(Al)	$\text{Ca}_2\text{MgAl}_2(\text{SiO}_4)(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$	50.00	1.000	1.540
56-0189 (*)	Forsterite, syn	$\text{Mg}_2\text{SiO}_4$	50.00	1.000	1.540
56-0215 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_6\text{Al}_2\text{O}_6(\text{CO}_3)_3 \cdot 32\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaCO}_3 \cdot 32\text{H}_2\text{O}$	50.00	1.000	1.540
56-0219 (*)	Calcium Aluminum Oxide Carbonate Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6\text{CO}_3 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaCO}_3 \cdot 11\text{H}_2\text{O}$	50.00	1.000	1.540
56-0251 (*)	Calcium Aluminum Oxide	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-0269 (*)	Aluminum Silicate Hydroxide	$\text{Al}_2\text{SiO}_4(\text{OH})_2$	50.00	1.000	1.540
56-0289 (*)	Vuagnatite	$\text{CaAlSiO}_4(\text{OH})$	50.00	1.000	1.540
56-0297 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0298 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0299 (*)	Calcium Silicate	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0301 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0302 (*)	Larnite, syn	$\text{Ca}_2\text{SiO}_4$	50.00	1.000	1.540
56-0311 (*)	Gypsum, syn	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-0376 (*)	Andalusite	$\text{Al}_2(\text{SiO}_4)\text{O}$	50.00	1.000	1.540
56-0399 (*)	Bredigite, syn	$\text{Ca}_{14}\text{Mg}_2(\text{SiO}_4)_8$	50.00	1.000	1.540
56-0419 (*)	Epsomite, syn	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	50.00	1.000	1.540
56-0471 (*)	Sillimanite	$\text{Al}_2\text{SiO}_5$	50.00	1.000	1.540
56-0476 (*)	Calcium Aluminum Oxide Carbonate Sulfide Hydrate	$\text{Ca}_4\text{Al}_2\text{O}_6(\text{CO}_3)_0.67(\text{SO}_3)_0.33 \cdot 11\text{H}_2\text{O} / 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 0.33\text{CaSO}_3 \cdot 0.67\text{CaCO}_3$	50.00	1.000	1.540
56-0487 (*)	Calcium Aluminum Oxide Hydroxide Hydrate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Ca}(\text{OH})_2 \cdot 18\text{H}_2\text{O}$	50.00	1.000	1.540
56-0489 (*)	Magnesiocarpholite, syn	$\text{MgAl}_2\text{Si}_2\text{O}_6(\text{OH})_4$	50.00	1.000	1.540
56-0551 (*)	Calcium Silicate	$\text{Ca}_3\text{SiO}_5$	50.00	1.000	1.540
56-0590 (*)	Monticellite, syn	$\text{CaMgSiO}_4$	50.00	1.000	1.540
56-0591 (*)	Merwinite, syn	$\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$	50.00	1.000	1.540
56-0592 (*)	Akermanite, syn	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	50.00	1.000	1.540
56-0610 (*)	Clinoenstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-0669 (*)	Nesquehonite, syn	$\text{MgCO}_3 \cdot 3\text{H}_2\text{O}$	50.00	1.000	1.540
56-0719 (*)	Hexahydrate, syn	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$	50.00	1.000	1.540
56-0720 (*)	Starkeyite, syn	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-0725 (*)	Hannebachite, syn	$\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O}$	50.00	1.000	1.540
56-0755 (*)	Gehlenite, syn	$\text{Ca}_2\text{Al}_2\text{SiO}_7$	50.00	1.000	1.540
56-0768 (*)	Enstatite, syn	$\text{MgSiO}_3$	50.00	1.000	1.540
56-1037 (*)	Grossite, syn	$\text{CaAl}_4\text{O}_7 / \text{CaO} \cdot 2\text{Al}_2\text{O}_3$	50.00	1.000	1.540
56-1370 (*)	Diopside	$\text{Ca}(\text{Mg}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$	50.00	1.000	1.540
56-1372 (*)	Yugawaralite	$\text{Ca}(\text{Si}_6\text{Al}_2)\text{O}_{16} \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1373 (*)	Gismondine	$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$	50.00	1.000	1.540
56-1381 (*)	Epistilbite	$\text{Ca}_2(\text{Si}_9\text{Al}_3)\text{O}_{24} \cdot 8\text{H}_2\text{O}$	50.00	1.000	1.540
56-1400 (*)	Clinozoisite	$\text{Ca}_2\text{Al}_3(\text{SiO}_4)(\text{Si}_2\text{O}_7)\text{O}(\text{OH})$	50.00	1.000	1.540
56-1429 (*)	Calcium Aluminum Oxide tricalcium aluminate	$\text{Ca}_3\text{Al}_2\text{O}_6$	50.00	1.000	1.540
56-1451 (*)	Ettringite, syn	$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$	50.00	1.000	1.540
56-1451 (*)	Wairakite	$\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 2\text{H}_2\text{O}$	50.00	1.000	1.540
56-1460 (*)	Wollastonite-2M	$\text{CaSiO}_3$	50.00	1.000	1.540
56-1475 (*)	Aragonite	$\text{CaCO}_3$	50.00	1.000	1.540
56-1486 (*)	Anorthite, ordered	$\text{CaAl}_2\text{Si}_2\text{O}_8$	50.00	1.000	1.540
56-1498 (*)	Silicon Oxide Zeolite Sigma-2	$\text{SiO}_2$	50.00	1.000	1.540

**Appendix 5.1: Mixture proportions of vibrated high-performance concrete**

Mix No.	G type	Cement type	LS type	LS (%)	W/B	B (kg)	C (kg)	LS (kg)	G (kg)	S (kg)	W (kg)	SP (kg)
C1	G1	SPC2		0	0.35	488	488	0	988	808	170.8	3.413
C2A	G1	SPC2	LS1	10	0.35	488	439.2	48.8	983	804	170.8	3.362
C3A	G1	SPC2	LS2	10	0.35	488	439.2	48.8	985	806	170.8	2.146
C3B	G1	SPC2	LS2	10	0.30	500	450	50	1009	825	150.0	3.498
C3C	G1	SPC2	LS2	10	0.32	488	439.2	48.8	1005	822	156.2	3.264
C4A	G1	SPC2	LS2	20	0.35	488	390.4	97.6	980	802	170.8	2.306
C4B	G1	SPC2	LS2	20	0.30	500	400	100	1009	826	150.0	3.547
C4C	G1	SPC2	LS2	20	0.32	488	390.4	97.6	1001	819	156.2	3.275
C5A	G1	SPC2	LS2	30	0.35	488	341.6	146.4	976	798	170.8	2.306
C5B	G1	SPC2	LS2	30	0.30	500	350	150	1000	818	150.0	3.639
C5C	G1	SPC2	LS2	30	0.32	488	341.6	146.4	997	816	156.2	2.925
C6C	G1	SPC2	LS3	10	0.32	488	439.2	48.8	1005	822	156.2	2.931
C7A	G1	SPC2	LS2	40	0.35	488	292.8	195.2	972	795	170.8	2.000
C7B	G1	SPC2	LS2	40	0.28	500	300	200	1011	827	140.0	3.914
C7C	G1	SPC2	LS2	40	0.30	488	292.8	195.2	1007	824	146.4	3.415
C8A	G1	SPC2		0	0.60	350	350	0	997	816	210	0
C8B	G1	SPC2	LS2	10	0.59	350	315	35	999	817	206.5	0
C8C	G1	SPC2	LS2	20	0.58	350	280	70	1002	819	203	0
C8D	G1	SPC2	LS2	10	0.506	350	315	35	1043	853	177.2	0.853
C8E	G1	SPC2	LS2	20	0.500	350	280	70	1043	853	175.0	0.880
C8F	G1	SPC2	LS2	20	0.45	350	280	70	1069	874	157.5	1.750
C9A	G1	SPC1	LS2	20	0.32	488	390.2	97.6	999	817	156.1	2.810
C9B	G2	SPC1	LS2	20	0.32	488	390.4	97.6	999	817	156.1	3.268

Note:

G type: Combination of coarse aggregates

G1: 62% of 20-mm coarse aggregate A + 38% of 10-mm coarse aggregate E

G2: 70% of 14-mm coarse aggregate C + 30% of 10-mm coarse aggregate E

LS type: Limestone type

LS (%): Limestone weight percentage of total binder

W/B: Water to binder ratio

B: Binder content for m<sup>3</sup> concreteC: Cement content for m<sup>3</sup> concreteLS: Limestone content for m<sup>3</sup> concreteG: Coarse aggregate content for m<sup>3</sup> concreteS: Sand content for m<sup>3</sup> concreteW: Water content for m<sup>3</sup> concreteSP: Superplasticizer content for m<sup>3</sup> concrete

## Appendix 5.2: Properties of fresh and hardened vibrated high performance concrete

Mix No.	Slump value (mm)	Compressive strength (MPa)			Drying shrinkage (microstrain)						
		3 d	7 d	28 d	7 d	14 d	21 d	28 d	56 d	90 d	168 d
C1	200	57.5	69.3	78.7	261	327	361	435	500	-	-
C2A	225	51.6	61.6	73.4	285	375	461	488	587	-	-
C3A	220	48.7	60.0	72.0	205	287	367	405	488	-	-
C3B	210	66.4	73.3	90.1	213	280	355	387	455	-	-
C3C	200	65.5	76.6	89.9	248	337	368	375	465	-	568
C4A	200	51.0	63.0	72.0	222	245	326	363	433	-	493
C4B	205	60.8	74.3	85.8	213	268	316	360	433	-	516
C4C	220	55.8	66.7	79.4	-	-	-	-	-	-	-
C5A	200	42.4	53.0	62.1	187	289	321	333	436	-	584
C5B	230	53.6	65.1	73.5	200	296	332	345	440	-	547
C5C	220	49.7	60.4	67.3	201	291	325	339	431	-	592
C6C	205	60.9	70.7	78.9	241	331	356	364	456	-	623
C7A	190	33.2	42.5	49.6	147	277	296	337	456	-	545
C7B	197	51.7	60.8	68.0	222	374	380	406	512	-	604
C7C	250	45.0	54.9	62.3	192	339	343	360	483	-	561
C8A	155	20.7	-	40.3	115	170	229	293	393	-	539
C8B	155	21.6	-	38.6	106	179	251	311	401	-	536
C8C	160	19.7	-	32.6	77	180	257	288	356	-	-
C8D	150	29.8	-	49.7	109	168	245	296	393	-	519
C8E	190	27.1	-	43.0	84	187	213	285	383	-	-
C8F	150	31.5	-	49.8	96	201	223	306	381	-	-
C9A	200	38.9	61.1	74.3	164	240	361	415	412	-	-
C9B	190	44.6	68.4	80.8	201	263	407	452	481	541	-



### Appendix 6.1: Mixture proportions of self-compacting high performance concrete

Mix No.	Nga	Vpw (l)	LS type	LS (%)	W/B	C (kg)	LS (kg)	G (kg)	S (kg)	W (kg)	SP (kg)
SN1	0.40	413	LS3	20	0.30	500	125	637	955	187.5	5.072
SN2	0.52	413	LS3	20	0.30	500	125	831	767	187.5	4.438
SN3	0.55	413	LS3	20	0.30	500	125	881	721	187.5	4.428
SN4	0.60	413	LS3	20	0.30	500	125	966	644	187.5	3.438
SN5	0.52	346	LS2	20	0.30	413	103	932	860	154.8	6.588
SN6	0.55	346	LS2	20	0.30	413	103	988	809	154.8	6.587
SN7	0.52	416	LS1	20	0.30	498	125	834	770	186.9	8.717
SN8	0.52	413	LS2	20	0.30	500	125	831	767	187.5	4.438
SN9A	0.52	393	LS2	20	0.30	476	119	864	798	178.5	4.656
SN9B	0.52	393	LS2	20	0.30	476	119	864	798	178.5	4.453
SN10	0.52	393	LS3	20	0.30	476	119	864	798	178.5	4.333
SN11	0.52	393		0	0.30	600	0	864	798	180.0	7.257
SN12	0.52	391		0	0.30	595	0	864	798	178.5	7.349
SN13	0.52	393	LS2	10	0.30	535.5	59.5	864	798	178.5	5.672
SN14	0.52	393	LS2	25	0.30	443	148	864	798	178.5	4.556
SN15	0.52	393	LS2	30	0.30	416.5	178.5	864	798	178.5	4.655
SN16	0.52	393	LS2	40	0.30	351	234	864	798	175.5	4.446
SN17	0.52	346	LS2	25	0.30	386	129	932	860	154.2	8.125
SN18	0.52	346	LS2	40	0.30	305	203	932	860	152.4	5.800
SN19	0.52	393		0	0.35	557	0	864	798	194.95	3.983
SN20	0.52	393	LS2	10	0.35	500	55	864	798	194.25	3.600
SN21	0.52	393	LS2	20	0.35	441	110	864	798	192.85	3.325
SN22	0.52	393	LS2	40	0.35	326	217	864	798	190.05	2.945
SN23	0.52	346		0	0.35	482	0	932	860	168.7	5.900
SN24A	0.52	346	LS2	10	0.35	432	48	932	860	168.0	6.725
SN24B	0.52	346	LS2	10	0.35	432	48	932	860	168.0	4.938
SN25A	0.52	346	LS2	20	0.35	382	95	932	860	167.0	5.325
SN25B	0.52	346	LS2	20	0.35	382	95	932	860	167.0	4.663
SN26	0.52	346	LS2	40	0.35	283	188	932	860	164.85	3.288
SN27	0.485	347	LS2	20	0.30	413	103	864	917	154.8	8.887
SN28	0.483	346	LS2	20	0.35	382	95	864	923	167.0	4.834
SV1	0.52	395		0	0.30	600	0	862	795	180.0	6.600
SV2	0.52	395	LS2	20	0.30	474	119	862	795	177.8	4.379
SV3*)	0.52	395	LS2	20	0.30	474	119	862	795	177.8	4.316
SG1	0.52	393		0	0.30	597	0	864	798	179.1	4.864
SG2	0.52	393	LS2	10	0.30	535	59	864	798	178.4	4.536
SG3	0.52	393	LS2	20	0.30	474	118	864	798	177.6	4.133

Note:

Nga: Coarse to total aggregate ratio

Vpw: Paste volume for m<sup>3</sup> concrete

LS type: Limestone type

LS (%): Limestone weight percentage of total binder

C : Cement content

LS: Limestone content

S: Sand content

W: Water amount

G: Coarse aggregate content

SP: Superplasticizer amount

W/B: Water to binder ratio

\*) This mix contained blended coarse aggregates consisting of 70% and 30% of 14-mm and 10-mm maximum size coarse aggregates (C and E), respectively (all other mixes had coarse aggregates blended from 62% and 38% of 20-mm and 10-mm maximum size coarse aggregates (A and E), respectively).

### Appendix 6.2: Slump flow diameter, filling head drop, penetration depth, air content and compressive strength of self-compacting high performance concrete

Mix No.	Nga	Vpw (l)	%LS type	Fd (mm)	Hd (mm)	Pd (mm)	Air (%)	Compressive strength (MPa)			
								3 d	7 d	28 d	362 d
SN1	0.40	413	20%LS3	700	505 <sup>a)</sup>	7		58.2	65.1	75.0	-
SN2	0.52	413	20%LS3	685	500 <sup>a)</sup>	1		60.2	62.1	76.3	-
SN3	0.55	413	20%LS3	700	500 <sup>a)</sup>	2		55.4	63.6	69.4	-
SN4	0.60	413	20%LS3	660	450 <sup>a)</sup>	1		58.3	64.5	70.0	-
SN5	0.52	346	20%LS2	685	505 <sup>b)</sup>	1	2.4	55.2	64.7	76.9	-
SN6	0.55	346	20%LS2	680	504 <sup>b)</sup>	1	2.9	56.3	59.8	72.0	-
SN7	0.52	416	20%LS1	700	505 <sup>a)</sup>	6	2	60.3	65.9	75.5	-
SN8	0.52	413	20%LS2	670	490 <sup>a)</sup>	1	2	58.4	71.9	77.1	-
SN9A	0.52	393	20%LS2	705	500 <sup>a)</sup>	2	1.6	54.6	66.7	82.4	89.1
SN9B	0.52	393	20%LS2	695	505 <sup>a)</sup>	1		-	-	-	-
SN10	0.52	393	20%LS3	690	500 <sup>a)</sup>	1	2.4	55.5	69.6	77.5	-
SN11	0.52	393	0%LS	690	505 <sup>a)</sup>	3	2.9	56.3	65.5	82.1	89.7
SN12	0.52	391	0%LS	695	503 <sup>a)</sup>	4	1.8	-	-	-	-
SN13	0.52	393	10%LS2	690	500 <sup>a)</sup>	1	1.6	66.4	81.0	91.9	90.0
SN14	0.52	393	25%LS2	690	490 <sup>a)</sup>	2	2	60.5	70.5	80.1	89.1
SN15	0.52	393	30%LS2	690	500 <sup>a)</sup>	4	1.8	50.8	59.8	73.8	85.9
SN16	0.52	393	40%LS2	690	510 <sup>a)</sup>	2	2.2	45.6	54.6	64.2	75.0
SN17	0.52	346	25%LS2	695	503 <sup>b)</sup>	6.0	1.4	52.6	64.33	75.3	-
SN18	0.52	346	40%LS2	700	505 <sup>b)</sup>	4.0	1.2	42.9	53.73	63.6	-
SN19	0.52	393	0%LS	700	500 <sup>a)</sup>	7	1.9	55.6	69.6	83.8	-
SN20	0.52	393	10%LS2	670	490 <sup>a)</sup>	3	1.5	56.7	66.7	80.5	-
SN21	0.52	393	20%LS2	680	495 <sup>a)</sup>	2	1.2	48.6	59.8	68.9	-
SN22	0.52	393	40%LS2	690	495 <sup>a)</sup>	2	2.6	33.1	42.7	48.1	-
SN23	0.52	346	0%LS	670	498 <sup>b)</sup>	2	2.6	49.7	59.0	73.4	-
SN24A	0.52	346	10%LS2	700	505 <sup>b)</sup>	14	2.0	44.6	51.7	59.6	-
SN24B	0.52	346	10%LS2	680	503 <sup>b)</sup>	4	2.0	52.9	59.4	71.8	-
SN25A	0.52	346	20%LS2	680	505 <sup>b)</sup>	15	2.1	40.2	50.3	60.2	-
SN25B	0.52	346	20%LS2	680	505 <sup>b)</sup>	7	2.1	44.0	55.0	63.5	-
SN26	0.52	346	40%LS2	685	500 <sup>b)</sup>	1	1.9	34.0	42.4	48.8	-
SN27	0.485	347	20%LS2	685	503 <sup>b)</sup>	6	1.9	58.3	62.8	76.8	-
SN28	0.483	346	20%LS2	690	505 <sup>b)</sup>	4	1.6	47.5	56.9	66.9	-
SV1	0.52	395	0%LS	700	500 <sup>a)</sup>	7	2.9	54.8	70.6	78.1	-
SV2	0.52	395	20%LS2	680	500 <sup>a)</sup>	1	2	59.4	69.2	75.6	-
SV3*)	0.52	395	20%LS2	720	510 <sup>a)</sup>	4	1.6	49.9	70.7	83.3	-
SG1	0.52	393	0%LS	700	500 <sup>a)</sup>	8	2.6	59.1	-	76.8	-
SG2	0.52	393	10%LS2	695	490 <sup>a)</sup>	2	1.5	51.5	-	82.4	-
SG3	0.52	393	20%LS2	690	490 <sup>a)</sup>	2	1.9	54.2	-	75.6	-

Note:

Nga: Coarse to total aggregate ratio

Vpw: Paste volume for m<sup>3</sup> concrete

%LS type: Limestone weight percentage of total binder and limestone type

Fd: Slump flow diameter

Hd: Filling head drop

a) and b) Filling head drops of fresh concrete flowing through reinforcement clear spacings of 40.6mm and 58.3mm, respectively

Pd: Penetration depth used for evaluating segregation resistance of SC-HPC

Air: Air content in concrete

**Appendix 6.3: Drying shrinkage of self- compacting high performance concrete**

Mix No	Nga	Vpw (l)	LS type	Drying shrinkage (microstrain)						
				7 d	14 d	21 d	28 d	56 d	168 d	358 d
SN1	0.40	413	20%LS3	360	392	485	516	568		
SN2	0.52	413	20%LS3	229	264	403	430	456	517	-
SN3	0.55	413	20%LS3	200	255	375	405	453	523	-
SN4	0.60	413	20%LS3	287	392	452	556	587	-	-
SN5	0.52	346	20%LS2	219	323	372	389	454	604	-
SN6	0.55	346	20%LS2	235	336	389	415	497	617	-
SN7	0.52	416	20%LS1	397	465	603	660	697	-	-
SN8	0.52	413	20%LS2	185	308	385	432	513	517	1060
SN9A	0.52	393	20%LS2	159	298	317	360	405	561	
SN9B	0.52	393	20%LS2	141	332	348	399	428	-	-
SN10	0.52	393	20%LS3	237	367	419	464	515	580	678
SN11	0.52	393	0%LS	201	302	352	379	467	609	-
SN12	0.52	391	0%LS	216	303	394	391	493	607	
SN13	0.52	393	10%LS2	236	345	379	417	560	628	
SN14	0.52	393	25%LS2	190	284	348	383	466	597	
SN15	0.52	393	30%LS2	219	316	380	402	537	613	
SN16	0.52	393	40%LS	177	263	321	364	445	575	580
SN17	0.52	346	25%LS2	272	373	439	509	555	654	
SN18	0.52	346	40%LS2	184	260	299	400	444	576	
SN19	0.52	393	0%LS	287	368	436	453	541	692	
SN20	0.52	393	10%LS2	263	340	409	429	507	644	
SN21	0.52	393	20%LS2	253	335	420	448	523	662	
SN22	0.52	393	40%LS2	204	275	349	368	443	553	
SN23	0.52	346	0%LS	245	349	404	431	547	653	
SN24A	0.52	346	10%LS2	225	332	380	401	512	1003	
SN24B	0.52	346	10%LS2	244	332	404	424	521	617	
SN25A	0.52	346	20%LS2	260	336	403	421	524	594	
SN25B	0.52	346	20%LS2	209	311	375	393	500	595	
SN26	0.52	346	40%LS2	188	256	316	335	439	511	
SN27	0.485	347	20%LS2	304	377	443	452	555	660	
SN28	0.483	346	20%LS2	257	336	403	417	519	640	
SV1	0.52	395	0%LS	277	355	417	432	529		
SV2	0.52	395	20%LS2	236	327	395	459	496		
SV3*)	0.52	395	20%LS2	168	290	390	410	604		
SG1	0.52	393	0%LS	256	345	405	429	501	844	
SG2	0.52	393	10%LS2	272	383	447	463	543	671	
SG3	0.52	393	20%LS2	253	345	416	437	507	644	

Note:

Nga: Coarse to total aggregate ratio

Vpw: Paste volume for m<sup>3</sup> concrete

%LS type: Limestone weight percentage of total binder and limestone type

### Appendix 7.1: Mixture proportions, blocking behaviour and deformability of self-compacting concrete containing milled limestone

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Fd (mm)	Hd (mm)	Hf (mm)	Surf. Ass.	Def. Ass.	Bloc. Ass.
SN1	0.40	413	20%LS3	T1	0.30	700	505a)	-	-	-	No
SN1A	0.40	414	20%LS3	T1	0.30	710	505a)	62	LB	OK	No
SN1B	0.40	353	20%LS3	T1	0.30	655	490a)	85	LH	Poor	No
SN1C	0.40	355	20%LS3	T1	0.30	645	500a)	75	LH	Poor	No
SN2	0.52	413	20%LS3	T1	0.30	685	500a)	80	OK	OK	No
SN3	0.55	413	20%LS3	T1	0.30	700	500a)	80	OK	OK	No
SN4	0.60	413	20%LS3	T1	0.30	660	450a)	86	LH	Poor	Block
SN5	0.52	346	20%LS2	T1	0.30	685	505b)	83	LH	Poor	No
SN5A	0.52	346	20%LS3	T1	0.30	655	450a)	87	H	Poor	Block
SN5B	0.52	346	20%LS3	T1	0.30	660	450a)	85	LH	Poor	Block
SN5C	0.52	346	20%LS3	T1	0.30	705	450a)	73	OK	Poor	Block
SN6	0.55	346	20%LS2	T1	0.30	680	504b)	83	LH	Poor	No
SN7	0.52	416	20%LS1	T1	0.30	700	505a)	65	LB	OK	No
SN8	0.52	413	20%LS2	T1	0.30	670	500a)	84	OK	OK	No
SN8A	0.52	415	20%LS2	T1	0.30	670	490a)	90	H	Poor	No
SN8B	0.52	415	20%LS2	T1	0.30	725	502a)	71	OK	OK	No
SN9A	0.52	393	20%LS2	T1	0.30	705	500a)	-	-	-	No
SN9B	0.52	393	20%LS2	T1	0.30	695	505a)	-	-	-	No
SN9C	0.52	395	20%LS2	T1	0.30	705	502a)	74	OK	OK	No
SN9D	0.52	395	20%LS2	T1	0.30	690	500a)	81	OK	OK	No
SN10	0.52	393	20%LS3	T1	0.30	690	505a)	78	OK	OK	No
SN10A	0.52	393	20%LS3	T1	0.30	710	430a)	70	OK	OK	Block
SN10B	0.52	391	20%LS3	T1	0.30	720	500a)	60	OK	OK	No
SN10C	0.52	390	20%LS3	T1	0.30	700	450a)	62	OK	OK	Block
SN10D	0.52	389	20%LS3	T1	0.30	695	450a)	74	OK	OK	Block
SN11	0.52	393	0%	T1	0.30	690	505a)	81	OK	OK	No
SN12	0.52	391	0%LS	T1	0.30	695	503a)	-	-	-	No
SN13	0.52	393	10%LS2	T1	0.30	690	500a)	82	OK	OK	No
SN14	0.52	393	25%LS2	T1	0.30	690	490a)	80	OK	OK	No
SN15	0.52	395	30%LS2	T1	0.30	690	500a)	82	OK	OK	No
SN15A	0.52	396	30%LS2	T1	0.30	720	505a)	76	OK	OK	No
SN16	0.52	393	40%LS2	T1	0.30	690	495a)	82	OK	OK	No
SN17	0.52	346	25%LS2	T1	0.30	695	503b)	86	H	Poor	No
SN18	0.52	346	40%LS2	T1	0.30	700	505b)	88	H	Poor	No
SN19	0.52	393	0%LS	T1	0.35	700	500a)	78	OK	OK	No
SN20	0.52	393	10%LS2	T1	0.35	670	490a)	80	OK	OK	No
SN21	0.52	393	20%LS2	T1	0.35	680	495a)	75	OK	OK	No
SN22	0.52	393	40%LS2	T1	0.35	690	495a)	75	OK	OK	No
SN23	0.52	346	0%LS	T1	0.35	670	498b)	78	OK	OK	No
SN24A	0.52	346	10%LS2	T1	0.35	700	505b)	76	OK	OK	No
SN24B	0.52	346	10%LS2	T1	0.35	680	503b)	76	OK	OK	No
SN25A	0.52	346	20%LS2	T1	0.35	680	505b)	76	OK	OK	No
SN25B	0.52	346	20%LS2	T1	0.35	680	505b)	76	OK	OK	No
SN26	0.52	346	40%LS2	T1	0.35	685	500b)	82	OK	OK	No
SN27	0.485	347	20%LS2	T1	0.30	685	503b)	85	H	Poor	No
SN28	0.483	346	20%LS2	T1	0.35	690	505b)	84	LH	Poor	No
SN29	0.40	370	20%LS2	T1	0.35	685	505b)	-	-	-	No
SN30	0.40	350	20%LS2	T1	0.35	670	505b)	-	-	-	No
SN31	0.50	350	20%LS2	T1	0.35	675	500b)	-	-	-	No
SN32A	0.52	400	20%LS2	T2	0.32	715	505a)	73	OK	OK	No
SN32B	0.52	400	20%LS2	T2	0.32	690	508a)	-	-	-	No
SN33A	0.52	365	20%LS2	T2	0.32	690	500b)	-	-	-	No
SN33B	0.52	366	20%LS2	T2	0.32	730	505b)	-	-	-	No

### Appendix 7.1: Mixture proportions and properties of self-compacting concrete containing milled limestone (continued)

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Fd (mm)	Hd (mm)	Hf (mm)	Surf. Ass.	Def. Ass.	Bloc. Ass.
SN34	0.52	346	20%LS2	T2	0.32	650	495b)	-	-	-	No
SN35A	0.52	365	20%LS2	T3	0.34	680	500b)	75	OK	OK	No
SN35B	0.52	365	20%LS2	T3	0.34	675	460b)	100	H	Poor	Block
SN36A	0.40	352	20%LS2	T1	0.364	670	500b)	75	OK	OK	No
SN36B	0.40	355	20%LS2	T1	0.367	680	510b)	73	OK	OK	No
SN37	0.52	351	20%LS2	T1	0.364	690	500b)	83	LH	Poor	No
SN38	0.60	351	20%LS2	T1	0.364	640	450b)	85	H	Poor	Block
SV1	0.52	395	0%	T1	0.30	700	500a)	73	OK	OK	No
SV2	0.52	395	20%LS2	T1	0.30	680	500a)	80	OK	OK	No
SV3	0.52	395	20%LS2	T4	0.30	720	510a)	74	OK	OK	No
SV4	0.40	400	20%LS2	T4	0.30	680	510a)	-	-	-	No
SV5	0.50	410	20%LS2	T4	0.30	690	502a)	-	-	-	No
SV6	0.50	390	20%LS2	T4	0.30	680	500b)	-	-	-	No
SV7	0.50	346	20%LS2	T4	0.30	650	490b)	-	-	-	No
SV8	0.52	370	20%LS2	T4	0.30	680	503b)	-	-	-	No
SV9	0.52	346	20%LS2	T4	0.30	660	495b)	-	-	-	No
SV10	0.55	395	20%LS2	T4	0.30	670	500b)	-	-	-	No
SV11	0.55	350	20%LS2	T4	0.30	655	490b)	-	-	-	No
SV12	0.40	410	20%LS2	T4	0.35	680	510b)	-	-	-	No
SV13	0.40	390	20%LS2	T4	0.35	670	508b)	-	-	-	No
SV14	0.40	348	20%LS2	T4	0.35	660	495b)	-	-	-	No
SV15	0.52	380	20%LS2	T4	0.35	685	500b)	-	-	-	No
SV16	0.52	355	20%LS2	T4	0.35	660	497b)	-	-	-	No
SV17	0.60	380	20%LS2	T4	0.35	670	502b)	-	-	-	No
SV18	0.60	355	20%LS2	T4	0.35	650	500b)	-	-	-	No
SG1	0.52	393	0%LS	T1	0.30	700	500a)	82	OK	OK	No
SG2	0.52	393	10%LS2	T1	0.30	695	490a)	82	OK	OK	No
SG3	0.52	393	20%LS2	T1	0.30	690	490a)	73	OK	OK	No

**Note:**

Shrinkage limited cements SPC2 was used in mixes from SN1 to SN38, inclusive.

Shrinkage limited cements SPC1 was used in mixes from SV1 to SV18, inclusive.

Limestone was interground in mixes SG2 and SG3.

Nga: Coarse to total aggregate ratio

Vpw: Paste volume per m<sup>3</sup> of concrete

%LS source: Percentage and source of limestone in binder

Ag: Aggregate combination

T1: Aggregates consists of river sand RS1 and coarse aggregates that include 62% of aggregate A and 38% of aggregate E

T2: Aggregates consists of river sand RS1 and coarse aggregates that include 50% of aggregate A and 50% of aggregate E

T3: Aggregate combination consists of river sand RS1 and coarse aggregates that include 40% of aggregate A and 60% of aggregate E

T4: Aggregate combination consists of river sand RS1 and coarse aggregates that include 70% of aggregate C and 30% of aggregate E

W/B: Water to binder ratio

Fd: Slump flow diameter

Hd: Filling head drop

Hf: Final depth

Surf. Ass.: Surface assessment (LB, LH or H means little bubble, little honeycombing or honeycombing, respectively; OK indicates no honeycombing on surface of specimen)

Def. Ass.: Deformability assessment (Poor or OK indicate that specimen is of poor or satisfactory deformability, respectively)

Bloc. Ass.: Blocking assessment



**Appendix 7.2: Test results on penetration depth and segregation resistance of self-compacting concrete containing milled limestone**

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Fd (mm)	Pd (mm)	Ha (mm)	Rh (%)	Rv (%)	Seg. Ass.
SN1	0.40	413	20%LS3	T1	0.30	700	7	-	-	-	OK
SN1A	0.40	414	20%LS3	T1	0.30	710	15	14.8	-	-	Seg.
SN1B	0.40	353	20%LS3	T1	0.30	655	1	3	-	-	OK
SN1C	0.40	355	20%LS3	T1	0.30	645	2	5.0	-	-	OK
SN2	0.52	413	20%LS3	T1	0.30	685	1	3	-	-	OK
SN3	0.55	413	20%LS3	T1	0.30	700	2	4	-	-	OK
SN4*)	0.60	413	20%LS3	T1	0.30	660	1	2	-	-	OK
SN5*)	0.52	346	20%LS2	T1	0.30	685	1	2	2.0	-	OK
SN5A*)	0.52	346	20%LS3	T1	0.30	655	1	4.5	-	6.8	OK
SN5B*)	0.52	346	20%LS3	T1	0.30	660	1	2.5	-	-	OK
SN5C*)	0.52	346	20%LS3	T1	0.30	705	15	19.5	-	-	Seg.
SN6*)	0.55	346	20%LS2	T1	0.30	680	1	2	3.4	-	OK
SN7	0.52	416	20%LS1	T1	0.30	700	2	4	2.5	-	OK
SN8	0.52	413	20%LS2	T1	0.30	670	1	0	-	-	OK
SN8A	0.52	415	20%LS2	T1	0.30	670	1	5	-	-	OK
SN8B	0.52	415	20%LS2	T1	0.30	725	15	26	-	-	Seg.
SN9A	0.52	393	20%LS2	T1	0.30	705	2	-	-	-	OK
SN9B	0.52	393	20%LS2	T1	0.30	695	1	4	3.4	-	OK
SN9C	0.52	395	20%LS2	T1	0.30	705	2	4.5	-	-	OK
SN9D	0.52	395	20%LS2	T1	0.30	690	1	2.0	-	-	OK
SN10	0.52	393	20%LS3	T1	0.30	690	1	1	-	4.5	OK
SN10A	0.52	393	20%LS3	T1	0.30	710	27	35	-	23.9	Seg.
SN10B	0.52	391	20%LS3	T1	0.30	720	20	27.0	-	-	Seg.
SN10C	0.52	390	20%LS3	T1	0.30	700	15	19.5	-	-	Seg.
SN10D	0.52	389	20%LS3	T1	0.30	695	2	4.5	-	-	OK
SN11	0.52	393	0%	T1	0.30	690	3	6.0	6.2	8.6	OK
SN12	0.52	391	0%LS	T1	0.30	695	4	-	-	-	OK
SN13	0.52	393	10%LS2	T1	0.30	690	1	4	3.4	-	OK
SN14	0.52	393	25%LS2	T1	0.30	690	2	-	-	-	OK
SN15	0.52	393	30%LS2	T1	0.30	690	4	6.5	5.3	4.5	OK
SN15A	0.52	396	30%LS2	T1	0.30	720	15	9	13.5	12.2	Seg.
SN16	0.52	393	40%LS2	T1	0.30	690	2	-	-	-	OK
SN17*)	0.52	346	25%LS2	T1	0.30	695	6.0	-	-	-	OK
SN18*)	0.52	346	40%LS2	T1	0.30	700	4.0	-	-	-	OK
SN19	0.52	393	0%LS	T1	0.35	700	7	-	-	-	OK
SN20	0.52	393	10%LS2	T1	0.35	670	3	-	-	-	OK
SN21	0.52	393	20%LS2	T1	0.35	680	2	-	-	-	OK
SN22	0.52	393	40%LS2	T1	0.35	690	2	-	-	-	OK
SN23	0.52	346	0%LS	T1	0.35	670	2	-	-	-	OK
SN24A	0.52	346	10%LS2	T1	0.35	700	14	-	-	-	Seg.
SN24B	0.52	346	10%LS2	T1	0.35	680	4	-	-	-	OK
SN25A	0.52	346	20%LS2	T1	0.35	680	15	-	-	-	Seg.
SN25B	0.52	346	20%LS2	T1	0.35	680	7	-	-	-	OK
SN26	0.52	346	40%LS2	T1	0.35	685	1	-	-	-	OK
SN27*)	0.485	347	20%LS2	T1	0.30	685	6	-	-	-	OK
SN28*)	0.483	346	20%LS2	T1	0.35	690	4	-	-	-	OK
SN29	0.40	370	20%LS2	T1	0.35	685	5	-	-	-	OK
SN30	0.40	350	20%LS2	T1	0.35	670	13	-	-	-	Seg.
SN31	0.50	350	20%LS2	T1	0.35	675	2	-	-	-	OK
SN32A	0.52	400	20%LS2	T2	0.32	715	12	7	-	10.9	Seg.
SN32B	0.52	400	20%LS2	T2	0.32	690	4	-	-	-	OK
SN33A	0.52	365	20%LS2	T2	0.32	690	1	2.0	2.7	6.7	OK
SN33B	0.52	366	20%LS2	T2	0.32	730	18	17.5	13.8	12.4	Seg.

### Appendix 7.2: Test results on penetration depth and segregation resistance of self-compacting concrete containing milled limestone (continued)

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Fd (mm)	Pd (mm)	Ha (mm)	Rh (%)	Rv (%)	Seg. Ass.
SN34	0.52	346	20%LS2	T2	0.32	650	15	-	-	-	Seg.
SN35A	0.52	365	20%LS2	T3	0.34	680	2	4.5	5.4	5.4	OK
SN35B	0.52	365	20%LS2	T3	0.34	675	11	13.5	12.7	13.2	Seg.
SN36A	0.40	352	20%LS2	T1	0.364	670	3	5.0	5.5	-	OK
SN36B	0.40	355	20%LS2	T1	0.367	680	8	6.0	9.2	5.2	OK
SN37	0.52	351	20%LS2	T1	0.364	690	8	6.5	8.8	7.7	OK
SN38	0.60	351	20%LS2	T1	0.364	640	10	18.5	11.3	11.2	Seg.
SV1	0.52	395	0%	T1	0.30	700	7	-	-	-	OK
SV2	0.52	395	20%LS2	T1	0.30	680	1	-	-	-	OK
SV3	0.52	395	20%LS2	T4	0.30	720	4	-	-	-	OK
SV4	0.40	400	20%LS2	T4	0.30	680	2	-	-	-	OK
SV5	0.50	410	20%LS2	T4	0.30	690	3	-	-	-	OK
SV6	0.50	390	20%LS2	T4	0.30	680	6	-	-	-	OK
SV7	0.50	346	20%LS2	T4	0.30	650	10	-	-	-	Seg.
SV8	0.52	370	20%LS2	T4	0.30	680	3	-	-	-	OK
SV9	0.52	346	20%LS2	T4	0.30	660	18	-	-	-	Seg.
SV10	0.55	395	20%LS2	T4	0.30	670	3	-	-	-	OK
SV11	0.55	350	20%LS2	T4	0.30	655	20	-	-	-	Seg.
SV12	0.40	410	20%LS2	T4	0.35	680	4	-	-	-	OK
SV13	0.40	390	20%LS2	T4	0.35	670	3	-	-	-	OK
SV14	0.40	348	20%LS2	T4	0.35	660	19	-	-	-	Seg.
SV15	0.52	380	20%LS2	T4	0.35	685	5	-	-	-	OK
SV16	0.52	355	20%LS2	T4	0.35	660	20	-	-	-	Seg.
SV17	0.60	380	20%LS2	T4	0.35	670	6	-	-	-	OK
SV18	0.60	355	20%LS2	T4	0.35	650	20	-	-	-	Seg.
SG1	0.52	393	0%LS	T1	0.30	700	8	-	-	-	OK
SG2	0.52	393	10%LS2	T1	0.30	695	2	-	-	-	OK
SG3	0.52	393	20%LS2	T1	0.30	690	2	-	-	-	OK

Note:

\*) These mixes had honeycombing in hardened specimens.

Note:

Shrinkage limited cements SPC2 was used in mixes from SN1 to SN38, inclusive.

Shrinkage limited cements SPC1 was used in mixes from SV1 to SV18, inclusive.

Limestone was interground in mixes SG2 and SG3.

Nga: Coarse to total aggregate ratio

Vpw: Paste volume per m<sup>3</sup> of concrete

%LS source: Percentage and source of limestone in binder

Ag: Aggregate combination

T1: Aggregates consists of river sand RS1 and coarse aggregates that include 62% of aggregate A and 38% of aggregate E

T2: Aggregates consists of river sand RS1 and coarse aggregates that include 50% of aggregate A and 50% of aggregate E

T3: Aggregate combination consists of river sand RS1 and coarse aggregates that include 40% of aggregate A and 60% of aggregate E

T4: Aggregate combination consists of river sand RS1 and coarse aggregates that include 70% of aggregate C and 30% of aggregate E

W/B: Water to binder ratio

Fd: Slump flow diameter

Pd: Penetration depth

Ha: Aggregate depth

Rh: Difference between the average masses of coarse aggregate at the bottom of the vertical leg and at the end of L-box

Rv: Variation of the mass of coarse aggregate in the vertical direction

Seg. Ass.: Segregation assessment (Seg. or OK means segregation or satisfactory segregation resistance, respectively)

**Appendix 7.3: Test results on penetration depth and segregation resistance of self-compacting concrete containing fly ash and blast furnace slag cements (Wilton, 1998 and Mourad, 1998)**

Mix No.	Nga	Vpw (l)	% Adm. type	Ag	W/B	Fd (mm)	Pd (mm)	Ha (mm)	Rh (%)	Rv (%)	Seg. Ass.
OFA1	0.48	380	0%	T5	0.30	610	2	1	-	-	OK
OFA2	0.48	380	30%FA	T5	0.30	655	3	5.5	1.1	-	OK
OFA3	0.48	380	65%FA	T5	0.30	660	5	5	2.3	-	OK
OFA4	0.48	380	0%	T5	0.35	660	1	1	3.6	-	OK
OFA5	0.48	380	30%FA	T5	0.35	725	4	4	5.3	-	OK
OFA6	0.50	380	0%	T6	0.30	652	3	6	4.8	-	OK
OFA7	0.50	380	30%FA	T6	0.30	655	6	-	9.0	-	OK
OFA8	0.50	380	65%FA	T6	0.30	690	8	6	1.0	-	OK
OFA9	0.50	416	30%FA	T6	0.30	665	0	0.5	7.9	-	OK
OFA10	0.50	458	65%FA	T6	0.30	670	0.50	1.5	-	-	OK
OFA11	0.46	363	30%FA	T6	0.32	655	1	1.5	-	-	OK
OFA12	0.46	350	30%FA	T6	0.32	660	2.7	3.5	-	-	OK
OFA13	0.46	394	30%FA	T6	0.32	720	2.3	1.5	-	-	OK
OFA14	0.40	381	30%FA	T6	0.32	685	2.0	4.5	-	-	OK
OFA15	0.40	360	30%FA	T6	0.32	660	1.7	7	-	-	OK
OFA16	0.55	365	30%FA	T6	0.32	700	4.7	5.5	-	-	OK
OFA17	0.55	347	30%FA	T6	0.32	680	8.30	1	-	-	OK
BFC1	0.48	380	30%BF	T5	0.30	660	3.7	0.5	7.2	-	OK
BFC2	0.48	380	65%BF	T5	0.30	680	5.7	5.0	6.2	-	OK
BFC3	0.48	380	30%BF	T5	0.35	720	1	0.5	6.7	-	OK
BFC4	0.48	380	65%BF	T5	0.35	685	3.3	3.0	7.0	-	OK
BFC5	0.50	380	30%BF	T6	0.30	613	6.3	5.0	6.8	-	OK
BFC6	0.50	380	65%BF	T6	0.30	582.5	9	16.0	8.6	-	Seg.
BFC7	0.50	360	30%BF	T5	0.32	715	6.3	4.5	-	-	OK
BFC8	0.50	350	30%BF	T5	0.32	658	9.7	7.0	-	-	Seg.
BFC9	0.50	370	30%BF	T5	0.32	715	7.0	5.5	-	-	OK
BFC10	0.50	397	30%BF	T5	0.32	700	4.7	1.0	-	-	OK
BFC11	0.60	365	30%BF	T5	0.32	680	2.0	2.5	-	-	OK
BFC12	0.60	350	30%BF	T5	0.32	660	9.7	11.0	-	-	Seg.
BFC13	0.60	392	30%BF	T5	0.32	690	2.0	-	-	-	OK
BFC14	0.40	390	30%BF	T5	0.32	665	3.0	-	-	-	OK
BFC15	0.40	361	30%BF	T5	0.32	670	2.7	-	-	-	OK
BFC16	0.40	403	30%BF	T5	0.32	690	6.0	-	-	-	OK

Note:

Ordinary portland cement (OPC) was used in mixes from OFA1 to OFA17, inclusive.

Blast furnace slag cements were used in mixes from BFC1 to BFC16, inclusive.

Nga: Coarse to total aggregate ratio

Vpw: Paste volume ( $l/m^3$ )

%Adm. type: Percentage and type of mineral admixture

FA: Fly ash

BF: Blast furnace slag

Ag: Aggregate combination

T5: Aggregate combination consists of river sand RS2 and coarse aggregates that include 73% of aggregate D and 27% of aggregate F

T6: Aggregate combination consists of river sand RS2 and coarse aggregates that include 62% of aggregate B and 38% of aggregate F

W/B: Water to binder ratio

Fd: Slump flow diameter

Pd: Penetration depth

Ha: Aggregate depth

Rh: Difference between the average masses of coarse aggregate at the bottom of the vertical leg and at the end of L-box

Rv: Variation of the mass of coarse aggregate in the vertical direction

Seg. Ass.: Segregation assessment (Seg. or OK means segregation or satisfactory segregation resistance, respectively)



**Appendix 8.1: Mixture proportions and properties of self-compacting high performance concrete containing milled limestone**

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Dav (mm)	Dss (mm)	SP (kg)	Fd (mm)	T50 (s)	Pd (mm)
SN1	0.40	413	20%LS3	T1	0.30	5.095	0.431	5.072	700	4	7
SN1A	0.40	414	20%LS3	T1	0.30	5.095	0.434	5.719	710	4	15
SN1B	0.40	353	20%LS3	T1	0.30	5.095	0.255	15.63	655	13	1
SN1C	0.40	355	20%LS3	T1	0.30	5.095	0.260	18.44	645	9	2
SN2	0.52	413	20%LS3	T1	0.30	6.416	0.599	4.438	685	4	1
SN3	0.55	413	20%LS3	T1	0.30	6.746	0.606	4.428	700	3	2
SN4*)	0.60	413	20%LS3	T1	0.30	7.296	0.621	3.438	660	4	1
SN5*)	0.52	346	20%LS2	T1	0.30	6.416	0.350	6.588	685	11	1
SN5A*)	0.52	346	20%LS3	T1	0.30	6.416	0.350	5.00	655	12	1
SN5B*)	0.52	346	20%LS3	T1	0.30	6.416	0.350	5.250	660	11	1
SN5C*)	0.52	346	20%LS3	T1	0.30	6.416	0.350	5.625	705	12	15
SN6*)	0.55	346	20%LS2	T1	0.30	6.746	0.346	6.587	680	11	1
SN7	0.52	416	20%LS1	T1	0.30	6.416	0.611	8.717	700	6	2
SN8	0.52	413	20%LS2	T1	0.30	6.416	0.599	4.438	670	3	1
SN8A	0.52	415	20%LS2	T1	0.30	6.416	0.607	4.328	670	3	1
SN8B	0.52	415	20%LS2	T1	0.30	6.416	0.607	5.595	725	3	15
SN9A	0.52	393	20%LS2	T1	0.30	6.416	0.521	4.656	705	5	2
SN9B	0.52	393	20%LS2	T1	0.30	6.416	0.521	4.453	695	5	1
SN9C	0.52	395	20%LS2	T1	0.30	6.416	0.528	4.465	705	5	2
SN9D	0.52	395	20%LS2	T1	0.30	6.416	0.528	4.390	690	5	1
SN10	0.52	393	20%LS3	T1	0.30	6.416	0.521	5.169	690	6	1
SN10A	0.52	393	20%LS3	T1	0.30	6.416	0.521	5.652	710	4	27
SN10B	0.52	391	20%LS3	T1	0.30	6.416	0.513	8.619	720	3	20
SN10C	0.52	390	20%LS3	T1	0.30	6.416	0.509	6.616	700	3	15
SN10D	0.52	389	20%LS3	T1	0.30	6.416	0.505	4.594	695	5	2
SN11	0.52	393	0%	T1	0.30	6.416	0.521	7.257	690	7	3
SN12	0.52	391	0%LS	T1	0.30	6.416	0.513	7.349	695	7	4
SN13	0.52	393	10%LS2	T1	0.30	6.416	0.521	5.672	690	6	1
SN14	0.52	393	25%LS2	T1	0.30	6.416	0.521	4.556	690	7	2
SN15	0.52	393	30%LS2	T1	0.30	6.416	0.521	4.655	690	7	4
SN15A	0.52	396	30%LS2	T1	0.30	6.416	0.532	5.883	720	5	15
SN16	0.52	393	40%LS2	T1	0.30	6.416	0.521	4.446	690	6	2
SN17*)	0.52	346	25%LS2	T1	0.30	6.416	0.350	8.125	695	9	6.0
SN18*)	0.52	346	40%LS2	T1	0.30	6.416	0.350	5.800	700	9	4.0
SN19	0.52	393	0%LS	T1	0.35	6.416	0.521	3.983	700	3	7
SN20	0.52	393	10%LS2	T1	0.35	6.416	0.521	3.600	670	5	3
SN21	0.52	393	20%LS2	T1	0.35	6.416	0.521	3.325	680	4	2
SN22	0.52	393	40%LS2	T1	0.35	6.416	0.521	2.945	690	3	2
SN23	0.52	346	0%LS	T1	0.35	6.416	0.350	5.900	670	11	2
SN24A	0.52	346	10%LS2	T1	0.35	6.416	0.350	6.725	700	7	14
SN24B	0.52	346	10%LS2	T1	0.35	6.416	0.350	4.938	680	8	4
SN25A	0.52	346	20%LS2	T1	0.35	6.416	0.350	5.325	680	8	15
SN25B	0.52	346	20%LS2	T1	0.35	6.416	0.350	4.663	680	9	7
SN26	0.52	346	40%LS2	T1	0.35	6.416	0.350	3.288	685	6	1
SN27*)	0.485	347	20%LS2	T1	0.30	6.031	0.314	8.887	685	8	6
SN28*)	0.483	346	20%LS2	T1	0.35	6.009	0.310	4.834	690	7	4
SN29	0.40	370	20%LS2	T1	0.35	5.095	0.303	9.724	685	8	5
SN30	0.40	350	20%LS2	T1	0.35	5.095	0.247	13.58	670	10	13
SN31	0.50	350	20%LS2	T1	0.35	6.196	0.340	9.654	675	10	2
SN32A	0.52	400	20%LS2	T2	0.32	5.984	0.510	5.691	715	3	12
SN32B	0.52	400	20%LS2	T2	0.32	5.984	0.510	5.008	690	3	4
SN33A	0.52	365	20%LS2	T2	0.32	5.984	0.405	5.456	690	8	1

### Appendix 8.1: Mixture proportions and properties of self-compacting high performance concrete containing milled limestone (continued)

Mix No.	Nga	Vpw (l)	%LS source	Ag	W/B	Dav (mm)	Dss (mm)	SP (kg)	Fd (mm)	T50 (s)	Pd (mm)
SN33B	0.52	366	20%LS2	T2	0.32	5.984	0.408	6.593	730	6	18
SN34	0.52	346	20%LS2	T2	0.32	5.984	0.326	5.575	650	10	15
SN35A	0.52	365	20%LS2	T3	0.34	5.624	-	7.998	680	9	2
SN35B	0.52	365	20%LS2	T3	0.34	5.624	-	8.502	675	7	11
SN36A	0.40	352	20%LS2	T1	0.364	5.095	0.252	7.192	670	8	3
SN36B	0.40	355	20%LS2	T1	0.367	5.095	0.260	9.625	680	7	8
SN37	0.52	351	20%LS2	T1	0.364	6.416	0.368	4.714	690	9	8
SN38	0.60	351	20%LS2	T1	0.364	7.296	0.360	4.959	640	9	10
SV1	0.52	395	0%	T1	0.30	6.416	0.528	6.600	700	5	7
SV2	0.52	395	20%LS2	T1	0.30	6.416	0.528	4.379	680	6	1
SV3	0.52	395	20%LS2	T4	0.30	5.639	0.445	4.316	720	11	4
SV4	0.40	400	20%LS2	T4	0.30	4.498	0.339	8.757	680	15	2
SV5	0.50	410	20%LS2	T4	0.30	5.449	0.475	5.865	690	8	3
SV6	0.50	390	20%LS2	T4	0.30	5.449	0.410	6.806	680	14	6
SV7	0.50	346	20%LS2	T4	0.30	5.449	0.275	9.965	650	12	10
SV8	0.52	370	20%LS2	T4	0.30	5.639	0.363	5.890	680	13	3
SV9	0.52	346	20%LS2	T4	0.30	5.639	0.289	8.826	660	12	18
SV10	0.55	395	20%LS2	T4	0.30	5.924	0.443	4.254	670	11	3
SV11	0.55	350	20%LS2	T4	0.30	5.924	0.292	8.705	655	13	20
SV12	0.40	410	20%LS2	T4	0.35	4.498	0.366	4.878	680	10	4
SV13	0.40	390	20%LS2	T4	0.35	4.498	0.312	5.648	670	13	3
SV14	0.40	348	20%LS2	T4	0.35	4.498	0.207	7.084	660	15	19
SV15	0.52	380	20%LS2	T4	0.35	5.639	0.395	4.970	685	10	5
SV16	0.52	355	20%LS2	T4	0.35	5.639	0.316	6.257	660	15	20
SV17	0.60	380	20%LS2	T4	0.35	6.400	0.393	4.253	670	9	6
SV18	0.60	355	20%LS2	T4	0.35	6.400	0.304	6.032	650	13	20
SG1	0.52	393	0%LS	T1	0.30	6.416	0.521	4.864	700	5	8
SG2	0.52	393	10%LS2	T1	0.30	6.416	0.521	4.536	695	5	2
SG3	0.52	393	20%LS2	T1	0.30	6.416	0.521	4.133	690	4	2

Note:

\*) These mixes had honeycombing in hardened specimens.

Shrinkage limited cement SPC2 was used in mixes from SN1 to SN38, inclusive.

Shrinkage limited cement SPC1 was used in mixes from SV1 to SV18, inclusive.

Limestone was interground in mixes SG2 and SG3.

Nga: Coarse to total aggregate ratio

Vpw: Paste volume per m<sup>3</sup> of concrete

%LS source: Percentage and source of limestone in binder

Ag: Aggregate combination

T1: Aggregates consists of river sand RS1 and coarse aggregates that include 62% of aggregate A and 38% of aggregate E

T2: Aggregates consists of river sand RS1 and coarse aggregates that include 50% of aggregate A and 50% of aggregate E

T3: Aggregate combination consists of river sand RS1 and coarse aggregates that include 40% of aggregate A and 60% of aggregate E

T4: Aggregate combination consists of river sand RS1 and coarse aggregates that include 70% of aggregate C and 30% of aggregate E

W/B: Water to binder ratio

Dav: Average diameter of aggregate particles (calculated from Eq. 8.29).

Dss: Average spacing between surfaces of aggregate particles (computed from Eq. 8.28)

SP: Superplasticizer dosage per m<sup>3</sup> concrete

Fd: Slump flow diameter

T50: Flow time for which SCC reaches a diameter of 50 cm during its slump flow test

Pd: Penetration depth used for evaluating segregation resistance of SC-HPC

### Appendix 8.2: Mixture proportions and properties of self-compacting high performance concrete containing fly ash and blast furnace slag cements (Wilton, 1998 and Mourad, 1998)

Mix No.	Nga	Vpw (l)	% Adm. type	Ag	W/B	Dav (mm)	Dss (mm)	SP (kg)	Fd (mm)	T50 (s)	Pd (mm)
OFA1	0.48	380	0%	T5	0.30	5.422	0.453	29.83	610	-	2
OFA2	0.48	380	30%FA	T5	0.30	5.422	0.453	13.09	655	-	3
OFA3	0.48	380	65%FA	T5	0.30	5.422	0.453	6.016	660	-	5
OFA4	0.48	380	0%	T5	0.35	5.422	0.453	2.383	660	-	1
OFA5	0.48	380	30%FA	T5	0.35	5.422	0.453	2.485	725	-	4
OFA6	0.50	380	0%	T6	0.30	6.833	0.592	7.406	652	-	3
OFA7	0.50	380	30%FA	T6	0.30	6.833	0.592	5.714	655	-	6
OFA8	0.50	380	65%FA	T6	0.30	6.833	0.592	8.509	690	-	8
OFA9	0.50	416	30%FA	T6	0.30	6.833	0.742	2.314	665	-	0
OFA10	0.50	458	65%FA	T6	0.30	6.833	0.933	2.283	670	-	0.5
OFA11	0.46	363	30%FA	T6	0.32	6.341	0.419	4.000	655	9	1
OFA12	0.46	350	30%FA	T6	0.32	6.341	0.373	24.00	660	20	2.7
OFA13	0.46	394	30%FA	T6	0.32	6.341	0.532	3.884	720	5	2.3
OFA14	0.40	381	30%FA	T6	0.32	5.602	0.404	4.800	685	8	2.0
OFA15	0.40	360	30%FA	T6	0.32	5.602	0.338	23.94	660	10	1.7
OFA16	0.55	365	30%FA	T6	0.32	7.449	0.532	4.000	700	8	4.7
OFA17	0.55	347	30%FA	T6	0.32	7.449	0.458	11.85	680	13	8.3
BFC1	0.48	380	30%BF	T5	0.30	5.422	0.453	4.494	660	-	3.7
BFC2	0.48	380	65%BF	T5	0.30	5.422	0.453	8.106	680	-	5.7
BFC3	0.48	380	30%BF	T5	0.35	5.422	0.453	2.800	720	-	1
BFC4	0.48	380	65%BF	T5	0.35	5.422	0.453	3.031	685	-	3.3
BFC5	0.50	380	30%BF	T6	0.30	6.833	0.592	7.886	613	-	6.3
BFC6	0.50	380	65%BF	T6	0.30	6.833	0.592	6.317	582.5	-	9
BFC7	0.50	360	30%BF	T5	0.32	5.619	0.401	5.424	715	10	6.3
BFC8	0.50	350	30%BF	T5	0.32	5.619	0.370	6.276	658	12	9.7
BFC9	0.50	370	30%BF	T5	0.32	5.619	0.433	5.484	715	10	7.0
BFC10	0.50	397	30%BF	T5	0.32	5.619	0.522	2.708	700	9	4.7
BFC11	0.60	365	30%BF	T5	0.32	6.608	0.408	2.768	680	10	2.0
BFC12	0.60	350	30%BF	T5	0.32	6.608	0.353	3.164	660	15	9.7
BFC13	0.60	392	30%BF	T5	0.32	6.608	0.510	2.600	690	7	2.0
BFC14	0.40	390	30%BF	T5	0.32	4.631	0.365	4.748	665	16	3.0
BFC15	0.40	361	30%BF	T5	0.32	4.631	0.288	11.11	670	20	2.7
BFC16	0.40	403	30%BF	T5	0.32	4.631	0.401	4.400	690	12	6.0

Note: Ordinary portland cement (OPC) was used in mixes from OFA1 to OFA17, inclusive.

Blast furnace slag cements were used in mixes from BFC1 to BFC16, inclusive.

Nga: Coarse to total aggregate ratio

Vpw: Paste volume per m<sup>3</sup> of concrete

%Adm. type: Percentage and type of mineral admixture

FA: Fly ash

BF: Blast furnace slag

Ag: Aggregate combination

T5: Aggregate combination consists of river sand RS2 and coarse aggregates that include 73% of aggregate D and 27% of aggregate F

T6: Aggregate combination consists of river sand RS2 and coarse aggregates that include 62% of aggregate B and 38% of aggregate F

W/B: Water to binder ratio

Dav: Average diameter of aggregate particles (calculated from Eq. 8.29).

Dss: Average spacing between surfaces of aggregate particles (computed from Eq. 8.28)

SP: Superplasticizer dosage per m<sup>3</sup> concrete

Fd: Slump flow diameter

T50: Flow time for which SCC reaches a diameter of 50 cm during its slump flow test

Pd: Penetration depth used for evaluating segregation resistance of SC-HPC

**Appendix 8.3: Average aggregate diameter ( $D_{av}$ ), void content, minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum required paste volume ( $V_{pdmin}$ ) considering liquid criteria (for aggregate combination T1)**

Nga	0	0.40	0.45	0.50	0.52	0.55	0.60	1
$D_{av}$ (mm)	0.694	5.095	5.646	6.196	6.416	6.746	7.296	11.70
Void content ( $l/m^3$ )	325.5	251.0	244.2	236.9	232.9	240.2	250.1	395.9
$D_{ssmin}$ (W/B=0.30) (mm)	0.422	0.427	0.457	0.487	0.498	0.575	0.735	2.017
$D_{ssmin}$ (W/B=0.32) (mm)	0.369	0.371	0.384	0.397	0.402	0.431	0.490	0.966
$D_{ssmin}$ (W/B=0.35) (mm)	0.289	0.293	0.315	0.338	0.347	0.373	0.424	0.834
$V_{pdmin}$ (W/B=0.30) ( $l/m^3$ )	837.7	411.7	401.6	391.8	387.1	405.4	437.7	625.2
$V_{pdmin}$ (W/B=0.32) ( $l/m^3$ )	812.2	393.4	379.6	366.6	360.8	368.9	383.0	523.9
$V_{pdmin}$ (W/B=0.35) ( $l/m^3$ )	762.5	366.6	357.9	349.2	344.9	353.5	367.0	508.6

Note:

- Nga: Coarse to total aggregate ratio by weight  
 $D_{av}$ : Average diameter (mm) of aggregate particles, that is calculated from Eq. 8.29.  
 Void content: Aggregate void content of compacted aggregate matrix, measured according to ASTM C29/C29M  
 $V_{pdmin}$ : Minimum required paste volume ( $l/m^3$ ) for certain coarse to total aggregate ratio (Nga);  
 $D_{ssmin}$ : Minimum required average spacing (mm) of aggregate particle surfaces calculated by using the appropriate equation from Eq. 8.30 to 8.44, inclusive; and

**Appendix 8.4: Average aggregate diameter ( $D_{av}$ ), void content, minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum required paste volume ( $V_{pdmin}$ ) considering liquid criteria (for aggregate combination T2)**

Nga	0	0.40	0.45	0.50	0.52	0.55	0.60	1
$D_{av}$ (mm)	0.694	4.763	5.272	5.780	5.984	6.289	6.797	10.87
Void content ( $l/m^3$ )	325.5	252.2	245.4	237.6	233.2	242.0	251.7	395.9
$D_{ssmin}$ (W/B=0.30) (mm)	0.422	0.422	0.437	0.464	0.475	0.492	0.590	1.775
$D_{ssmin}$ (W/B=0.32) (mm)	0.369	0.369	0.375	0.387	0.392	0.399	0.436	0.876
$D_{ssmin}$ (W/B=0.35) (mm)	0.289	0.289	0.300	0.321	0.329	0.342	0.378	0.757
$V_{pdmin}$ (W/B=0.30) ( $l/m^3$ )	837.7	420.3	405.7	395.7	390.3	395.2	417.0	616.3
$V_{pdmin}$ (W/B=0.32) ( $l/m^3$ )	812.2	402.2	386.0	372.3	366.0	369.7	379.0	521.3
$V_{pdmin}$ (W/B=0.35) ( $l/m^3$ )	762.6	373.3	360.9	351.7	347.0	353.2	363.8	506.4

Note: (see note in Appendix 8.3)

**Appendix 8.5: Average aggregate diameter ( $D_{av}$ ), void content, minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum required paste volume ( $V_{pdmin}$ ) considering liquid criteria (for aggregate combination T4)**

Nga	0	0.40	0.45	0.50	0.52	0.55	0.60	1
$D_{av}$ (mm)	0.694	4.498	4.973	5.449	5.639	5.924	6.400	10.20
Void content ( $l/m^3$ )	325.5	254.0	250.3	241.7	240.3	249.0	258.6	421.1
$D_{ssmin}$ (W/B=0.30) (mm)	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.609
$D_{ssmin}$ (W/B=0.32) (mm)	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.572
$D_{ssmin}$ (W/B=0.35) (mm)	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.522
$V_{pdmin}$ (W/B=0.30) ( $l/m^3$ )	844.1	435.2	417.7	398.4	392.7	393.4	391.9	513.4
$V_{pdmin}$ (W/B=0.32) ( $l/m^3$ )	827.7	422.3	405.6	386.9	381.5	382.7	381.9	508.4
$V_{pdmin}$ (W/B=0.35) ( $l/m^3$ )	801.8	404.2	388.7	370.9	365.9	367.8	368.1	501.6

Note: (see note in Appendix 8.3)

**Appendix 8.6: Average aggregate diameter ( $D_{av}$ ), void content, minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum required paste volume ( $V_{pdmin}$ ) considering liquid criteria (for aggregate combination T5)**

Nga	0	0.40	0.45	0.48	0.50	0.52	0.60	1
$D_{av}$ (mm)	0.678	4.631	5.125	5.422	5.619	5.817	6.608	10.56
Void content ( $l/m^3$ )	330.2	234.0	220.6	211.3	213.0	220.6	240.0	399.9
$D_{ssmin}$ (W/B=0.30) (mm)	0.437	0.437	0.437	0.437	0.437	0.437	0.437	0.609
$D_{ssmin}$ (W/B=0.32) (mm)	0.400	0.400	0.400	0.400	0.400	0.400	0.400	0.572
$D_{ssmin}$ (W/B=0.35) (mm)	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.522
$V_{pdmin}$ (W/B=0.30) ( $l/m^3$ )	849.5	415.6	390.3	375.0	371.4	372.8	374.2	495.0
$V_{pdmin}$ (W/B=0.32) ( $l/m^3$ )	833.5	402.6	377.9	363.0	359.7	361.6	364.2	489.9
$V_{pdmin}$ (W/B=0.35) ( $l/m^3$ )	808.0	384.4	360.7	346.3	343.5	345.9	350.4	483.0

Note: (see note in Appendix 8.3)

**Appendix 8.7: Average aggregate diameter ( $D_{av}$ ), void content, minimum average aggregate spacing ( $D_{ssmin}$ ) and minimum required paste volume ( $V_{pdmin}$ ) considering liquid criteria (for aggregate combination T6)**

Nga	0.00	0.40	0.45	0.46	0.50	0.52	0.55	1.00
$D_{av}$ (mm)	0.678	5.602	6.218	6.341	6.833	7.079	7.449	12.99
Void content ( $l/m^3$ )	330.2	237.2	234.3	229.8	212.0	216.4	219.1	401.1
$D_{ssmin}$ (W/B=0.30) (mm)	0.422	0.452	0.487	0.494	0.600	0.664	0.761	2.207
$D_{ssmin}$ (W/B=0.32) (mm)	0.369	0.383	0.397	0.400	0.440	0.467	0.507	1.105
$D_{ssmin}$ (W/B=0.35) (mm)	0.289	0.311	0.338	0.343	0.380	0.401	0.433	0.909
$V_{pdmin}$ (W/B=0.30) ( $l/m^3$ )	843.3	395.5	389.4	385.1	387.9	401.3	416.7	626.0
$V_{pdmin}$ (W/B=0.32) ( $l/m^3$ )	818.2	374.4	364.1	359.0	346.5	353.0	359.0	531.3
$V_{pdmin}$ (W/B=0.35) ( $l/m^3$ )	769.3	351.3	346.6	342.4	330.0	335.7	340.8	511.1

Note: (see note in Appendix 8.3)