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Mix design of rice husk ash concrete: an Australian experience

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MIX DESIGN OF RICE HUSK ASH CONCRETE -AN AUSTRALIAN EXPERIENCE

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DECLARATION

I hereby declare that the work reported in this thesis was done by me unless specified otherwise in the text, and that my part of it has not been submitted in a thesis to any other University.

Nelson Semaan

SYNOPSIS

Research carried out in various parts of the world, has led to the conclusion that rice husk ash (RHA) a pozzolanic material can be used as partial replacement for ordinary Portland cement (OPC) in making concrete.

Recently a new mix design procedure has been established in which two parameters are identified. They are the strength correlation factor, e, and the differential lubrication constant, f, both of which can be obtained by routine laboratory tests. This design procedure has been proved to be reliable for RHA produced at the Asian Institute of Technology. (AIT) in Thailand. The applicability of this new design procedure for the Australian RHA is investigated herein.

Experiments were carried out to find the two parameters for four different types of ash available from the Rice Growers Co-Operative Mills Ltd, Leeton, N.S.W. One of these four types was chosen for detailed investigation; this is known herein as Type C ash.

Conflicting results were obtained in the characteristics of the local RHA which affected the applicability of the said mix design procedure. The values of standard consistence of the Australian RHA are considerably higher than those of the AIT RHA. This rendered the mix design procedure unworkable. Some other differences between the Australian and AIT ashes, such as relative density, fineness and water absorption, also affected the reliability of the mix design procedure.

Based on the experimental data obtained in this study, a new mix design procedure is introduced for the use of Type C RHA in concrete. The proposed design aids consist of graphs for strength and wet densities, as well as tables for workability (slump) and free water content. Illustrative design examples are given.

The performances of the Australian RHA in concrete is examined. It is found that the compressive strength of the RHA concrete with 50% volume replacement of cement by RHA is higher than the comparable ordinary cement concrete by 2% to 11% for the four types of RHA. Type C is the most strength-effective.

Durability tests were also carried out. This led to the conclusion that RHA concrete is less prone to acid attack than comparable OPC concrete. The improvement is considerable.

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NOTATION

A	= Total aggregate content
A_c	= Coarse aggregate
A_f	= Fine aggregate
C	= Weight of OPC
c	= Subscript denoting OPC or OPC concrete
D	= Wet density of RHA concrete
e	= Strength Correlation Factor
f	= Differential Lubrication Constant
LA	= Free water for lubrication of Aggregate
LC	= Free water for lubrication of Cement
R	= Weight of RHA-Cement
r	= Subscript denoting RHA cement or RHA concrete
S_c/C	= Standard consistence of OPC
S_r/R	= Standard consistence of RHA cement
W	= Amount of free water in a concrete mix
W_c	= Weight of the free water in the reference concrete.
W_r	= Weight of the free water in the RHA concrete.
W/C	= Water/cement ratio for OPC concrete
W/R	= Water/RHA cement ratio for RHA concrete

TERMINOLOGY

OPC	= Ordinary portland cement
RHA	= Rice husk ash
OPC concrete	= Ordinary portland cement concrete
RHA concrete	= Rice husk ash cement concrete
S.C.	= Standard consistence
S.G.	= Specific gravity
DOE	= Department of the Environment
AS	= Australian standard
BS	= British standard

AIT = Asian Institute of Technology.

Note: the symbols in the appendices are defined as they first appear.

CHAPTER 1 - INTRODUCTION

1.1 General Remarks

According to the Food and Agricultural Organisation (1976), the world's annual production of paddy is around 300 million tonnes (ref. 10). From this amount about 60 million tonnes of husks are produced. If undisposed of, the husks would occupy about 600 million cubic meters of storage space. From a current estimate, approximately 150,000 tonnes of husks are generated annually in the rice growing regions of NSW, Australia. Due to their abrasive character, poor nutritive value, very low bulk density, and high ash content only a portion of the husks can be used as chicken litter, juice pressing aid, animal roughage and pesticide carrier. The remaining husks are transported back to field for disposal, usually by open field burning, (Mehta and Pirtz, 1978).

In Australia, RHA is used in the following areas:

a. Filter media, filter air and decoloring.

b. Insecticide powders.

c. Spill absorbing or sweeping compounds.

d. Insulating/refractory application.

e. Ceramic applications (porosity control).

f. Silica source.

g. Sludge dewatering aid for effluent treatment.

Research works carried out in many countries, including Australia, [Mehta and Pitt 1976; Mehta 1977; Mehta and Pirtz 1978; Loo et al 1984; Ismail 1982; We 1981; Yamamoto 1982; Cook 1984] have led to the conclusion that rice husks, if properly burnt and ground down to a certain fineness can yield a reactive ash which is suitable for partially replacing cement in making concrete. This is because as high as 85% to 95% of the ash by weight is silica (SiO_2) and most of which is reactive depending on the burning

process amongst other factors. Mehta (1977) was one of the first to report that mortar of even higher strengths than the control specimens could be produced by including 30% to 70% of RHA.

Weragama (1984) has shown that a 50% volume replacement of cement by RHA in concrete can yield strengths higher than that using only ordinary portland cement (OPC). Mehta and Pirtz (1978), Yamamoto (1982), and Weragama (1984) have proved that this new cement (RHA cement) demands a higher free W/C ratio than the OPC.

1.2 Objectives and Scope of Study

It is now evident from the literature that RHA is used as partial replacement for cement in concrete and mortar in some developing countries. Because RHA can successfully replace 50% OPC by volume (35% to 45% weight replacement or even higher), it can prove to be economical for the construction industry in the developing countries. It has also been proved to reduce the heat of hydration in mass concrete. RHA - cement paste also has a better resistance to acidic environment than the comparable OPC concrete.

The properties of RHA vary with locality and depend very much on the manufacturing processes, including the burning process and the grinding process (if applicable). This variability in the properties of the ashes opens up the way to do research on the N.S.W. RHA's.

This study can be divided into three main phases. Throughout this research the ratio of RHA and OPC used was 50% by volume. The objective of the first phase was to determine the values of the strength correlation factor, e, and the differential lubrication constant, f, for the four types of RHA from the Riverina (Leeton/Griffith) area of N.S.W. An attempt is then made to incorporate these values in the mix design method developed by Loo and Weragama (1985).

The second phase deals with the performance of the Australian RHA in concrete. The four types of RHA, supplied by the Rice Growers Pty Ltd, were different in colour, fineness, specific gravity and carbon content. They are called Type A,B,C and D respectively. In addition to having a very dark colour, they all have lower strengths and absorb more water than Type C. Type C RHA has a grey (OPC) appearance, a very low carbon content (1.9%) and the highest specific gravity (2.10). It also gave a better workability and compressive strength than the rest. New design aids for using Type C RHA in concrete were obtained. These design aids are based on numerous laboratory tests.

In the third phase, durability tests were carried out for the RHA concrete specimens, following the same approach as other researchers (Mehta (1977), We (1981) and Weragama (1984)). Results have shown that RHA concrete is more resistant to acid attacks than OPC concrete.

1.3 Literature Review

Mehta and Pitt (1976) developed a process of converting rice husks into energy and valuable industrial products. The X-ray diffraction analysis they carried out showed that no crystalline phases of silica, such as cristabalite, tridymite and quartz were present. Chemically, in addition to silica, the ash contained some residual carbon and a small amount of alkalies. They concluded that hydraulic cements with strength characteristics similar to OPC can be made from the rice husk ash.

Loo, Nimityongskul and Karasudhi (1984) presented a simple method of burning rice husks in a ferrocement incinerator. Also, for grinding RHA a newly developed device is introduced. It is built to use readily available components, such as an oil drum and low horse-power electric motor. The device is inexpensive and proved

extremely efficient. The procedure is well suited for adoption in the rural areas of developing countries.

Yamamoto and Lakho (1982) studied the effect of the existence of carbon in RHA. They revealed that carbon, in its free form, can be removed by further burning and further grinding. The removal of this carbon enhanced considerably the activity of the ash. They also stated that rapid cooling also improved the activity of the ash.

Cook et. al. (1976) reported that RHA conforms to ASTM C618-72 standard specification for fly ash and raw calcined natural pozzolans for use in Portland cement concrete. However, this conformation depends on the fineness and method of burning of the RHA. The pozzolanic activity index of ordinary Portland cement is the ratio of the compressive strength of OPC to RHA concrete of the test specimen at 28 days. Azam (1982) stated that the pozzolanic activity index depends very much on the fineness of the RHA. It increases with increased fineness of the ash. For 75% and 85% fineness*, the pozzolanic activity index is lower than the minimum limits specified for ASTM class N, F and C pozzolana. For 85% to 95% fineness it is higher than the ASTM minimum requirement for the three classes of pozzolana.

Rice husk ash, in addition to being a partial substitute for OPC for economic reasons, can be used to reduce the heat of hydration in mass concrete. It was shown by Mehta and Pirtz (1978) that for a 28 day period, with 30% weight replacement of OPC by RHA, it is possible to reduce the temperature by approximately 20% . These mean that a considerable amount of money could be saved in two areas. One, the cement content is reduced and two the cooling cost of concrete is also reduced or eliminated, both of which would lead to considerable saving in mass concrete construction.

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* Footnote: percentage by weight passing #325 sieve.

We (1981) concluded that the compressive strength of RHA concrete at various ages and with different cement contents was reduced when the RHA is present in large amount in lean mixes. However, there is an increase in the amount of water needed to meet a specified consistency which in effect increases the water/cement ratio. Thus, RHA is particularly useful in lean mixes.

Loo, Nimityongskul and Karasudhi (1984) compared the structural performance of five RHA concrete beams to those of OPC concrete. They reported that the experimental ultimate moments of RHA concrete beams were comparable to those of OPC concrete beams, where the difference was insignificant. Both the RHA and OPC concrete beams were found to be generally higher than the values of moments calculated according to ACI 318-77 (ref. 8). It was also observed that in almost all comparisons the RHA concrete beams had slightly higher creep deflections than the normal concrete beams.

Mehta (1977) compared the durability of OPC concrete to RHA concrete. Two cylinders, one of OPC concrete and the other of RHA concrete were submerged continuously in a 5% HCl solution for a period of 63 days. He found that OPC concrete registered 35% weight loss during the test period, and RHA concrete showed only 8% weight loss.

For RHA concrete mix proportioning, Loo and Weragama (1985) introduced two design parameters. They are f, the differential lubrication constant and e, the strength correlation factor. Both constants can be incorporated in any established mix design procedure for OPC concrete. As an example they made use of the British Department of the Environment (DOE) and Murdock mix design methods (ref. 12 and 16) to produce the required RHA concrete. The writer concluded that with 50% replacement by volume, the increase in strength was 11%.

CHAPTER 2 - THEORETICAL CONSIDERATION

2.1 Introduction

Rice husk ash, like pulverised fuel ash or fly ash, is an artificial pozzolan. In finely divided form and in the presence of moisture, it chemically reacts with calcium hydroxide $Ca(OH)_2$ at ordinary temperatures to form compounds possessing cementitious properties. The reactivity of RHA depends on various factors including the burning process, fineness and carbon content.

The hydration process of RHA cement has a great effect on the resistance of RHA concrete to acidic attack. In simple terms, RHA reacts with $Ca(OH)_2$, which is a by-product of OPC hydration, to form calcium silicate hydrates (C-S-H). This reduction in the amount of free lime in concrete leads to a great increase in resistance to attacks by acidic solutions.

Variables and parameters that control the characteristics of RHA cement and concrete are discussed in this chapter.

2.2 Strength Correlation Factor, e

Smith (1967), has introduced an efficiency factor, K, for fly-ash in the design of fly-ash concrete. Smith's efficiency factor may not be applicable to RHA concrete due to the differences in strength and water requirement characteristics of the two cement blends.

Loo and Weragama (1985), following a similar concept, proposed a design parameter called the strength correlation factor, e for the RHA concrete which is given as

$$e = (W/R)/(W/C) \qquad (2.1)$$

where, W/R is the water/RHA cement ratio
W/C is the water/cement ratio which gives the same strength as that of W/R ratio.

The value of e can be obtained by routine laboratory tests.

Equation (2.1) appears to be general and can be applied to all pozzolanic materials. For a given blend of RHA cement, once the curves of compressive strength versus W/C ratio for both the RHA concrete and OPC concrete are plotted, the e values can be easily evaluated.

In this study, equation (2.1) is adopted throughout to relate the strength of RHA concrete to that of OPC concrete having the same W/C ratio.

2.3 Differential Lubrication Constant, f

The amount of free water, W, in any concrete mix may be considered to comprise two parts:

a) the part required by the cement to reach standard consistence or that which causes the chemical reactions enabling setting and hardening to proceed, and

b) the part which provides workability for the fresh concrete.

Loo and Weragama (1985) have illustrated the functions of the free water as follows:

Free Water (W)

For reaching standard consistence (S)

For lubrication of consituents (L)

For lubrication of cement (LC)

For lubrication of aggregate (LA)

Representing the above in simple equations, we have

$$L = LC + LA \qquad (2.2)$$

and

$$W = S + LC + LA \qquad (2.3)$$

By writing equation (2.3) for the reference OPC concrete* and for the RHA concrete separately, it gives

$$W_c = S_c + LC_c + LA_c \qquad (2.4)$$

and

$$W_r = S_r + LC_r + LA_r \qquad (2.5)$$

By rearranging these equations and identifying some constants,a general basic formula for the so-called differential lubrication constant, f, is obtained, where:

$$f = (W_c - W_r + S_r - S_c)/C \qquad (2.6)$$

in which, W_r is the water required to give a workability equal to that of the reference OPC concrete which has W_c as its free water content. S_r and S_c are the weights of water required to provide the standard consistences of the RHA cement and OPC respectiv

The proposed design parameter, f, may be used in conjunction with any established mix design procedure for OPC concrete. As an example, Loo and Weragama incorporated f in the British Department of the Environment method and Murdock's design method for OPC concrete to obtain mixes of desired workability.

The value of f can be obtained by routine laboratory tests. However, the application of equation (2.6) depends very much on the standard consistence value of RHA cement (or S_r).

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*Footnote: The reference OPC concrete is that which gives the same workability as the RHA concrete (see ref. 7).

† f is constant for a given blend of RHA cement.

Applying Loo and Weragama's design procedure, the following equation is used to find the amount of free water for lubrication of aggregate

$$LC_r + LA_r = W_r - S_r \qquad (2.7)$$

in which, LA_r = free water content for lubrication of aggregates
LC_r = free water content for lubrication of RHA
W_r = free water content of the RHA concrete
S_r = weight of water required to achieve standard consistence of RHA cement

However, when the value of S_r is higher than W_r, the breakdown of equation (2.7) occurs because a negative value of LA_r will result. This will reduce inadvertently the W/C ratio of OPC leading to a very dry mix with a high cement content. A sample example of Loo and Weragama's design procedure is shown in Appendix A.

For equation (2.7) to be universally applicable, S_r/R has to be within the range of approximately 0.3 - 0.58, to avoid any breakdown in the procedure. Equation (2.7) is adopted in this study as it seems to be very general and appears to be applicable to all pozzolanic materials within the range of 0.3 - 0.58 for S_r/R.

2.4 Effects of Carbon in RHA

Carbon in RHA is the reason for the blackish colour the ash exhibits. Yamamoto and Lakho (1982) reported that the blackish ash grains, which were sorted out from the ashes obtained by burning rice husks at 400°C for 4 hours, had inferior quality compared to the whitish ones. They then removed the carbon from the black ash by further burning at the same temperature as before for one hour. The residue was a whitish (or light grey) ash similar to the earlier extraction. The result was that the quality

of the reburned ash was improved remarkably to reach the same level as that of the companion whitish portion. This indicated that the existence of carbon in RHA is not beneficial and it is possible to remove it by the reburning process. It was claimed by Ismail (1979) that carbon content in RHA exceeding 10% reduced the overall activity of the ash. However, Mehta and Pitt (1976) stated that the presence of some well dispersed carbon atoms in silica is believed useful in stabilising the disordered structure of silica in a manner analogous to the stabilisation of martensitic structure in the physical metallurgy of iron and steel. Within limits, the presence of some carbon in silica ash, therefore may help rather than hurt the performance of the material in many applications, such as the use of RHA as a semi-reinforcing agent for rubber compounds and as an ingredient of hydraulic cement.

Yamamoto and Lakho (1982) also found that the rate of increase in the activity of the black ash was enhanced by additional grinding. Another factor, which affects the activity of RHA is the rate of cooling. Rapid cooling is required for the production of more active RHA.

Cook (1984) claimed that the ash reactivity is reduced if the carbon content exceeds 15% . The presence of carbon can mask the influence of the pyroprocessing parameters on ash reactivity.

2.5 Acid Attack

The chemical composition of a typical sample of RHA may be given as follows:

oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	loss
percentage	93.15	0.41	0.20	0.41	0.45	0.08	2.31	2.77

In the hydration of ordinary Portland cement, calcium silicate hydrates

$3CaO.2SiO_2.3H_2O$, or in short (C-S-H) are formed liberating $Ca(OH)_2$. The latter reacts with the reactive silica in the RHA to form further C-S-H. The chemical reactions may be represented by the following equations:

$$2(3CaO.SiO_2) + 6H_2O \rightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2$$

$$2(2CaO.SiO_2) + 4H_2O \rightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2$$

$$3Ca(OH)_2 + 2SiO_2 \rightarrow 3CaO.2SiO_2.3H_2O$$

With regard to the durability of cement paste to acidic attack, it may be noted that OPC contains 60-65% CaO and, upon hydration, a considerable portion of lime is released as free $Ca(OH)_2$, which is primarily responsible for the poor performance of OPC concrete in acidic environments. RHA cement, on the other hand, may contain as low as 20% CaO. Further upon hydration of the RHA cement, RHA reacts with the released $Ca(OH)_2$ to form more products of C-S-H. Therefore, RHA cement paste is more resistant to acid attacks. Its resistance to acid attack makes it useful as a material of construction for applications in some chemical environment.

CHAPTER 3 - EXPERIMENTAL STUDY

3.1 Introduction

The experimental study conducted in this thesis project may be divided into three phases:

(1) The first phase involved the determination of the two mix design parameters, the strength correlation factor, e, and the differential lubrication constant, f, for each of the four types of Australian RHA.

(2) In the second phase, a series of tests were conducted with the main aim of developing new design aids for the Australian RHA concrete, following the same approach as the DOE design method.

(3) The third phase included a durability study of the Australian RHA concrete, by carrying out acid attack tests on RHA and OPC concrete cylinders.

3.2 Rice Husk Ash

The RHA 's used in the present research were supplied by Griffith's Biocon, a division of Ricegrowers' Co-operative Limited in N.S.W. All the products of RHA are formed from the controlled combustion of rice husks and subsequent size grading. The four types of ash were different in appearance, fineness, specific gravity and carbon content. For the sake of identification, they are referred to as Types A, B, C and D respectively. They had two different colours, (three) black and (one) grey. Chemical composition tests were carried out with the help of the Departments of Chemistry and Geology at the University of Wollongong. The results are shown in Table 3.1*. It is obvious by comparing Tables 3.1 and 3.2 that the compositions are very similar to

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* Footnote: All tables and figures are presented at the end of the chapter.

RHA's from other countries. Table 3.2 (Loo and Weragama, 1985) contains samples of RHA collected from different places mainly in Asia.

Types A and D are known to have low carbon content. They are both by-products from a fluidised bed combustor. Typical particle size distributions are shown in Table 3.3.

Type A is a black ash with amorphous particles and fine surface, whilst Type D is a black ash with semi-crystalline particles and rough surface (ref. 1). Two specific gravity tests per RHA type were carried out. The specific gravity values of Types A and D are 1.72 and 1.88 respectively. Some of the properties of low carbon content RHA, such as water absorption, water solubility and so on, are shown in Table 3.4.

Type B RHA is resulted from a mechanically fluidised furnace (fig. 3.1), where ashes with high carbon content are usually obtained. The combustion unit which is designed and constructed locally, is known as the K.C. Reactor (see fig. 3.1). A typical particle size distribution is shown in Table 3.3. Type B is a black ash with amorphous particles and rough surface (ref. 1). Its specific gravity is 1.60. Types A, B and D, all have higher water absorbent characteristics than Type C. This will be shown in chapter 4, where Type C RHA concrete exhibited higher workability than others for the same W/R ratio.

Type C has shown better characteristics than others, i.e. low water absorption, better workability and slightly higher compressive strength. It has a low carbon content (1.9%), and high specific gravity (2.10). Its brand name is AMOSIL SILICA which is a free flowing high silica granular solid, grey in colour, with a typical size of 25 - 300 microns.

3.3 Other Materials

3.3.1 Portland cement

Ordinary Portland cement, Blue Circle brand, type A was used throughout the whole testing program.

3.3.2 Fine aggregates

Natural, washed, beach sand with maximun aggregate size passing 2.36mm sieve was used for all mixes. The sand is washed by the supplier to eliminate all organic matters as well as salt. Sieve analysis results are tabulated in Table 3.5. A typical grading curve of sand is shown in Fig. 3.2. Beach sand is usually used commercially in Australia. The sand belonged to grading zone 4 according to BS882: 1973. Table 3.6 gives the ranges for different grading zones for sand (Neville 1981).

Crushed basalt having 5mm maximum size was also incorporated as fine aggregate, as the sand was considered too fine. A proportion averaging 40% of the total aggregate content is taken to be fine aggregage throughout the study. Sieve analysis results of the 5mm aggregate are shown in Table 3.7. A typical grading curve of the 5mm aggregate is shown in Fig. 3.3.

Water absorption tests for the two fine aggregates were conducted according to AS1141, Sect. 5 - 1974. The water absorption capacity of sand is 2.0% and for 5mm aggregate is 1.1%.

3.3.3 Coarse aggregates

Crushed basalt with sizes of 10, 20 and 40mm were used in this study. Water absorption tests were carried out, following AS1141, Sect. 6 - 1974. These gave an average absorption capacity of 1.1% for the basalt aggregates. Sieve analysis test for coarse aggregates was based on AS1141.11 - 1980.

3.3.4 Mixing Water

Fresh tap water was used throughout the experimental programme.

3.4 Fineness of RHA

Fineness has been proved to influence the properties of RHA. These include the specific gravity, moisture content, pozzolanic activity indices with both OPC and lime, water requirement, workability and compressive strengths of both RHA cement and RHA concrete.

We (1981) and Weragama (1984) of the Asian Institute of Technology, Bangkok proposed the use of a 45μm sieve for determining the fineness of RHA. This was done by wet sieving analysis of the RHA, which does not react with water.

In this study, some of the ashes supplied were not fine enough to suit the requirements specified by the AIT group. Further grinding of the ashes was not carried out due to the lack of equipment in the laboratory. Type C RHA is finer than the others, about 92% of the ash passed the 75μm sieve. Fineness was determined by wet sieving test according to the AS1141, Sect. 12 - 1974. One fineness test per RHA type was carried out. A mass portion of 500g was placed in a pan, and sufficient clean potable water was added to cover it. The contents of the pan were agitated vigorously, taking the fine material into suspension, and the wash water was immediately poured through a pair of sieves, a 1.18mm test sieve and a 75μm test sieve nested together with the 1.18mm sieve on top.

The material retained on the nested sieves were returned to the washed sample and repeat the washing operations with clean water until the wash water was clear.

The washed particles were dried at a nominal temperature of 105°C and the mass of the dried particles was determined to the nearest 0.1 percent.

3.5 Standard Consistence and Setting Time

Standard consistence is an indication of the initial chemical reaction. Some ash is more or less reactive than the others. Experiments, to determine the standard consistence values of various blends of RHA cement (or various percentage replacements of OPC by RHA), were conducted. Standard consistence and setting time tests were carried out according to AS2350.3 - 1980. The replacement of OPC by RHA ranged from 0 to 80% by weight.

The standard consistence and setting time were determined using the following procedure:

a) 600g of the sample were weighed and transfered directly from the balance pan to the 4.5L bowl of the mixer unit. Then the amount of water needed was placed near the mix. The mixer was set at a low speed of 140 ± 5 rpm Then the water is poured rapidly over the lip of the bowl.

b) Timing was started while the water was being poured. The bulk of water should be transferred to the bowl within 1.5 seconds. Mixing was continued for 2.5 min. from the addition of water, then the mixer was stopped.

c) A paste was formed into a ball in the rubber-gloved hand. The ball was pressed into the larger end of the Vicat mould, completely filling the mould with paste. Excess was striked off with the trowel.

d) The filled mould was centered on its glass plate under the plunger on the Vicat apparatus. The lower end of the plunger was brought into contact with the surface of the paste and clamped by means of a set-screw. The set-screw was released and settlement, of the plunger on the expiration of 30 seconds was noted.

e) The paste would be of normal consistency when the proportion of water was such as would give a settlement of the plunger to a point of 5mm to 7mm from the bottom of the cement paste in 30 seconds after being released as described above.

The same procedure was used for determining initial and final setting time. However, the time elapsed between the addition of the water and the first refusal of the needle to penetrate the paste to within 1mm of the surface of the glass plate 30 seconds after release as described, is the time of initial set. The time elapsed between the addition of water and the first refusal of the needle to penetrate the paste more than 0.5mm is the time of final set.

This procedure was repeated as necessary as required per blend of RHA cement, until reliable results were obtained.

3.6 OPC and RHA Concrete Mixes

In the first part of the work, a total of six standard cylinders were cast for each of the six different mixes in both OPC and RHA concretes. From these, three cylinders were tested in compression at 14 and 28 days for each of the two types of concrete. For type C RHA, tests were also carried out at 90 days. To be consistent, identical types of fine and coarse aggregate were used throughout the study. There were four different aggregate sizes used in the mixes of the first part of the work. The 10 and 20mm aggregates were used as coarse aggregate. The 5mm aggregate was used with the beach sand as fine aggregate. The 40mm basalt aggregate was used in the second part of the study, where a new aids procedure for Australian RHA concrete was to be established.

The proportioning of the aggregates in the first part of the work was done by trial and error, as the two parameters e and f would have to be found before Loo and Weragama's (1985) mix design procedure could be used. The replacement of OPC by

RHA was 50% by volume throughout. The proportion by weight of the RHA concrete with a constant free water ratio is shown below.

	Binder		Fine & Coarse Aggregate			
Water	OPC	RHA	Sand	5mm	10mm	20mm
0.75	0.6	0.4	1.5	0.5	1.0	2.2

Compaction was done by an electric vibrating table so that adequate compaction is achieved. An air void test showed only 1% air void content. As a result of this phase, the strength correlation factor, e, can be obtained. When plotting the curves of compressive strength versus W/C ratio or W/R ratio for both the OPC and RHA concretes on the same graph, each curve will show a different W/C or W/R ratio for a particular strength. This analogy was made useful by Loo and Weragama (1985) in comparing the compressive strengths of RHA concrete and OPC concrete.

3.7 <u>Determination of Lubrication Constant, f</u>

The values of lubrication constant were obtained from routine laboratory tests. Four mixes were carried out aiming at finding the free water content or W/R ratio of RHA concrete which would give the same slump as that of the OPC concrete having a given W/C ratio. The water/binder ratios found, for both the OPC and RHA concretes with similar workabilities, were supplemented by the values of S_C and S_r (standard consistence for OPC and RHA cements respectively) to determine the difference in quantities of water required for lubricating the OPC and RHA cements. It was found that to obtain a slump of 50mm equal to that of the OPC concrete, having a W/C ratio of 0.48, the W/R ratio of the RHA concrete was 0.80; this is for RHA type C only.

The procedure used to determine the lubrication constant, f is outlined below:

OPC(Weight C).

free water $W_c = 0.48C$

$S_1 = 0.255C$

$L_c = W_c - S_1$
$= (.48 - .255)C$
$= 0.225C$

RHA(Weight R).

free water $W_r = 0.80R$

$S_r = 0.71C$

$L_r = W_r - S_r$
$= (0.80 - .71)R$
$= 0.09R$

But $$R = 0.5C + 0.5 \times \frac{2.10}{3.15}C$$
$$= 0.833C$$

therefore $$L_c - L_r = 0.225C - 0.09(0.833)C$$
$$= 0.15C$$

But, $$f = [(W_c - S_c) - (W_r - S_r)]/C$$
$$= (L_c - L_r)/C$$
$$= \frac{0.15C}{C}$$

therefore, $f = 0.15$.

The f values of all ashes were calculated following the same procedure as above.

3.8 Acid Attack Tests

Three concrete cylinders were submerged continuously for a period of 90 days, in a 5% solution of HCl acid. Two of them were RHA concretes with 0.80 W/R ratio for type B and 0.70 W/R for type C, and one OPC concrete with 0.48 W/C ratio.

The cylinders were checked every 30 days. All the samples showed a weight loss. The weight loss of OPC concrete was about 2.5 times that of RHA concrete despite the much lower W/C ratio. Other observations were also noted.

Results are shown and discussed in the next chapter. It should be mentioned that other researchers (Mehta 1977, We 1981), following the same procedure, have also tested only three cylinders for the same experiment.

3.9 Design Aids

For the purpose of establishing new design aids for using the Type C RHA in concrete, numerous RHA concrete mixes were cast and tested. In the test programme, three different maximum aggregate sizes were used. They were 10, 20 and 40mm. Four different ranges of slump were adopted, namely 0 - 10mm, 10 - 30mm, 30 - 60mm and 60 - 180mm. These various slumps were calculated for each of the three maximum aggregate sizes used. The wet density values for different ranges of water content were also obtained. Graphs for the wet density versus free water content are plotted for each maximum aggregate size.

Table 3.8 shows the proportion by weight of all the RHA concrete mixes in the second phase of the study. All the other constituent ratios were kept constant; water content was the only variable.

The design aids followed the same approach as the DOE method (ref. 16). Two basic reference tables for both compressive strength and approximate water content for a required slump were obtained (see tables 5.1 - 5.2). Also graphs for the wet density versus free water content for each maximum crushed aggregate size used were plotted.

TABLE 3.1 CHEMICAL COMPOSITION OF RHA †

TYPE NO	A*	B	C	D	E*
Silica as SiO_2	94.90%	94.5%	93.95%	93.9%	95.59%
Aluminum as Al_2O_3	0.49%	0.90%	0.69%	0.45%	1.97%
Iron as Fe_2O_3	0.20%	0.30%	0.35%	0.20%	0.12%
Calcium as CaO	0.63%	0.99%	1.18%	0.62%	0.17%
Magnesium as HgO	1.01%	0.67%	0.8%	1.0%	0.21%
Sodium as Na_2O	0.018%	0.016%	0.066%	0.12%	0.08%
potassium K_2O	2.62%	3.12%	2.99%	2.6%	1.21%
Manganese as MnO_2	0.21%	0.32%	0.32%	0.2%	0.13%
Phosphorus as P_2O_5	0.49%	0.65%	0.72%	0.49%	0.30%
Sulphur as SO_3	0.05%	-	-	0.05%	0.05%
Titanium as TiO_2	0.08%	0.02%	0.02%	0.08%	0.08%
Carbon	0.4%	28.4%	1.9%	3.65%	-

* Types A and E are the same ash. Type E is analysed by the Supplier while Type A is analysed by the Department of Geology at the University using X-Ray diffraction.

† The following heavy metals also exist in RHA:

lead	less than 5 ppm
cadium	less than 0.05 ppm
copper	approx. 9 ppm
zinc	approx. 35 ppm

Table 3.2 Chemical Composition of RHA

Sample No.	Ignit loss	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	P_2O_5	Total
1.	2.99	92.96	0.14	0.05	0.01	0.45	0.19	0.29	2.38	0.29	99.75
2	4.18	91.69	0.14	0.06	0.01	0.58	0.26	0.09	2.54	0.52	100.07
3	4.35	88.29	2.33	0.51	0.07	0.79	0.32	0.67	2.42	0.42	100.17
4	2.61	92.94	0.17	0.11	0.01	0.72	0.34	0.27	2.29	0.38	99.84
5	5.63	89.99	0.84	0.50	trace	0.67	0.65	0.69	0.94	0.53	99.84
6	1.30	95.75	0.33	0.13	-	0.18	0.13	0.30	0.22	-	98.34
7	0.96	95.64	0.14	0.06	0.01	0.36	0.35	0.27	1.87	0.62	100.28
8	0.52	95.60	0.18	0.05	trace	0.31	0.51	trace	2.14	0.74	100.05
9	0.50	97.12	0.14	0.04	trace	0.31	0.35	0.04	1.11	0.37	99.98
10	3.40	92.64	0.19	0.06	0.01	0.40	0.41	0.10	1.91	0.86	99.98
11	3.36	91.66	0.27	0.06	0.01	0.58	0.64	0.02	1.98	1.47	100.05
12	32.84	65.20	0.14	0.14	0.01	0.36	0.09	0.13	0.77	0.20	99.87
13	12.06	85.18	0.20	0.32	0.01	0.22	0.40	0.08	0.96	0.46	99.89
14	9.20	79.50	5.43	0.11	-	0.28	0.15	1.07	0.09	-	95.83
15	5.04	91.26	0.58	0.60	0.09	0.54	0.32	1.04	trace	0.45	99.92
16	-	86.90	-	trace	-	0.20	0.12	0.0	0.58	0.20	
17	1.91	93.20	0.59	0.22	-	0.51	0.41	0.05	2.93	-	99.82
18	3.05	92.36	0.66	1.05	-	0.53	0.27	0.06	1.62	-	99.60
19	0.28	91.16	0.51	0.86	-	0.57	0.24	0.07	2.88	-	96.57

Cont'd next page

TABLE 3.2 COMPOSITION OF RHA

Origin and brief description of samples:

1. Tosu, Saga-ken, Japan, 1980. RH was first let smouldering for a few minutes in a gas-burnt frying pan. The 'charred' RHA was further heated at 600° for 15 minutes.
2. RH from the crop of 1981 in Tosu was treated as sample 1.
3. Tosu, Japan 1980. A small pile of RH was burnt with a small chimney located at the center of the pile.
4. Miwa-machi, Fukuoka-ken, Japan. Obtained from a cylone burner.
5 Sapporo, Japan. Obtained from a fluidised- bed burner at 650°C.
6. Kelang, Malaysia. Open-field burnt white ash.
7. Tanjong Karang, Malaysia, 1980. Open-field burnt white ash.
8. Sampled at the same locality as sample 7 but in 1981.
9. Sampled at the same locality as sample 7 but in 1982.
10. Selangor, Malaysia. RH was first let smouldering at 350∞C for one minute, and then further heated at 600°C for 15 minutes.
11. Kelantan, Malaysia. Open-field burnt RHA.
12. Malaysia. Black ash from a 'Yamamoto' burner.
13. Malaysia. Black ash from a 'Philippine' burner.
14. Kedah, Malaysia. Black ash from a RH boiler.
15. Grey ash from Jawa, Indonesia.
16. Data summarised by D F Housten, 1972. Rice Chemistry and Technology, American Association of Cereal Chemists.
17. RHA produced by the Building Research Institute Roorkee, India.

Table 3.2 (cont'd)

18. Type A, grey ash produced by the Asian Institute of Technology (AIT) process, 1983 with a Blaine specific surface of 14410cm^2/g.

19. Type B, blackish grey ash produced by the AIT process, 1983 with a Blaine specific surface of 12450cm^2/g.

TABLE 3.3 TYPICAL PARTICLE SIZE DISTRIBUTIONS

*Fluidised Bed Combustor Low Carbon Ash			**Mechanically Fluidised Furnace High Carbon Ash		
Size Range (μm)	Screen Analysis (% by weight)		Size Range (μm)	Screen Analysis^ (% by weight)	
	Bulk Density 390 Kg/m^3 (Types A & D)	Bulk Density 480 Kg/m^3 (Type C)		Bulk Density 200 kg/m^3 (Type B)	Bulk Density 300 kg/m^3
300	0.7	3.4	300	53.20	24.3
180-300	8.1	1.7	180-300	24.70	33.7
125-180	19.6	4.3	125-180	16.10	23.50
90-125	19.9	16.9	90-125	3.0	9.40
45-90	40.2	44.0	45-90	2.6	7.50
45	11.4	29.7	45	0.70	1.60

* Types A,C and D RHA

** Type B RHA

^ Produced by the supplier but not included in the study

TABLE 3.4 PROPERTIES OF TYPES A AND D RHA

water absorption	170 cm^3/100 g
oil absorption	180 cm^3/100 g
water soluble	1.1%
PH of 10% water slurry	9.0
loss on drying @ 140 °C	0.1%
loss on ignition @ 1000°C	1.0%

TABLE 3.5 GRADING AND FINENESS OF SAND

Sieve Size	Weight Retained (gm)	Weight Retained %	% age passing
4.75 mm	0	0	100
2.36 mm	0	0	100
1.18 mm	1.0	0.29	99.71
600 mm	19.2	5.5	94.21
300 mm	211.4	61.5	32.71
150 mm	107.8	31.36	1.35
75 mm	4.32	1.26	0.09
		Sum	428.07 %

Table 3.5 (cont'd)

$$\text{Fineness of Sand} = \frac{\text{\% age passing}}{100} = \frac{428.07}{100} = 4.28$$

TABLE 3.6 GRADING REQUIREMENTS FOR FINE AGGREGATE ACCORDING TO THE B S882: 1973

Sieve Size	Percentage by Weight Passing			
	Grading Zone 1	Grading Zone 2	Grading Zone 3	Grading Zone 4
9.5 mm	100	100	100	100
4.75 mm	90-100	90-100	90-100	95-100
2.36 mm	60-95	75-100	85-100	95-100
1.18 mm	30-70	55-90	75-100	90-100
600 mm	15-34	35-59	60-79	80-100
300 mm	5-20	8-30	12-40	15-50
150 mm	0-10	0-10	0-10	0-15

TABLE 3.7 SIEVE ANALYSIS OF 5mm BASALT AGGREGATE

Sieve Size	Weight retained (gm)	% retained	% passing
8 mm	0.0	0.0	100
4.75 mm	326.3	27.61	72.39
2.36 mm	778.6	65.88	6.51
1.18 mm	70.5	5.96	0.55
600 mm	4.2	0.35	0.20
300 mm	0.8	0.07	0.13
150 mm	0.8	0.07	0.06
75 mm	0.5	0.04	0.02

Fineness Modulus of 5 mm agg. $= \frac{\% \text{ passing}}{100}$

$= 0.79$

TABLE 3.8 TYPICAL EXPERIMENTAL MIX DESIGN USED FOR THE DESIGN AIDS

Mix	Binder		Fine and Coarse aggregates				
	OPC	RHA	Sand	5mm	10m	20m	40m
1	0.6	0.4	1.5	0.5	2.0	-	-
2	0.6	0.4	1.5	0.5	1.0	2.0	-
3	0.6	0.4	1.5	0.5	1.0	1.5	2.0

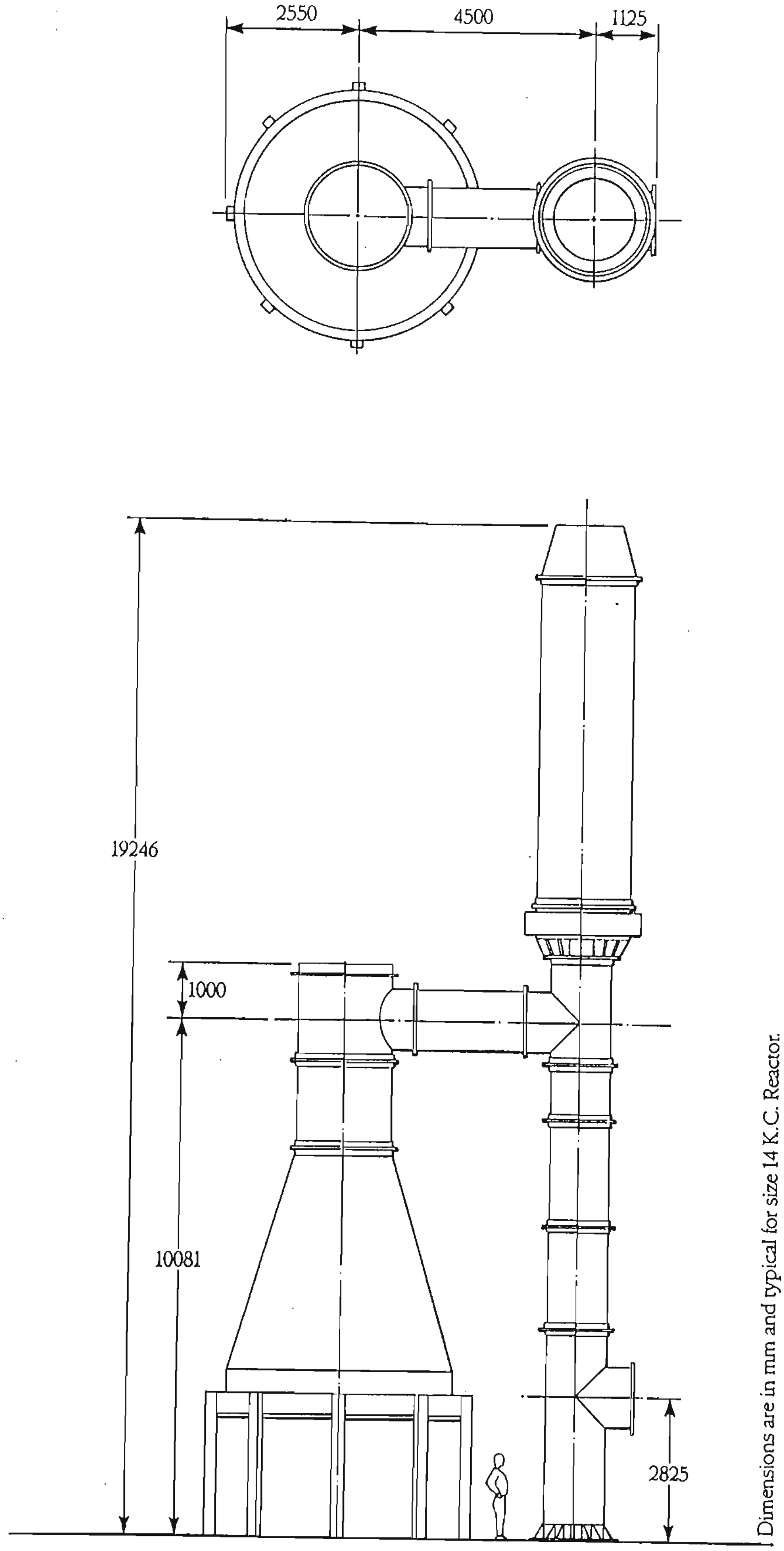

Fig. 3.1 Size 14 K.C. Reactor.

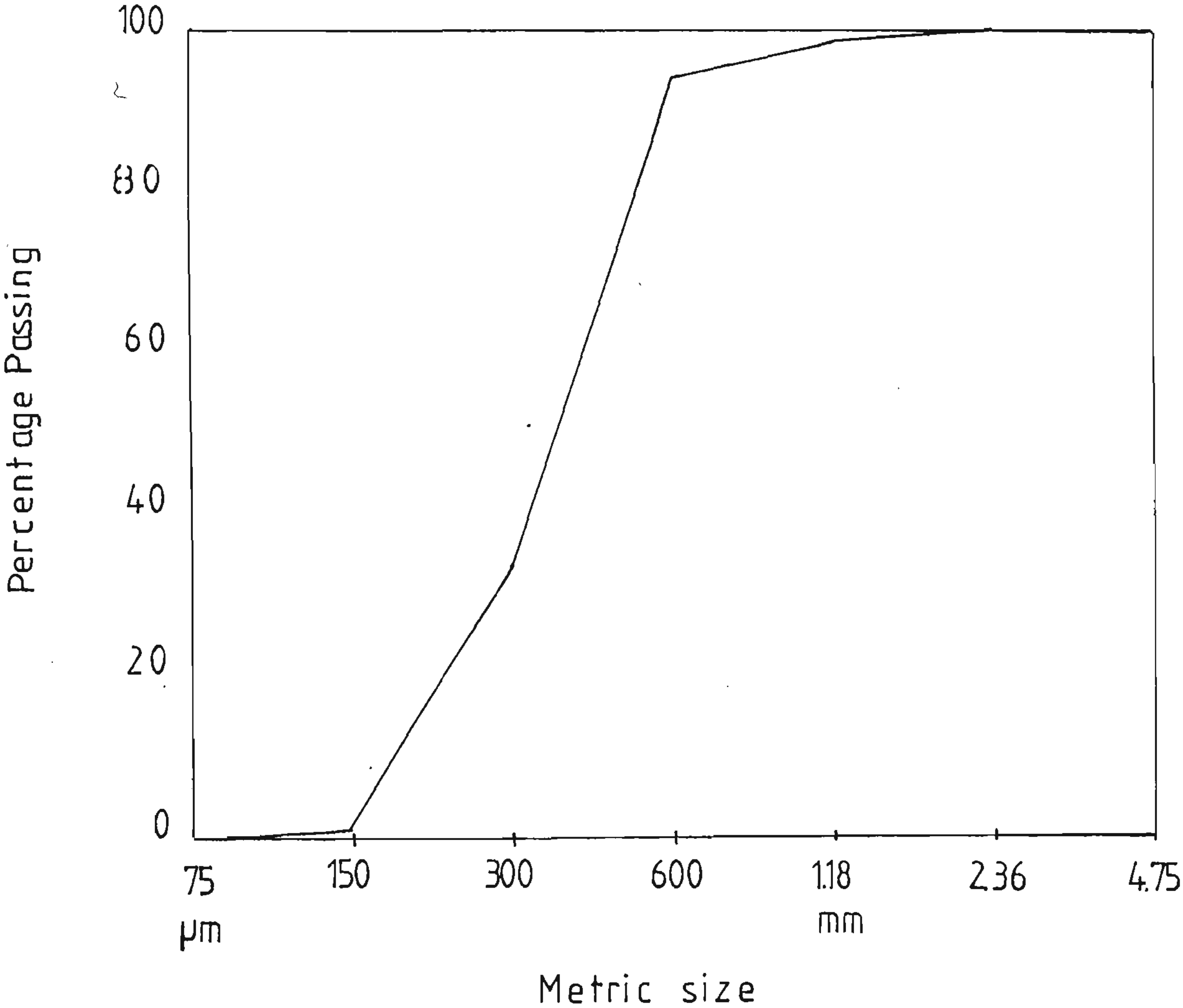

Fig.3.2 Grading curve of sand

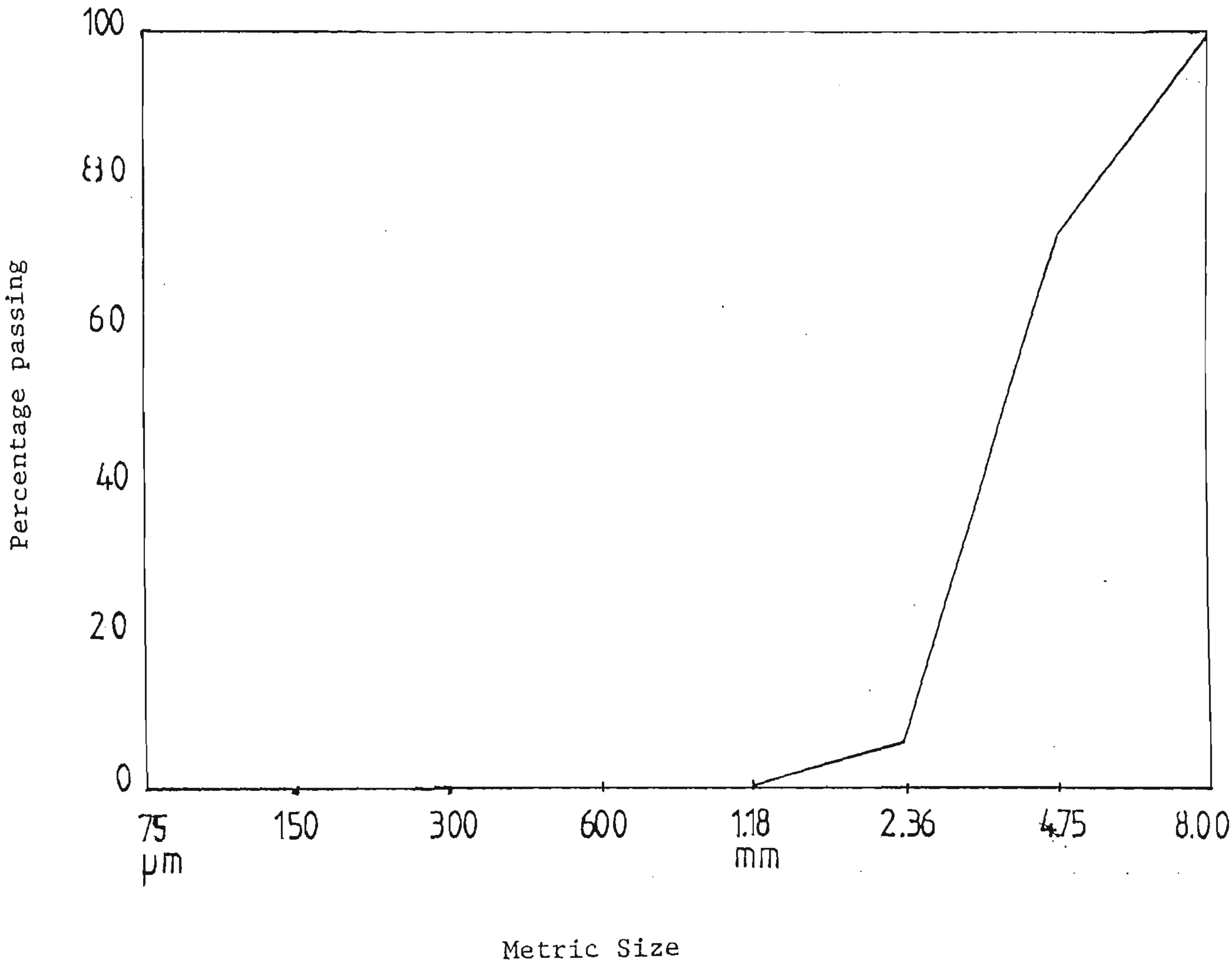

Fig.3.3 Grading curve of 5mm basalt aggregate

CHAPTER 4 - TEST RESULTS AND DISCUSSION

4.1 General

The properties and charateristics of the Australian RHA cement and RHA concrete are presented in this chapter. These properties, including fineness, standard consistence, workability, compressive strength are presented, based on the test results of the research study.

It is necessary to re-iterate that the ratio of RHA to OPC is 1 to 1 by volume in all the RHA concrete mixes.

4.2 Fineness of RHA

The fineness of RHA type C was found to be 92% passing the 75μm sieve. Fineness was determined by wet sieving test according to AS1141, Sect.12 - 1974 (Ref. 23) see Section 3.4.

As mentioned previously in Section 3.4, fineness has a great influence on the properties of both RHA cement and RHA concrete. The specific gravity of RHA increases with the fineness. This is shown by the different values of specific gravity for the various types of RHA used in this study. Starting with the finest RHA, Type C, going to the coarsest one, the values of specific gravity are listed below.

Type of RHA	Specific gravity
C	2.10
D	1.88
A	1.72
B	1.60

Fineness has also a great effect on the compressive strength. The finer the ash, the higher the compressive strength. This is clearly shown in Fig. 4.1* where RHA made with Type C RHA, the finest ash, has the highest strength in comparison with other RHA concrete having the same W/R. This is true since the hydration starts at the surface of the RHA particles. Thus the rate of hydration, which contributes to the formation of concrete strength, depends on the fineness of the RHA cement particles.

4.3 Workability of RHA Concrete

The workability of RHA concrete is very low compared to that of OPC concrete with similar water content. As shown in the design example in Appendix A, a W/R = 0.8 was required for the Type C RHA concrete to give the same slump as that of an OPC concrete with W/C = 0.48. This is due to the high water absorption rate of the RHA.

However, the workability of RHA concrete can increase very rapidly with the W/R ratio. This is clearly noticeable from Tables 4.1 - 4.4, where, for example, a jump in slump from 15mm to 35mm occurs with only a slight change in W/R ratio, (from W/R = 0.82 to W/R = 0.85). This is for the Type B RHA cement blend. Similar observation has also been made for the Type C blend:

W/R = 0.75 for slump = 15mm

W/R = 0.85 for slump = 149mm.

The standard consistence values of Types B and C are 0.94 and 0.71 respectively for a 50% volume replacement.

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* Footnote: Tables and figures are presented at the end of this chapter.

4.4 Standard Consistence and Setting Times of RHA Cement

The standard consistence values for the various blends of RHA cement have been found.* It was concluded that, as RHA content increased, the standard consistence also increased rapidly. The trend is a (concave) parabolic curve as shown in Fig. 4.2.

It is noticed in Fig. 4.2 that the higher the carbon content, the steeper the slope of the standard consistence curve. This phenomenon coincides with the observation previously reported by Yamamoto and Lakho (1982) that as carbon content gets higher, the mix would require more water to lubricate the excess RHA. The excess ash acts only as a filler with very low or no cementitious value.

Another interesting observation which can be made from Fig. 4.2, is that the slope of the standard consistence curve becomes steeper as the specific gravity values of the RHA decreases. The curve of the RHA Type C is almost a straight line. This result is similar to that of Weragama (1984). This ash had the highest specific gravity of 2.10 with a low carbon content (1.9%). It appears that, as the specific gravity of RHA approaches that of OPC, a linear variation in the standard consistence of percentage replacement occurs. This is due to the better characteristics and physical properties of an ash with high specific gravity than another with a low one.

Initial and final setting times were determined for different percentages of weight replacement of OPC having the RHA Type C only. The difference between initial and final setting times for each percentage replacement was always around 50 - 60 minutes. See Tables 4.11 - 4.12.

Fig. 4.3 shows the graph of setting time versus weight replacement of OPC by Type C RHA. A linear relationship appeared to exist in between 0% to 30% replacement. However, when weight replacement was beyond 30%, almost a horizontal straight line was obtained. This is because the ash above 30% replacement acted as a filler thereby retarding the setting time.

* See Page 43

The results, as shown in Fig. 4.3, confirm with the observation of Yamamoto and Lakho (1982). The excess of RHA beyond 40% weight replacement only acts as a filler and reduces strength, or, at least in this study retarded the early hydration. In the initial hydration process, tricalcium silicate (C_3S) and tricalcium aluminate (C_3A) are the two compounds to react with water causing the setting of the paste to occur. With less than or equal to 40% weight replacement, the silica in the RHA reacts with enough amount of $Ca(OH)_2$ released during the early stages of hydration to form C-S-H. However, if the replacement is beyond 40% by weight then there is an excess of RHA not having $Ca(OH)_2$ to react with. Therefore, the process of initial setting is obviously retarded.

4.5 Compressive Strength of RHA Concrete

All the Australian RHA concretes studied herein exhibited reliable compressive strengths. The curves of the compressive strength obtained for the experimental mixes are shown in Figs. 4.1 and 4.4 to 4.7.

It can be clearly seen from Fig. 4.4 that the RHA concrete (Type C) exhibits a higher compressive strength than the OPC concrete having the same W/C ratios. For W/C = 0.7 the slump of OPC concrete collapsed whilst for W/R = 0.7 (Type C) the slump for the RHA concrete was only 10mm.

An interesting point to note is that, if the content of RHA in the RHA concrete is removed, then the true W/C ratio would be very high, giving a very low strength. A W/R = 0.7 of RHA (Type C) concrete has a compressive strength of 20Mpa at 28 days, when RHA is removed the W/C becomes 1.05 and its strength is around 5Mpa at 28 days. This shows clearly that the addition of the Australian RHA to concrete, not only contributes to the volume of the concrete, but also to the strength.

From experimental results and by inspecting Figs. 4.4 - 4.7, it can be seen that RHA contributes to the strength of RHA concretes at all ages. This is due to the pozzolanic activity of the RHA which is related to the ability of silica to combine with $Ca(OH)_2$ to produce C-S-H. The reaction is a secondary one to the hydration of the clinker compounds and therefore, occurs at a slower rate than the main chemical reaction. However, at later stages the pozzolanic activity increases more rapidly than OPC because silica in RHA reacts with $Ca(OH)_2$ to form more C-S-H which contributes to higher strength.

It can be seen from Fig. 4.5 that for Type C RHA concrete, the increase in strength from 28 days to 90 days is over 100% in some cases. This is different from OPC concrete for which the correponding increase is much smaller.

4.6 Strength Correlation Factor, e

As mention previously in Section 2.2, the strength correlation factor, e, was computed using equation 2.1

i.e. $$e = (W/R) / (W/C)$$

The average e value for Type C RHA is found to be equal to 1.11. The data used in reaching this e value may be found in Table 4.5 which were in turn extracted from Fig. 4.4.

A similar procedure was used for the calculation of e for all other ashes. Results are shown in Tables 4.6 - 4.8 respectively for Types A, B and D. From these, the following average e values are obtained.

Type of RHA	e
A	1.08
B	1.02
C	1.11
D	1.06

The above results show that Type C RHA has the highest e value. However, it is also clear that all the Australian RHA used have proved to be reactive. They all give a strength correlation factor greater than 1.0.

4.7 Differential Lubrication Constant, f

The values of the differential lubrication constant, f, were obtained from routine laboratory tests. The procedure used for the calculations of the f values is already outlined in Section 3.7. This procedure is established by Loo & Weragama (1985).

The values of f are listed below:

Type of RHA	f
A	0.161
B	0.194
C	0.150
D	0.187

The values of f obtained herein are higher than those RHA investigated at the Asian Institute of Technology. The difference is mainly due to the differences in fineness, specific gravity and carbon content between the Australian and overseas RHA.

Some of the differences are listed below:

Overseas	Australia
Fineness: 85% passing 45 μm sieve	92% passing 75 μm sieve
Specific gravity: 2.3 (Weragama)	2.10 (Type C)
Standard consistence: 0.445 (Weragama)	0.71 (Type C)

Type C RHA has the lowest f value of 0.15 but the highest e value among all the RHA.

It was observed that a relationship seems to exist between the values of e and f. The lower the value of f, the higher its e value. The constant f quantifies the difference in water demands between the OPC and RHA cement . Therefore, the higher the f value, the more water is needed for lubricating a mix. This in turn tends to lower the strength. A decrease in strength leads to a decrease in the e value of the RHA concrete. Thus, a decrease in f leads to an increase in e.

4.8 Durability of RHA Concretes

The RHA concretes showed better resistance to acidic attack than OPC concrete. Three interesting observations were made.

(a) The RHA concrete was less prone to surface softening and disintegration than the OPC concrete. RHA concrete cylinders held their original hard surfaces and sharp edges, whereas OPC concrete cylinders did not keep these characteristics.

(b) More weight loss was registered for the OPC concrete cylinder than the other two RHA concrete cylinders. The results are summarised in Table 4.10.

(c) The blackish colour, of the two RHA concretes, was not affected by the acid solution. This is useful for making black concrete for architectural applications. Usually black concretes are produced by adding black pigments, such as carbon black to portland cement. Therefore, the preservation in colour pigmentation is achieved when using RHA concrete.

TABLE 4.1 COMPRESSIVE STRENGTHS USING 50% RHA BY VOLUME FOR RHA TYPE A (S.G. = 1.72)

W/R		Slump (mm)	Compressive Strength (MPa)
		14 days	28 days
0.70	0	8.35	11.40
0.80	5	12.35	14.50
0.85	7	9.85	11.45
0.945	13.5	6.50	9.25

TABLE 4.2 COMPRESSIVE STRENGTHS USING 50% RHA BY VOLUME FOR RHA TYPE B (S.G. = 1.60)

W/R	Slump (mm)	Compressive Strength (MPa)	
		14 days	28 days
0.75	0	8.60	12.45
0.80	4	6.45	9.55
0.82	15	6.40	9.10
0.85	35	4.50	6.82

TABLE 4.3 COMPRESSIVE STRENGTHS USING 50% RHA BY VOLUME FOR TYPE C (S.G. = 2.10)

W/R	Slump (mm)	Compressive Strength (MPa)		
		14 days	28 days	90 days
0.65	4	17.35	25.95	37.85
0.70	10	15.40	20.40	35.10
0.75	15	13.80	17.90	33.20
0.85	149	8.55	14.85	30.50

TABLE 4.4 COMPRESSIVE STRENGTHS USING 50% RHA BY VOLUME FOR TYPE D (S.G. = 1.88)

W/R	Slump (mm)	Compressive Strength (MPa)	
		14 days	28 days
0.70	0.00	5.50	18.60
0.76	20	9.65	15.40
0.78	30	9.45	13.80
0.82	50	8.70	13.60
0.85	60	7.80	11.20
0.89	70	5.00	9.10

TABLE 4.5 EFFICIENCY OF RHA CEMENT FOR RHA TYPE C (S.G. = 2.10)

Strength (MPa)	OPC Concrete W/C	RHA Concrete W/R	$e = \frac{W/R}{W/C}$
20	-	-	-
21	0.630	0.688	1.110
22	0.612	0.675	1.103
23	0.605	0.665	1.099
24	0.600	0.660	1.100
25	0.590	0.653	1.107
26	0.582	0.649	1.115

TABLE 4.6 EFFICIENCY OF RHA CEMENT TYPE A (S.G. = 1.72)

Strength (MPa)	OPC concrete W/C	RHA concrete W/R	e
22	0.612	0.67	1.09
23	0.605	0.65	1.07
24	0.600	0.648	1.08
25	0.590	0.64	1.08

TABLE 4.7 EFFICIENCY OF RHA CEMENT TYPE B (S.G. = 1.60)

Strength (MPa)	OPC concrete W/C	RHA concrete W/R	e
22	0.612	0.63	1.03
23	0.605	0.617	1.02
24	0.600	0.62	1.03
25	0.590	0.601	1.02

TABLE 4.8 EFFICIENCY OF RHA CEMENT TYPE D (S.G. = 1.88)

Strength (MPa)	OPC concrete W/C	RHA concrete W/R	e
22	0.612	0.650	1.062
23	0.605	0.641	1.059
24	0.600	0.635	1.058
25	0.590	0.624	1.057

TABLE 4.9 COMPRESSIVE STRENGTHS USING 100% OPC

W/C	Slump (mm)	Compressive Strength (MPa)	
		14 days	28 days
0.40	3	58.45	66.40
0.45	30	43.95	48.00
0.48	45	39.55	46.00
0.55	Collapse	24.50	31.30
0.62	Collapse	16.00	21.00
0.72	Collapse	7.50	14.50

TABLE 4.10 PERCENTAGE WEIGHT CHANGE DUE TO 5% HCL SOLUTION

	W/C	0	30	60	90 (Days)
OPC Concrete	0.45	13.20	13.00	12.90	12.90 (Kg)
RHA Concrete (Type C)	0.70	11.70	11.65	11.60	11.60
RHA concrete (Type B)	0.80	11.75	11.72	11.70	11.70
% Change	OPC		1.51	2.32	2.32
	RHA(C)		0.43	0.86	0.86
	RHA(B)		0.25	0.42	0.42

TABLE 4.11 STANDARD CONSISTENCE PERCENTAGE REPLACEMENTS OF OPC BY RHA TYPE A,B,C AND D

Percentage Replacement by Weight	Standard Consistence			
	Type A	Type B	Type C	Type D
0	0.255	0.255	0.255	0.255
10	0.34	0.35	0.37	0.40
15	-	-	-	0.49
20	0.48	0.48	0.50	0.55
25	-	-	-	0.65
30	0.70	0.72	0.60	0.69
35	0.86	0.94	-	0.73
40	-	-	0.71	0.78
50	-	-	0.80	-
60	-	-	1.02	-
70	-	-	1.20	-

RHA Type A - S.G. = 1.72
RHA Type B - S.G. = 1.60
RHA Type C - S.G. = 2.10
RHA Type D - S.G. = 1.88

TABLE 4.12 INITIAL AND FINAL SETTING TIMES FOR RHA TYPE C

% RHA to OPC	Initial Setting Time (min.)	Final Setting Time (min.)	% Standard Consistence
0	205	235	25.5
10	315	369	37.0
20	405	455	50.0
30	420	470	60.0
40	428	480	71.0
50	750	800	86.0
60	-	-	102.0
70	-	-	120.0

Average Temperature 20%
Average Humidity 30%

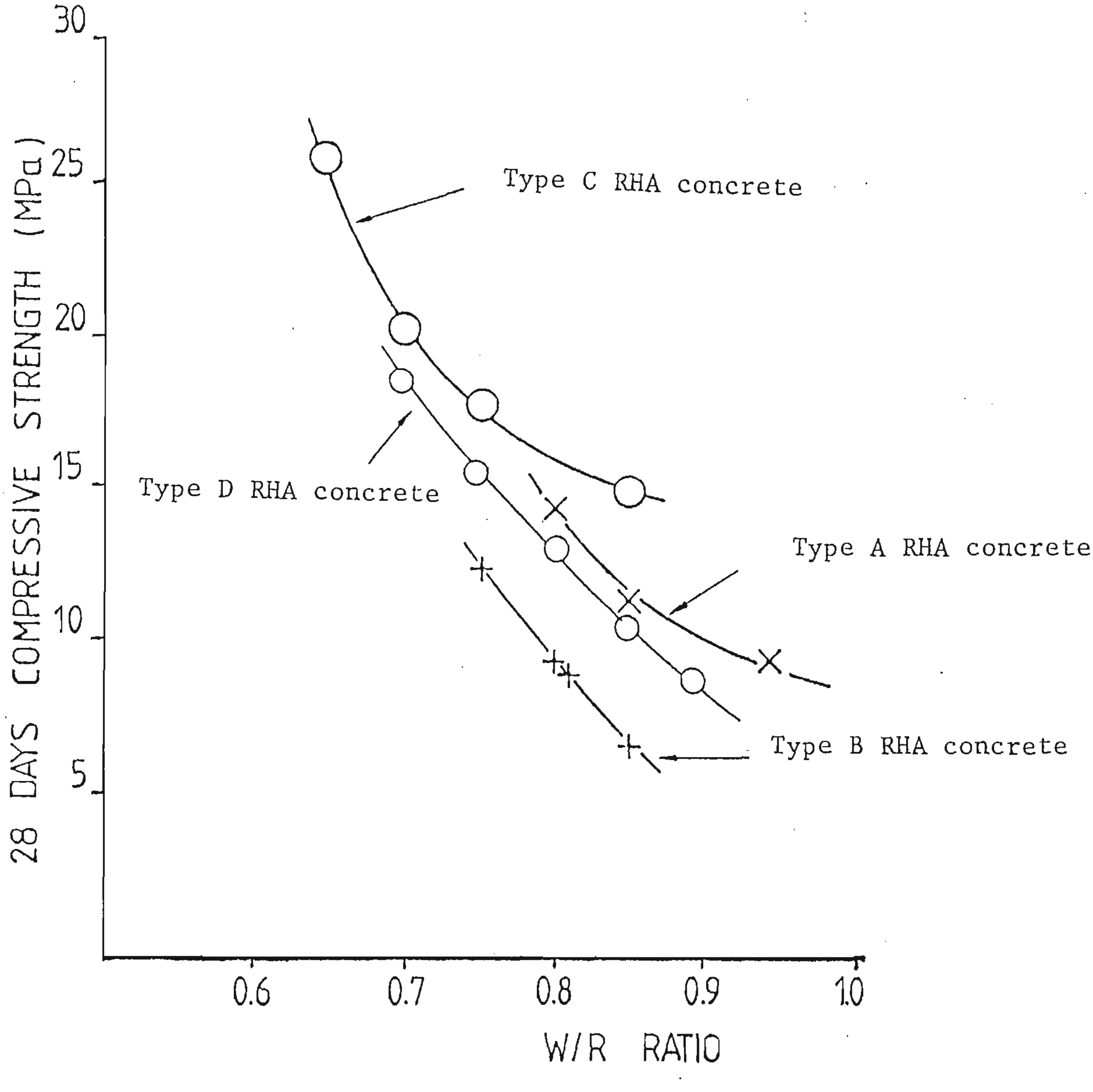


Fig. 4.1 Compressive strength versus water/RHA ratio for four types of RHA

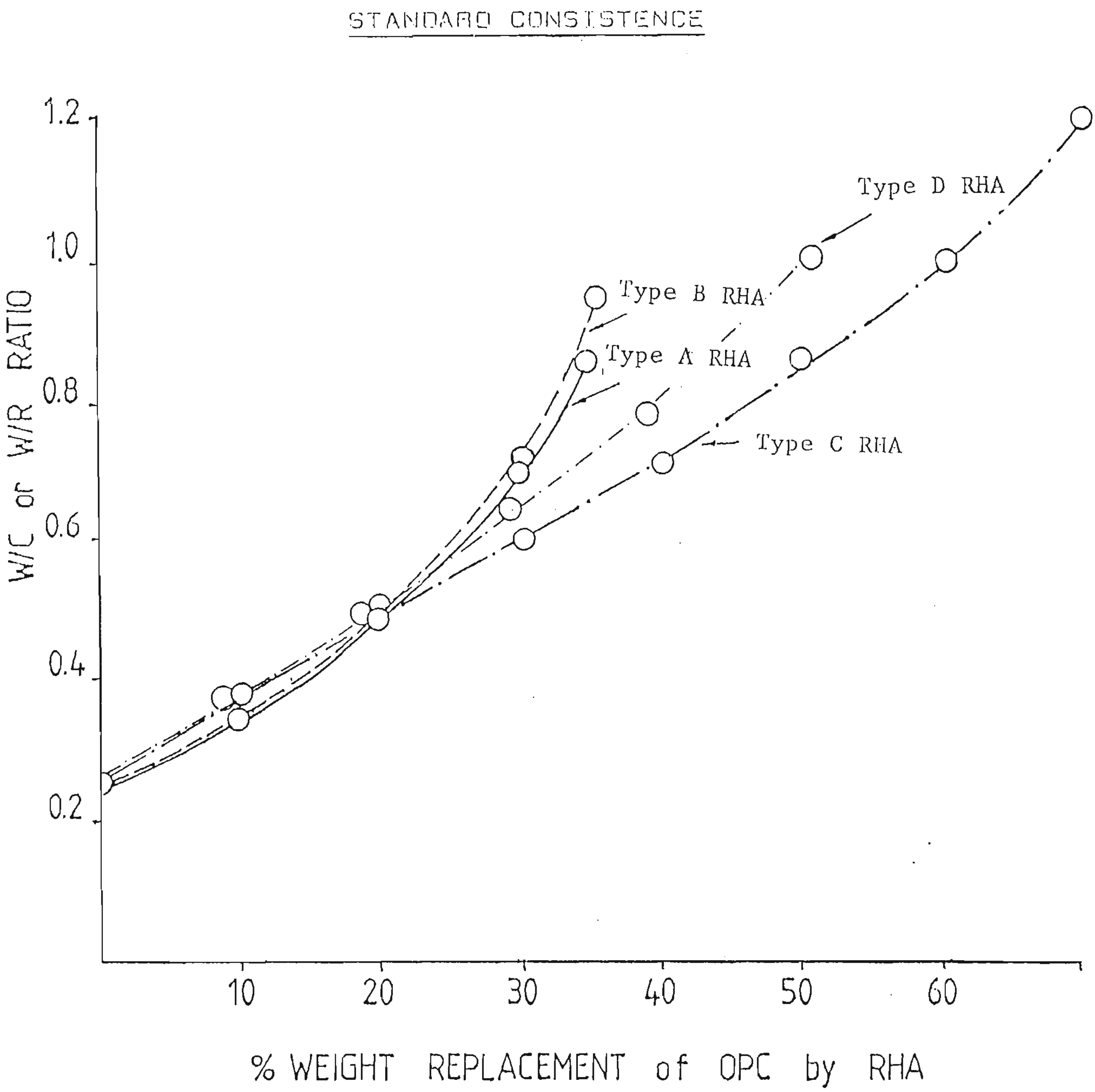


Fig. 4.2 Comparison of standard consistence for different types of RHA cements.

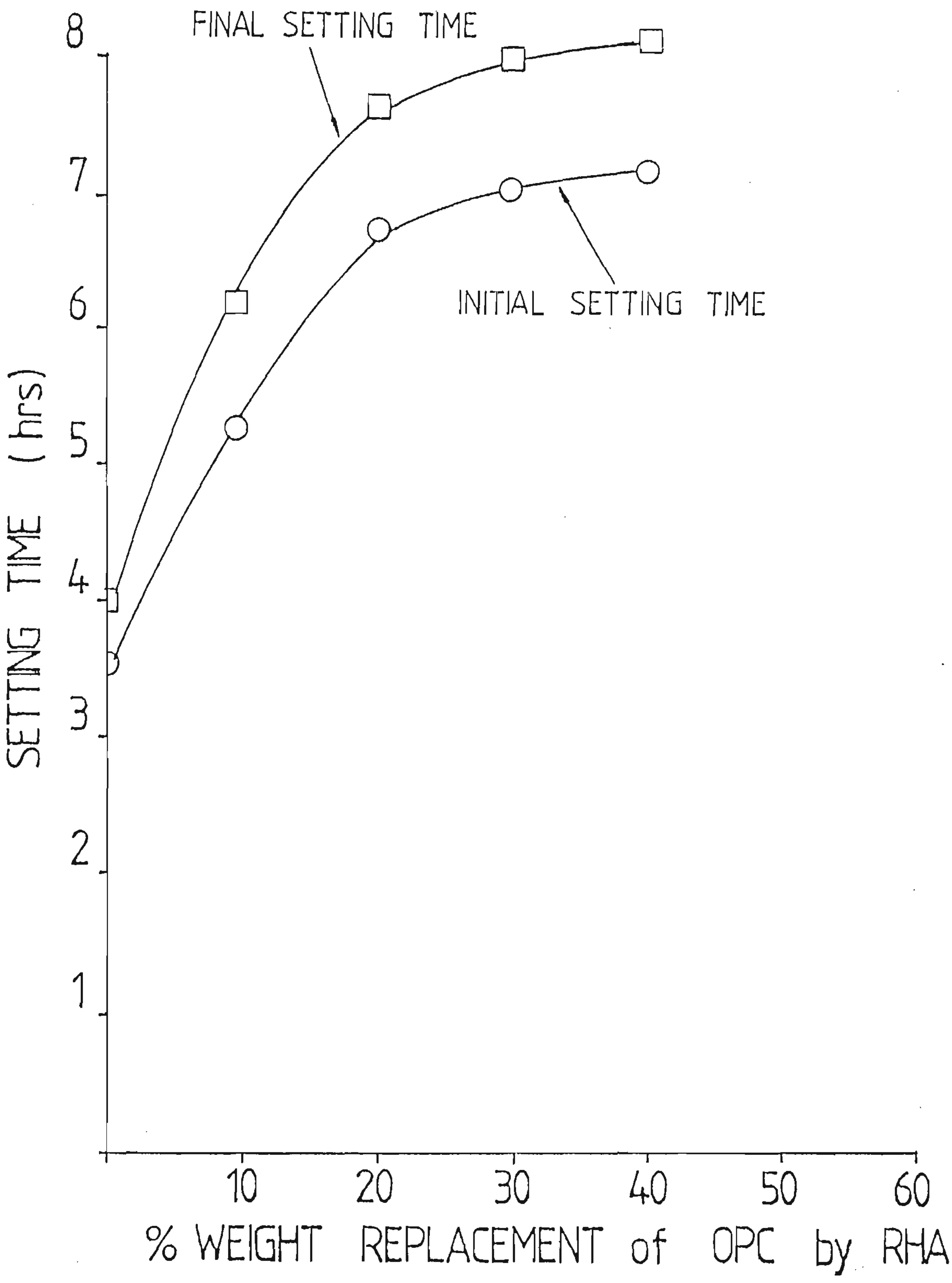


Fig. 4.3 Setting times for standard consistence of Type C RHA cements.

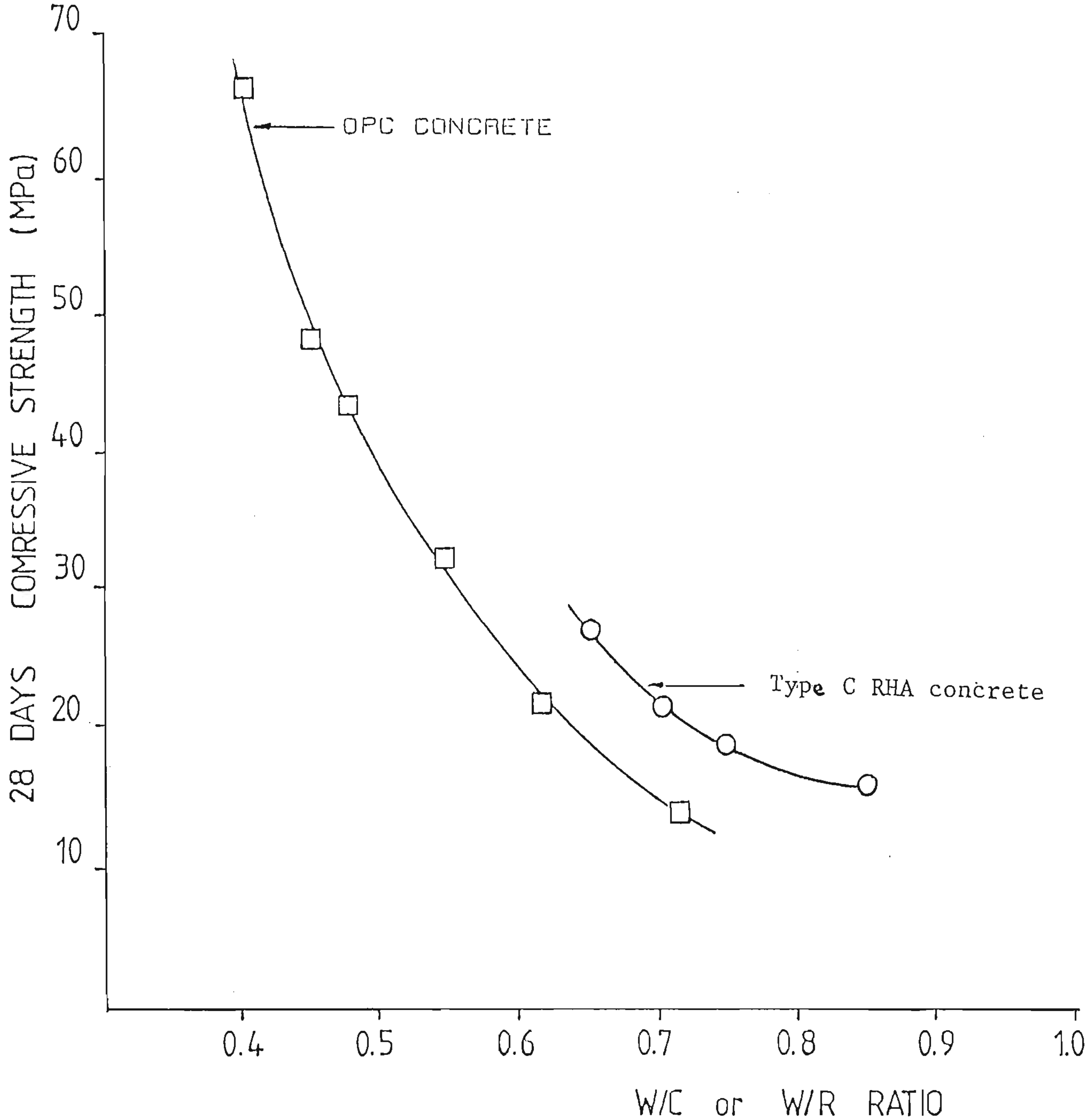


Fig. 4.4 Compressive strength versus W/C or W/R ratio for OPC concrete and Type C RHA concrete.

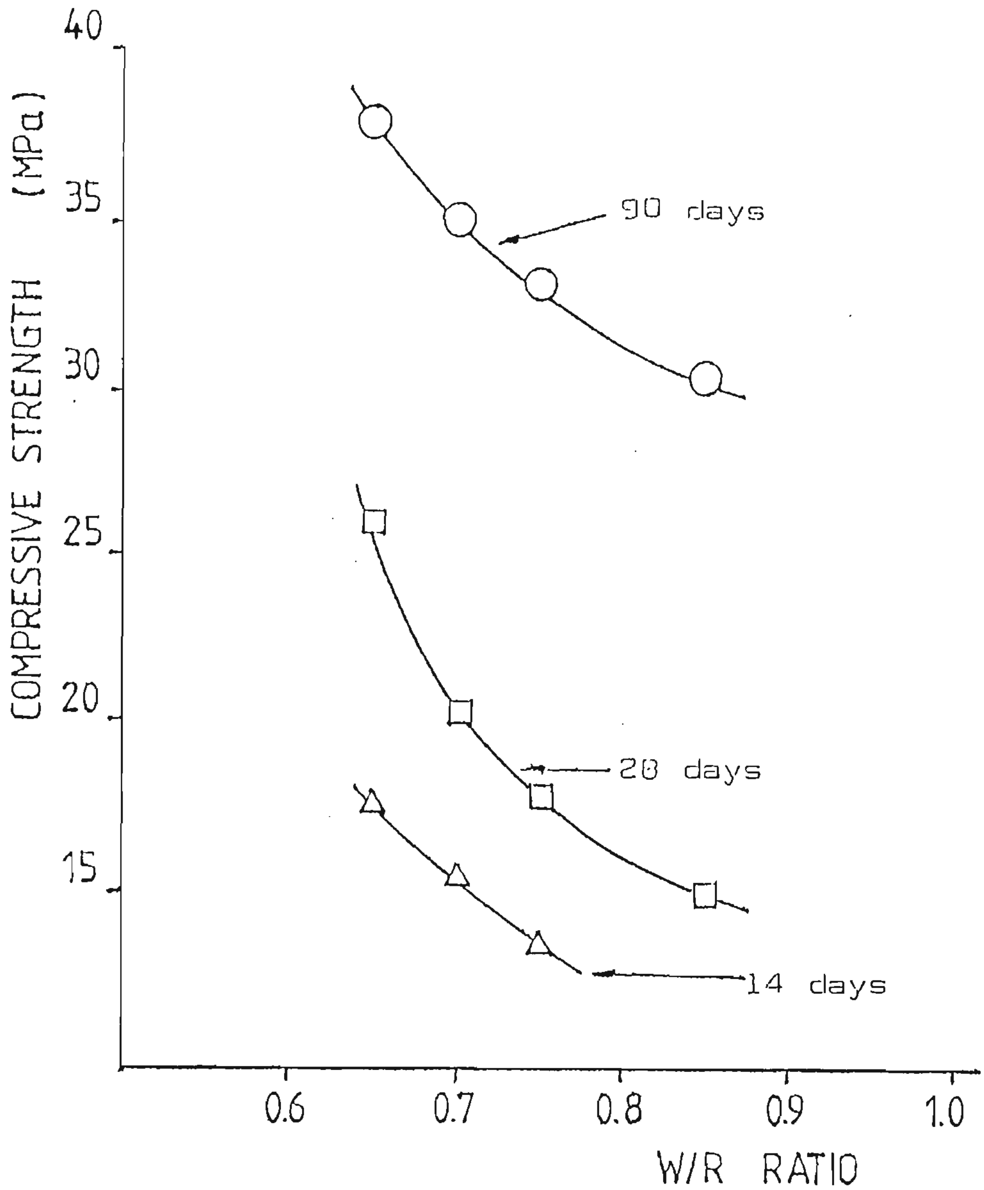


Fig. 4.5 Comparison of the change of strength for Type C RHA concrete for 14,28 and 90 days.

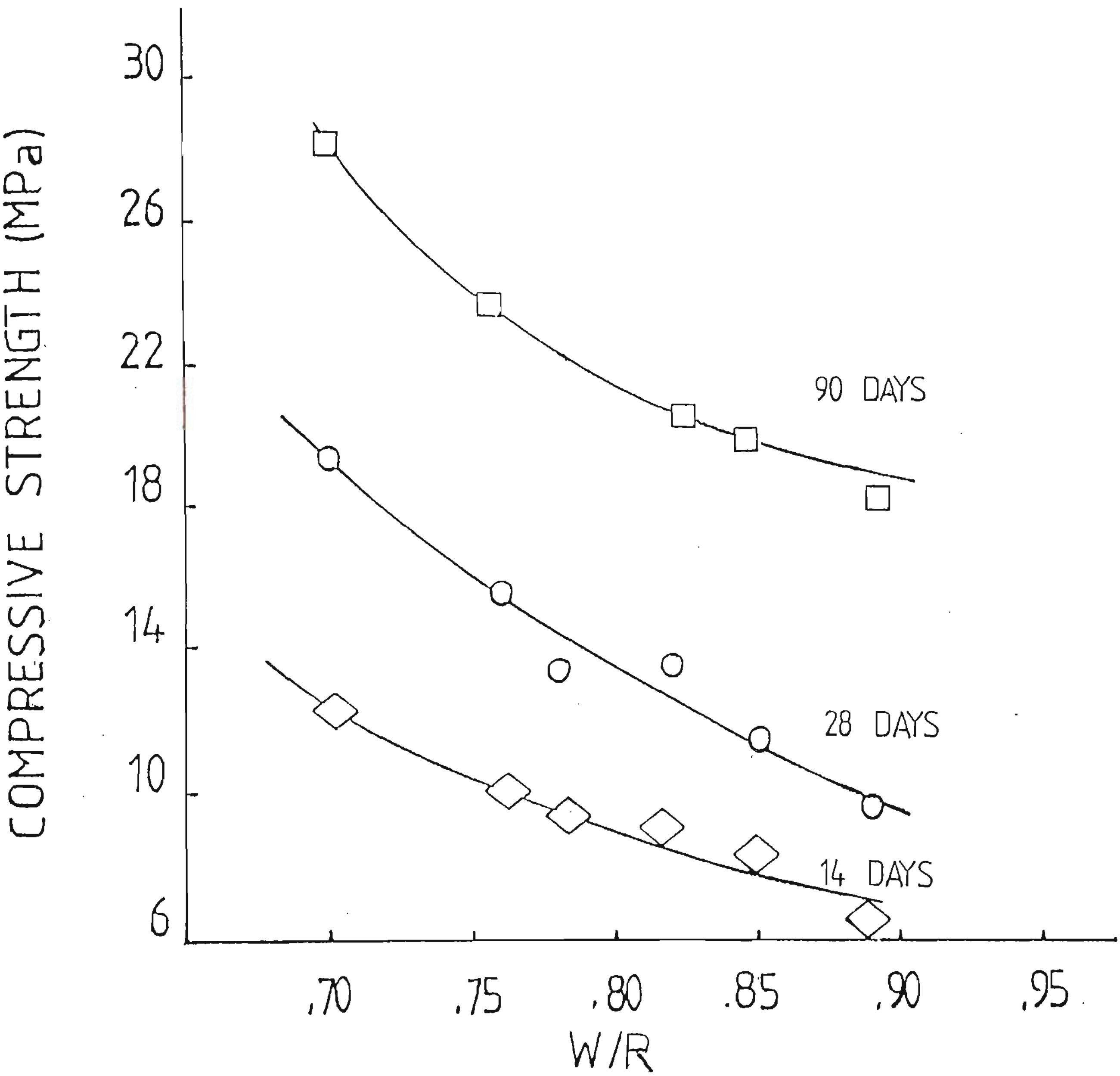


Fig. 4.6 Compressive strength versus W/R ratio for Type D RHA concrete

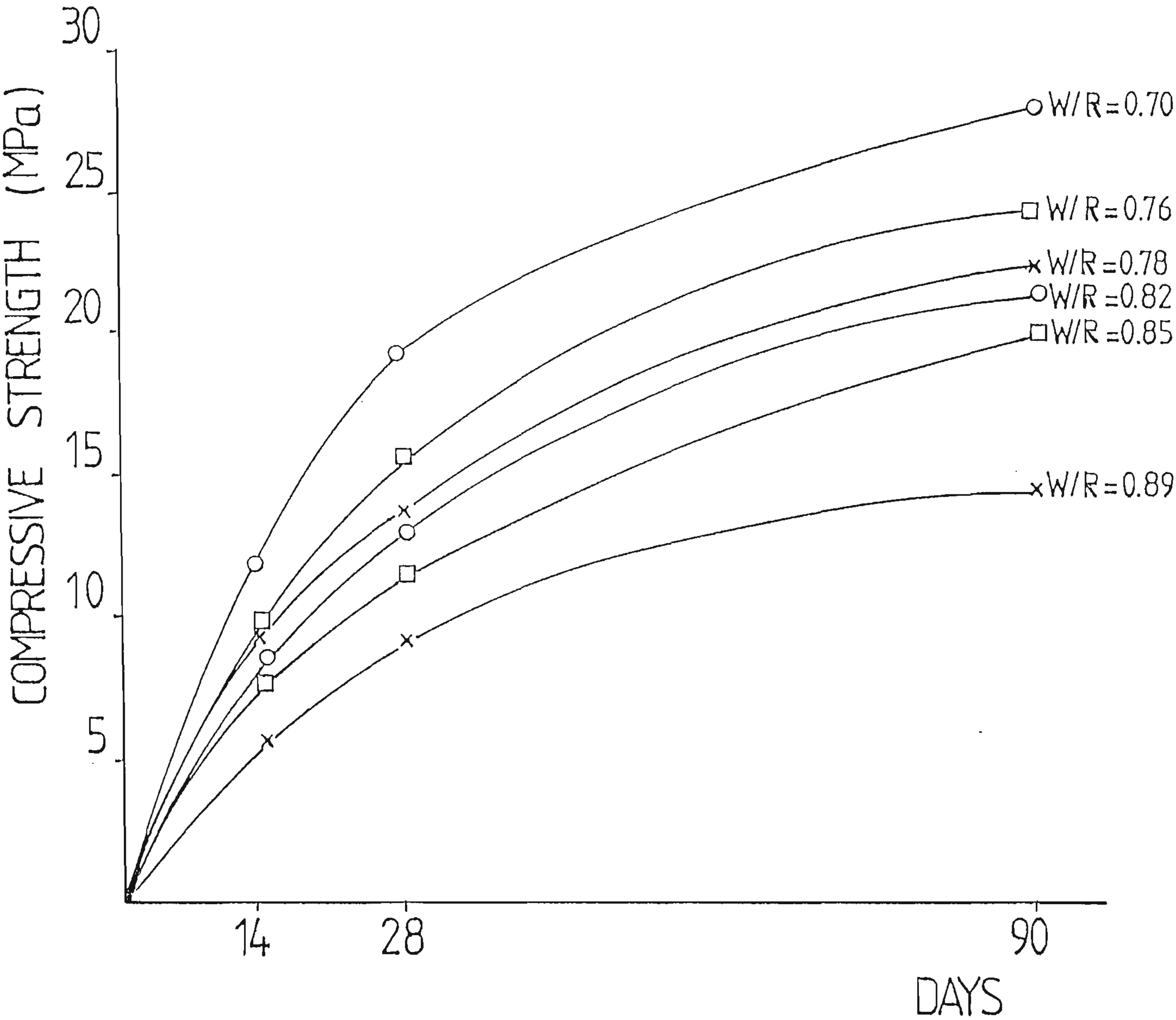


Fig. 4.7 Compressive strength versus Age (Type D)

CHAPTER 5 - DESIGN AIDS

5.1 Introduction

Results based on tests described in Section 3.9, are presented in Tables 5.1 - 5.3 and also in Figs. 5.1 - 5.3*. Table 5.1 gives the compressive strengths for different W/C ratios at different ages. Tables 5.2 and 5.3 show the approximate free-water contents for various workability and the wet density of RHA concrete respectively. Figs. 5.1-5.3 illustrate the graphs of wet density versus the free water content for different aggregate sizes. In view of the fact that the ranges of variable are rather wide, these may be used as design aids for the use of Type C RHA in concrete. Herein, the proposed procedure follows that of the Department of the Environment design method (1975).

5.2 Design Example

The following is an example of the new design aids. The design process is divided into six stages. Each of these stages deals with a particular aspect of the design and ends with a final unit proportion.

Design Requirements: Compressive strength = 20MPa at 28 days

Workability = 50mm

Maximum aggregate size = 20mm

Stages:

1. From Table 5.1 for compressive strength, choose the W/R ratio for the corresponding strength at 28 days. (20MPa). We have

W/R = 0.70.

---

* Footnote: Tables and Figures are presented at the end of each chapter.

2. Select the free water content from Table 5.2, for the given aggregate size, this gives

$$W_r = 270 \text{ Kg/m}^3.$$

3.

$$\text{RHA cement content} = \frac{W_r}{W/R}$$

$$= \frac{270}{0.70} = 385.7 \text{ Kg/m}^3$$

For a 50% replacement by volume (see Appendix B):

$$C = 0.6 \times 357.8 = 231.40 \text{ Kg/m}^3$$

$$R = 0.4 \times 347.8 = 154.30 \text{ Kg/m}^3$$

4. Total aggregate content $= D - R - W_r$

where, D = wet density of RHA concrete (kg/m^3), the value of which can be obtained from Figs. 4.6 - 4.8

R = weight of the RHA cement (kg/m^3)

W_r = free water content (kg/m^3)

$$A = 2225 - 385.7 - 270$$

$$= 1569.3 \text{ Kg/m}^3).$$

5. Following the pre-determined proportion (see Section 3.3.2)

$$A_f = 0.4A$$

$$= 627.7 \text{ kg/m}^3$$

and the coarse aggregate,

$$A_c = A - A_f$$

$$= 1618 - 627.7$$

$$= 941.6 \text{ kg/m}^3.$$

The coarse aggregate content itself can be subdivided if single sized 10, 20 and 40mm materials are to be combined. The following ratios are suggested as a general guide.
For combination of 10 and 20mm material 1:2, and
For combination of 10, 20 and 40mm material 1:1.5:2.

6. Mix proportion.

Finally the mix proportions of the ingredients (kg/m^3) are as follows:

W	OPC	RHA	Sand	5mm	10mm	20mm
270	230	154	470	160	310	630

The design of the RHA concrete with a 28 day strength of 20MPa and a slump of 50mm is given in detail in Table 5.5. Note that the design form due to Loo and Weragama (1985) is a modified version of that recommended by the British Department of the Environment for conventional concretes (Ref. 16).

5.3 Verification

To check the reliability of the design procedure outlined in Section 5.2, four different mixes of RHA concrete using RHA Type C were cast. The Australian method for preparation for concrete mixes in laboratory, AS1012, part 2 - 1983 (Ref. 25) was followed. The maximum aggregate size used throughout the tests was 20mm.

Slump test and wet density test were carried out according to AS1012, part 3 - 1983 (Ref. 26) and AS1012, part 5 - 1983 (Ref. 27) respectively. Each mix consisted of three cylinders. The compressive stgrength of the cylinders were tested at 28 days according to AS1012, part 9 - 1973 (Ref. 29).

The test results are compared with the predictions in Table 5.4. The comparisons are considered satisfactory.

TABLE 5.1 COMPRESSIVE STRENGTH USING 50% RHA BY VOLUME FOR TYPE C (S.G. = 2.10)

W/R	Slump (mm)	Compressive Strength (MPa)		
		14 days	28 days	90 days
0.65	4	17.35	25.95	37.85
0.70	10	15.50	20.50	35.10
0.75	15	13.80	17.90	33.20
0.85	149	8.55	14.85	30.50

TABLE 5.2 APPROXIMATE FREE-WATER CONTENTS (kg/m^3) REQUIRED TO GIVE VARIOUS LEVELS OF WORKABILITY

Slump (mm) V-B (Secnds)		0-10 >12	10-30 6-12	30-60 3-6	60-180 0-3
Maximum Size of aggregate (mm)	Type of aggregate				
10	crushed	310	320	335	350
20	crushed	245	255	270	290
40	crushed	225	240	260	270

TABLE 5.3 WET DENSITY OF RHA CONCRETE (kg/m^3) FOR DIFFERENT WORKABILITY RANGES

Slump (mm) V-B (Secnds)		0-10 >12	10-30 6-12	30-60 3-6	60-180 0-3
Maximum Size of aggregate (mm)	Type of aggregate				
10	crushed	2195	2185	2170	2160
20	crushed	2245	2235	2225	2200
40	crushed	2250	2200	2160	2120

TABLE 5.4 TEST RESULTS COMPARED WITH THE PREDICTIONS

Design Requirements		Test Results		
slump (mm)	target strength (MPa)	slump (mm)	compressive strength (MPa)	wet density (kg/m^3)
30-60	20	42	19.70	2215
60-180	20	80	17.80	2185
0-10	25	15	23.50	2277
60-180	15	55	12.5	2155

[illegible] mm concrete mix design form

Stage	Item		Reference or calculation	Values
1.	1.1	Characteristic strength	Specified	______ N/mm^2 at ______ days; Proportion defective ______ per cent
	1.2	Standard deviation	Fig. 3	______ N/mm^2 or no data ______ N/mm^2
	1.3	Margin	C1	(k= ____) ____ x ____ = ____ N/mm^2
	1.4	Target mean strength	C2	____ + ____ = 20 N/mm^2
	1.5	RHA cement type	Specified	Replacement by volume 50 %; Weight ratio, η = ______
	1.6	Aggregate type : coarse		Crushed
		Aggregate type : fine		Uncrushed
	1.7	Free W/R ratio	Table 6.1	0.70
2.	2.1	Slump or V-B	Specified	Slump 50 mm or V-B ______ s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 5.2	270 kg/m^3
3.	3.1	Cement content, C	C3	270 ÷ 0.70 = 385.7 kg/m^3
4.	4.1	Relative density of aggregate (SSD)		2.67 known/assumed
	4.2	Concrete density	Fig. 5.2	2225 kg/m^3
	4.3	Total aggregate content	C4	2225 - 385.7 - 270 = 1569.3 kg/m^3
5.	5.1	Grading of fine aggregate	BS 882	Zone 4
	5.2	Proportion of fine aggregate		40 per cent
	5.3	Fine aggregate content	C5	0.4 x 1569.3 = 627.7 kg/m^3
	5.4	Coarse aggregate content	C5	1569.3 - 627.7 = 941.6 kg/m^3
6.	6.1	OPC content, $\bar{C}$		230 kg/m^3
	6.2	RHA content, $\bar{R}$		154 kg/m^3
	6.3	Free water content		270 kg/m^3

Quantities	RHA (kg)	OPC (kg)	Water (kg or l)	Fine aggregate (kg)	Coarse aggregate (kg)
per m^3 (to nearest 5 kg)	154	230	270	630	940

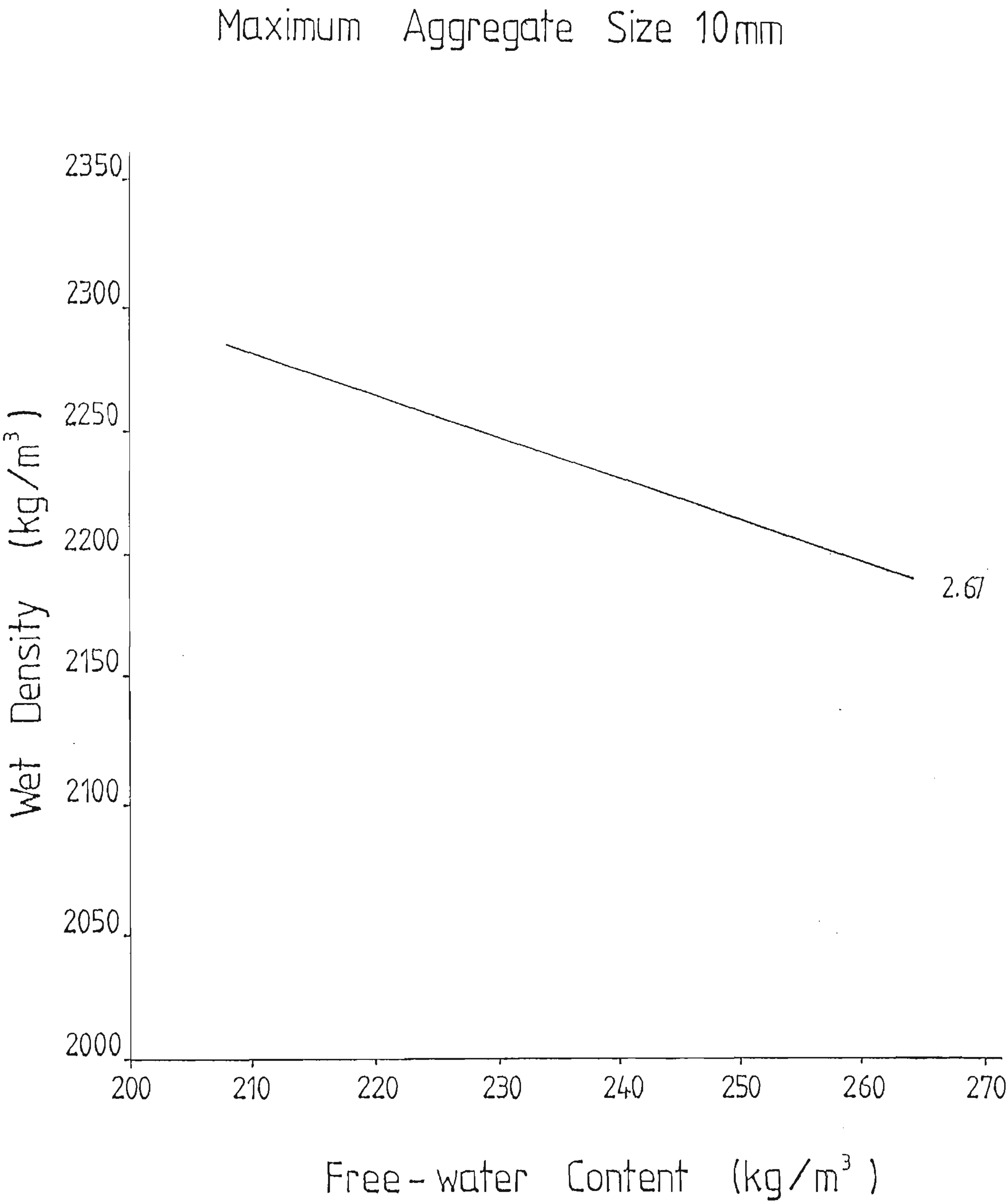


Fig. 5.1 Wet density VS free water content.

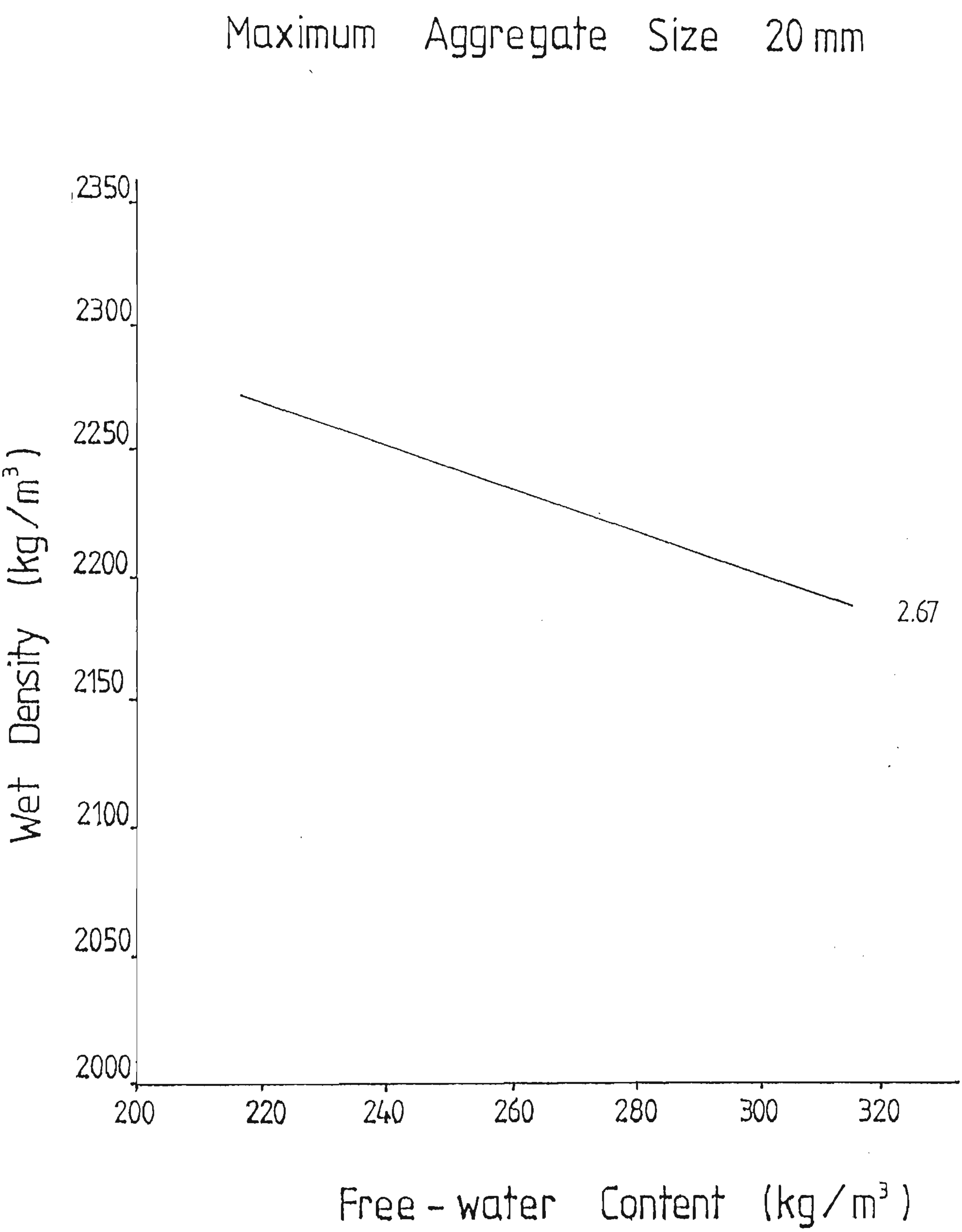
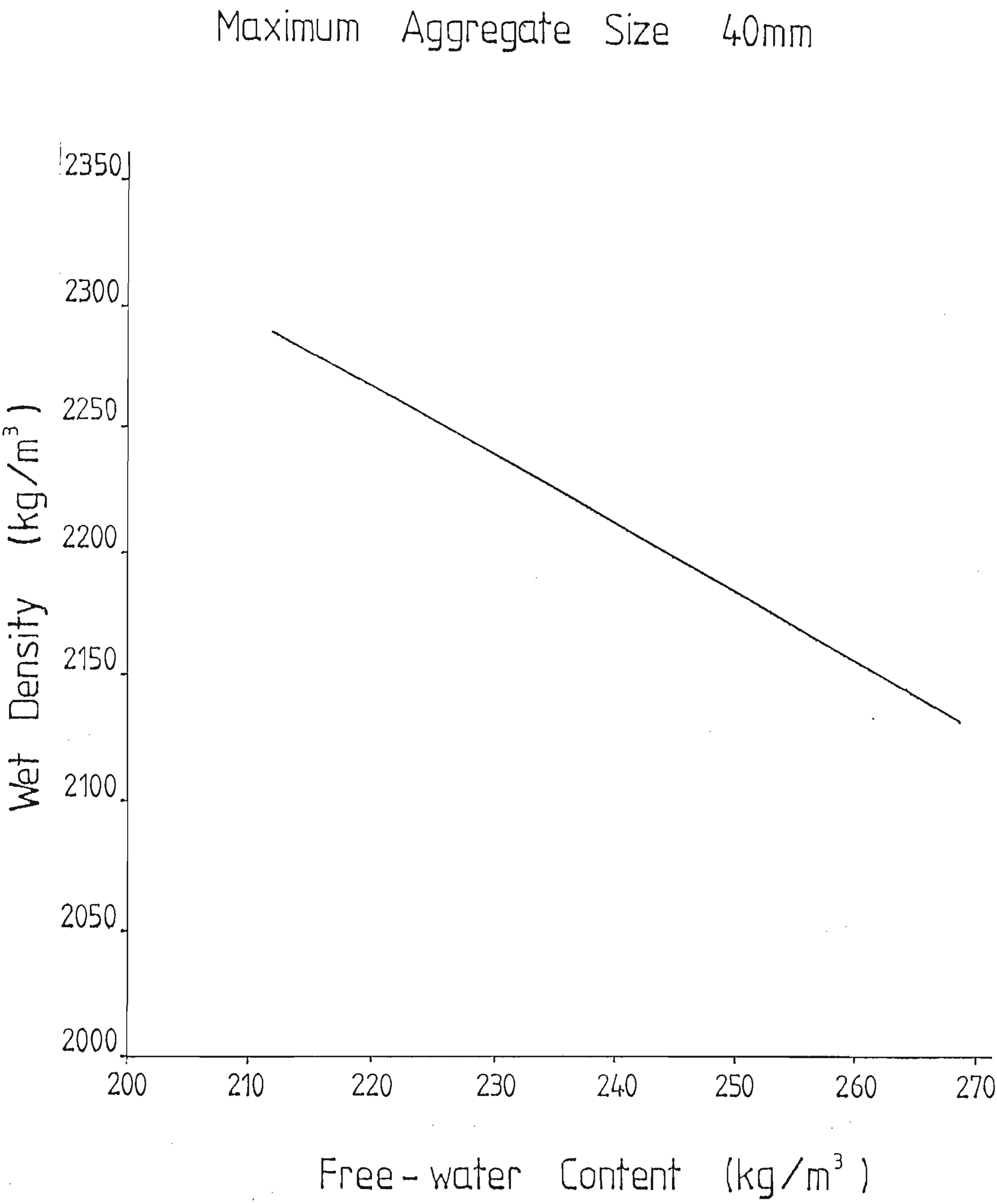


Fig. 5.2 Wet density VS free water content.



2.67

Fig. 5.3 Wet density VS free water content.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Four types of Australian RHA are used in this research study. They are referred to as Types A, B, C and D which are by-products from specially designed combustors and furnaces. Chemical and physical properties of each of the RHA have been presented.

Based on the compressive strengths test data obtained herein, new design aids have been established for using Type C RHA in making structural concrete. In the form of tables and charts, the simple aids are found to be useful for the design of a limited range of RHA concrete mixes.

From all the results of the present study, the following conclusions can be drawn:

(a) All types of RHA used are reactive. Results of compressive tests showed that the Australian RHA can be used as a partial replacement of OPC in making concrete. The highest compressive cylinder strength obtained was 26 MPa at 28 days, for a W/C ratio of 0.65. This was for a 50% volume replacement of OPC by Type C RHA.

(b) Standard consistence values for Types A,B, C and D are found to be 0.86, 0.95, 0.71 and 0.74 respectively.

(c) It is impossible to use a W/C ratio lower than the standard consistence of OPC in making OPC concrete, as the mix would be too dry and the water content would not be sufficient for a complete hydr ation. For RHA concrete on the other hand, a W/R ratio below the standard consistence of the given blend may be adopted to produce RHA concrete with some workability and a high compressive strength.

(d) The values of strength correlation factor e are found to be 1.08, 1.02, 1.11 and 1.06 respectively for the Types A, B, C and D RHA. These mean that a 50% volume replacement of OPC by the RHA, the cylinder strength of the RHA concrete is higher than

the OPC concrete with an identical water/binder ratio. Depending on the type of RHA used, the increase in strength can vary from 2% to 11%. However, due to the differences mainly in the water absorption properties between the Australian RHA and their overseas counterparts, the unit design procedure developed by Loo and Weragama may not be applicable for the local products.

(e) The RHA concrete found to be more resistant to acid attack than OPC concrete of much lower W/C ratio.

The following areas for future research are recommended:

(a) More work should be done on RHA Type C in order to establish standard specifications on fineness and chemical compositions, as it showed much superior characteristics than the other types of Australian ash used.

(b) More research should be carried out on the hydration of RHA cement so that a better insight can be gained in the chemical reaction process of the ash.

(c) The design aids should be further developed, following the British DOE approach to reduce limitations in application. Different blends of RHA cement should be used; the fine aggregate content should be varied.

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APPENDIX A

Design of RHA Concrete Using the DOE Method. (As Outlined by Loo & Weragama (1985))

Requirements

Strength = 40MPa at 28 days

Workability = 75mm slump

Data Material properties given:

Fine aggregate - uncrushed

Grading zone of fine aggregate - 4

Coarse aggregate - crushed

Maximum aggregate size used - 20mm

Absorption capacity of aggregates: Sand 2.3%; Basal 1.91%

Relative density of aggregates - 2.67

Standard consistence of OPC (S_1) = 0.255

Standard consistence of RHA Cement (Type C), (S_2) = 0.71

Strength correlation factor, e = 111%

Differential lubrication constant, f = 0.15

Specific gravity of OPC = 3.15

Specific gravity of RHA = 2.10

Design Procedure

Stage 1

(a) With given age, aggregate type and cement type shown determine OPC strength. (In this example values shown in Table A.1 are used).Superimpose an interpolating curve for the corresponding value in the DOE charts produced here as Fig A.2.

(b) Increase OPC concrete strength (for W/R = 0.5) by factor e, (in our case 111%) to give the RHA concrete strength for the same W/C ratio. Interpolated as above in Fig. A.2.

(c) From interpolated curve in step 2 determine the W/R ratio for RHA concrete for a strength of 40MPa. (In this case the W/R = 0.60). See Fig. A.2.

(d) Determine the W/C ratio of an OPC concrete of equivalent workability using the theory outlined by Loo and Weragama.

We know that, $W = S + L$

therefore, $L = W - S$

Now, $L_2 = W_2 - S_2$

$= (0.6 - 0.71)R$

$= -0.11[0.5 + (0.5 \times 2.1/3.15)]C$

therefore, $L_2 = -0.092C.$

where R and C are the weights of RHA cement and OPC respectively.

$$L_1 - L_2 = (LC_1 + LA_1) - (LC_2 + LA_2)$$

$= LC_1 - LC_2$ since $LA_1 = LA_2$ as identical types of aggregates are used.

But $LC_1 - LC_2 = fC$

i.e. $L_1 - L_2 = fC$

from which $L_1 = fC + L_2$

then, $L_1 = (f - 0.092)C$

$= (0.15 - 0.092)C$

$= 0.058C.$

The free water W_1, for OPC concrete is given by,

$$W_1 = S_1 + L_1$$

$$= (0.2555 + 0.058)C = 0.313C.$$

Stage 2

Determine the free water for OPC concrete, 75mm slump and the given material properties.

From Table (A.2), which is reproduced from the DOE Tables:

$$\text{free water} = 2/3\ W_f + 1/3\ W_c$$

$$= 2/3\ (225) + 1/3\ (225)$$

$$= 225\ kg/m^3.$$

Stage 3

Determine the weight of cement in OPC concrete:

$$W/C = 0.313$$

then, $C = 225/0.313 = 718.8\ kg/m^3$.

Stage 4

Determine the aggregate content.

concrete density Fig. (7.3) = 2360 kg/m^3

total aggregate content = 2360 - 225 - 718.8

= 1416.2 kg/m^3

proportion of fine aggregate Fig. (7.4) = 29%.

Fine aggregate content = 0.29 x 1416.2

= 410.7 kg/m^3

Coarse aggregate content = 1416.2 - 410.7

= 1005.5 kg/m^3

proportion of 5mm, 10mm, 20mm is 0.5 : 1 : 2

therefore, coarse aggregate content (kg/m^3)

5mm	10mm	20mm
143.6	287.3	574.6

Stage 5

(a) Final proportion of constituents in OPC concrete (kg/m^3)

water	OPC	Sand	5mm	10mm	20mm
225	718.8	410.7	143.6	287.3	574.6

(b) Determine the composition of RHA cement

weight of OPC = 718.8 x 0.5

= 359.4 kg/m^3

weight of RHA = 718.8 x 0.5(2.1/3.15)

= 239.6 kg/m^3

total weight of RHA cement

= 359.4 + 239.6

= 599 kg/m^3

(c) Determine free water in RHA concrete

W/R ratio = 0.6

therefore, free water = 0.6 x 599

= 359.4 kg/m^3

(d) Correction for absorption

sand, 2.3% water absorption = 410.7 / 1.023

= 401.5 kg/m^3

5mm, 1.91% water absorption = 143.6 / 1.019

= 140.9 kg/m^3

10mm, 1.91% water absorption = 287.3 / 1.019

= 281.9 kg/m^3

20mm, 1.19% water absorption = 574.6 / 1.019

= 563.9 kg/m^3

Stage 6

Final proportion of constituents of RHA concrete (kg/m^3)

water	OPC	RHA	Sand	5mm	10mm	20mm
359	359	240	400	140	285	570

TABLE A.1 APPROXIMATE COMPRESSIVE STRENGTHS (N/mm^2) OF CONCRETE MIXES MADE WITH A FREE-WATER/CEMENT RATIO OF 0.5

Type of cement	Type of coarse aggregate	Compressive Strengths (N/mm^2) Age (days) 3	7	28	91
Ordinary Portland (OPC) or sulphate-resisting Portland (SRPC)	Uncrushed	18	27	40	48
	Crushed	23	33	47	55
Rapid-hardening Portland (RHPC)	Uncrushed	25	34	46	53
	Crushed	30	40	53	60

TABLE A.2 APPROXIMATE FREE-WATER CONTENTS (kg/m^3) REQUIRED TO GIVE VARIOUS LEVELS OF WORKABILITY

Slump (mm)		0-10	10-30	30-60	60-180
V-B(s)			>12	6-12	3-6
0-3					
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

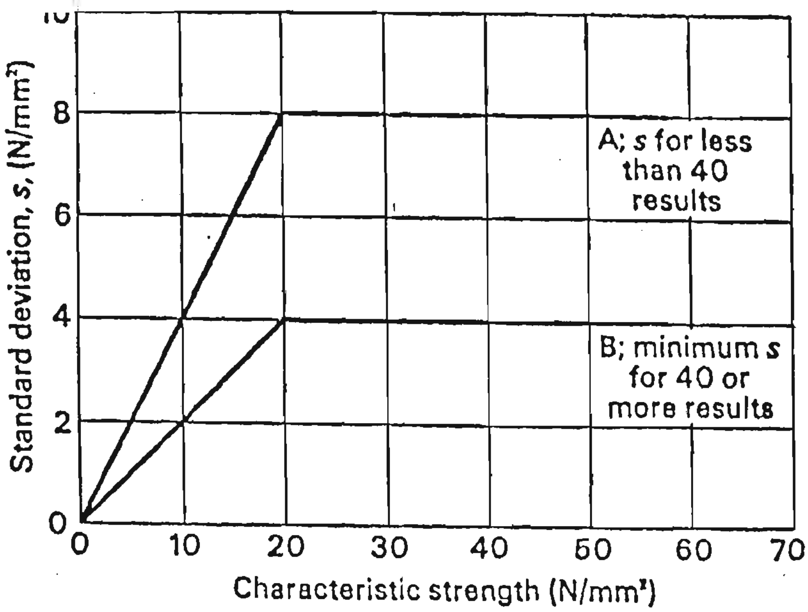
Standard deviation, s, (N/mm²)
A; s for less than 40 results
B; minimum s for 40 or more results
Characteristic strength (N/mm²)
0
10
20
30
40
50
60
70
2
4
6
8

Fig.A.1

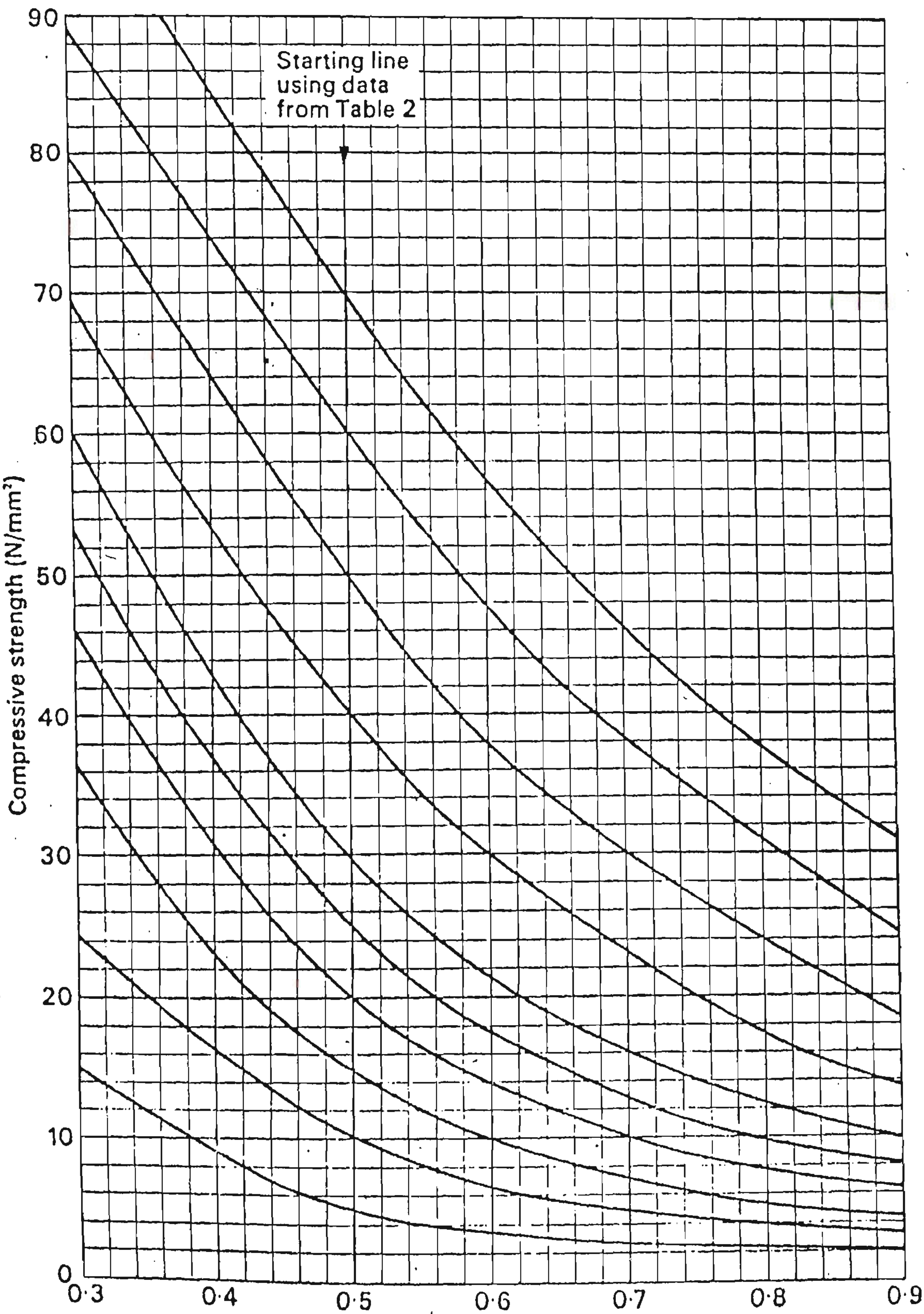
Starting line using data from Table 2
Compressive strength (N/mm²)
0
10
20
30
40
50
60
70
80
90
0·3
0·4
0·5
0·6
0·7
0·8
0·9

Fig.A.2

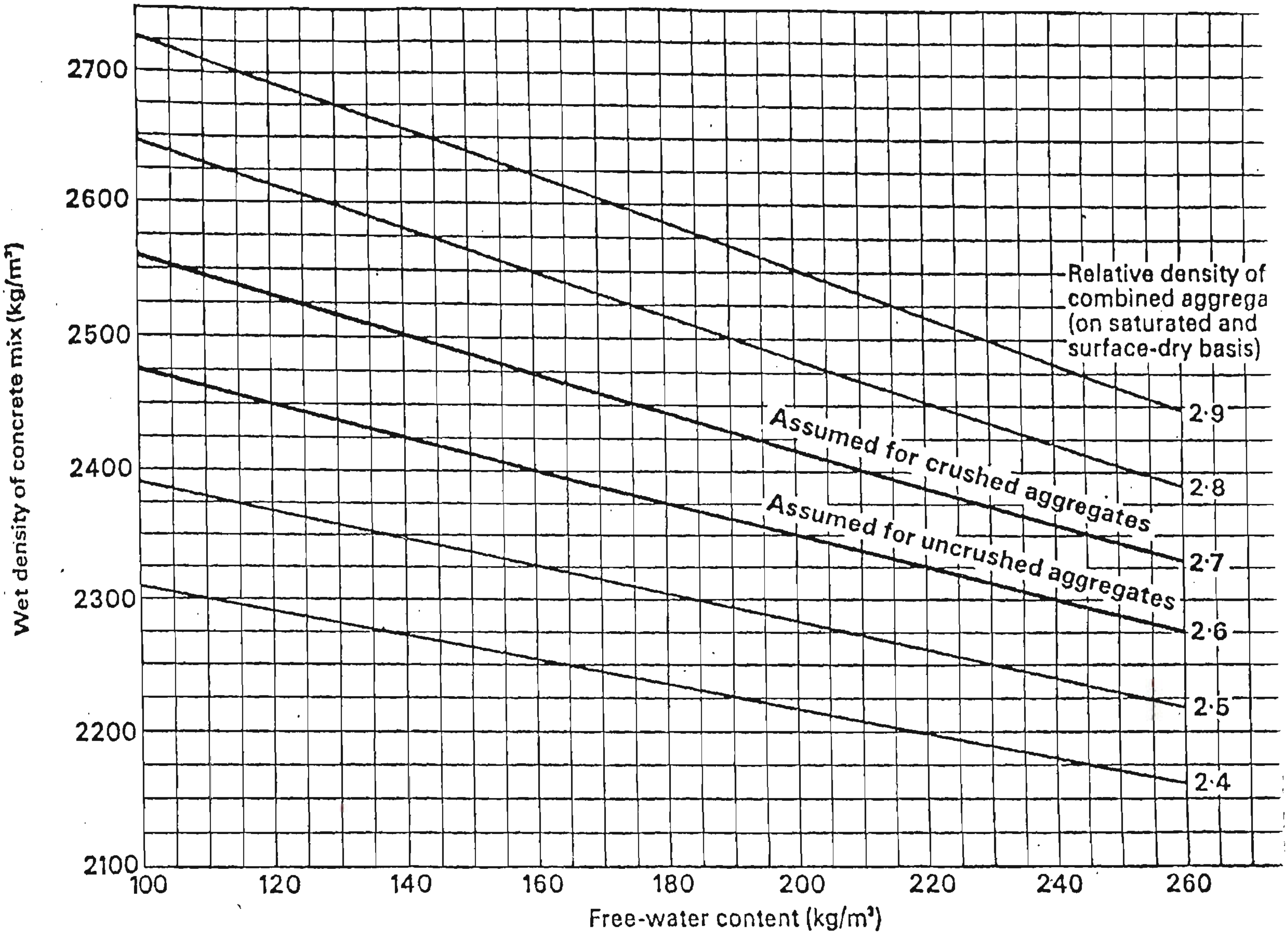
Wet density of concrete mix (kg/m³)
2700
2600
2500
2400
2300
2200
2100
Free-water content (kg/m³)
100
120
140
160
180
200
220
240
260
Relative density of combined aggrega (on saturated and surface-dry basis)
2·9
2·8
2·7
2·6
2·5
2·4
Assumed for crushed aggregates
Assumed for uncrushed aggregates

Fig.A.3

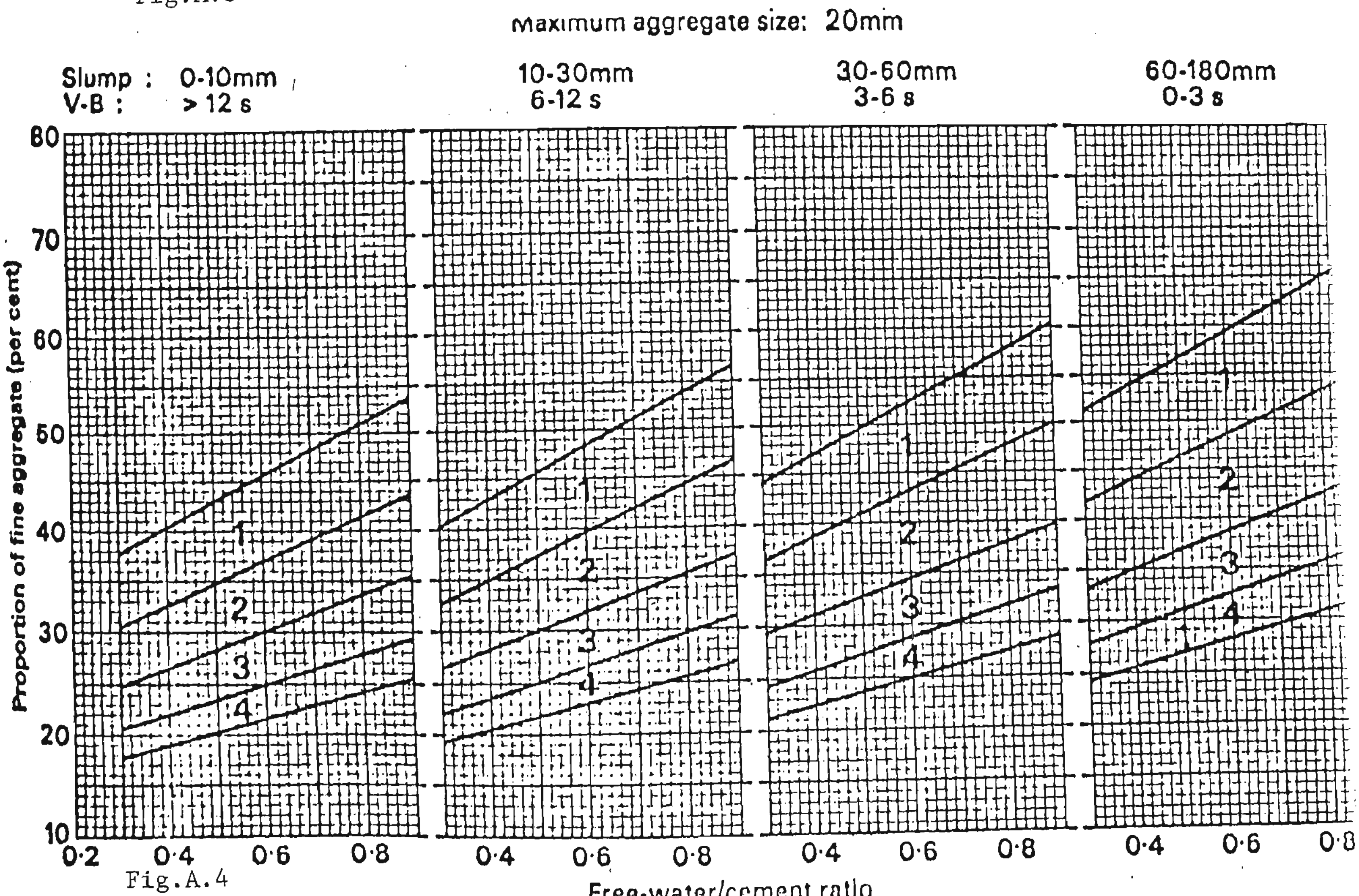
Maximum aggregate size: 20mm
Slump : 0-10mm
V-B : > 12 s
10-30mm
6-12 s
30-60mm
3-6 s
60-180mm
0-3 s
Proportion of fine aggregate (per cent)
80
70
60
50
40
30
20
10
0·2
0·4
0·6
0·8
Free-water/cement ratio
1
2
3
4

Fig.A.4

APPENDIX B

Proportioning of OPC to RHA

The proportioning of OPC to RHA was 50% volume replacement. This is already proved by overseas researchers (AIT), Weragama (1984), to be more reliable and economical for RHA concrete. This volume replacement was found using the specific gravities of both the RHA and OPC.

Specific gravity tests are in accordance with AS1287. CS.1 - 1977.

This is a sample example on the computation of 50% volume replacement of OPC by RHA.

Specific gravity of OPC = 3.15

Specific gravity of RHA = 2.10 (Type C)

$$W_c + W_r = W_{rc} \qquad (1)$$

where: W_c = weight of the OPC.

W_r = weight of the RHA.

W_{rc} = weight of the combined RHA and OPC.

For equal volumes:

$$W_c / 3.15 = W_r / 2.10$$

therefore,

$$W_r = 2.10/3.15 \times W_c \qquad (2)$$

Substitute (2) in (1)

$$W_c + 0.667W_c = W_{rc}$$

therefore,

$$(1 + 0.667)W_c = W_{rc} \qquad (3)$$

$$W_c = 0.5999W_{rc} \qquad (4)$$

and $$W_{rr} = 0.40W_{rc} \qquad (5)$$

Equation (5) gives the weight replacement for RHA with S.G. = 2.10 for 50% volume replacement. This weight replacement is equal to 40% of that of OPC.

Note: The wet density of RHA concrete designed by this method is 2223 kg/m^3 compared with that of the corresponding OPC concrete which is 2360 kg/m^3.