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Keywords

due, strength, reduction, concrete, over, compaction

Disciplines

Engineering | Science and Technology Studies

Publication Details

Howes, R., Hadi, M. N. S. & South, W. (2019). Concrete strength reduction due to over compaction. *Construction and Building Materials*, 197 725-733.

Concrete Strength Reduction Due to Over Compaction

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Abstract:

The purpose of this study was to evaluate the effect of over-compaction on the strength of concrete with regards to commercial and industry practices. Normal concrete, which is commonly used in construction was chosen. Samples were cast using a varying vibration time and testing was performed to determine concrete compressive strength, air content, density and a measure for segregation. These parameters were used to determine the relative sensitivity of concrete to under- versus over-compaction. If segregation was present, it was hypothesized the results would indicate a mathematical relationship between the segregation and strength reduction. This relationship would allow for determination of an optimum vibration time range. It was found in this study there was no segregation or strength reduction in vibrated samples. This result proved the concrete was far more sensitive to under-compaction, with over-compaction not being a practical concern. It was also determined that concrete compressive strength and vibration time had a basically logarithmic relationship and 30 seconds of continuous internal vibration provided the most efficient result of approximately 92% of maximum strength. The study recommends adjustment of standard concrete vibration practice to accommodate the more efficient 30 second duration. Alternatively, a 1.4x 'vibration factor' can be applied during design of compressive strength of concrete to accommodate the current 5-15 second vibration time window.

Keywords: concrete; compaction; segregation; strength; vibration.

1. Introduction

The production of concrete is a multi-stage process with many important factors. However it is generally known that two of the most important factors are the water to cement ratio and the degree of consolidation. 'Concrete consolidation' or 'concrete compaction' is a process by which entrapped air is removed from the concrete's plastic matrix. This reduction in voids results in a denser, stronger concrete mix with reduced permeability and hence increased durability. Conversely, if the entrapped air remains in the concrete matrix, the mix generally has reduced strength and an increased permeability (1).

There are many methods to achieve concrete consolidation in commercial practice, chief among them being vibration. The flexible shaft vibrator is typically the most widely used form of internal vibrator for in-situ application, and internal vibration itself is generally the most typical method of concrete compaction in practical industry (1). The effects of the vibrator frequency and area of influence have been exhaustively discussed by ACI Standards 309.1R (2) and later collated by Neville (3). However, the 'optimal limits' between over and under vibration are never thoroughly quantitatively investigated due to the inherent differences between every concrete mix.

This study explores the misinformation that has penetrated commercial practices with regard to the vibration and over consolidation of concrete and seeks to provide guidance in ensuring optimum consolidation of a concrete mix.

The aim of this study is to provide industry operators and supervising engineers with clear guidelines to allow optimum compaction of concrete without concern for over-compaction and to test if there are major quantifiable detriments to exceeding the optimum vibration time of a standardised concrete mix when using internal vibration.

The scope of this investigation extends to the selection and analysis of one value of concrete slump and water to cement ratio for a standardised mix design due to time constraints.

58 The objectives of this study are to:

- 59 a) Determine if concrete strength is reduced by extended internal vibration;
- 60 b) Determine if any concrete strength reduction is due to segregation;
- 61 c) Determine relative sensitivity of concrete to under vs over vibration;
- 62 d) Analyse concrete relative sensitivity in terms of cost/benefit for industry;
- 63 e) Propose optimum vibration time range to ensure full compaction.

64 Concrete compaction operators are instructed to be careful not to 'over-vibrate' concrete due to the risk of
65 segregation. An outcome of this instruction is construction crews moving the head of an internal vibrator
66 before air bubbles have stopped coming to the surface of the concrete mix, leaving entrapped air in the
67 finished product. This can result in diminished concrete performance, as much as three to five percent
68 strength reduction for every one percent of entrapped air (4). In contrast to these field practices,
69 guidelines from Cement, Concrete & Aggregates Australia (5) qualitatively outline that under-vibrating
70 concrete yields worse results than over-vibrating it.

71
72 Segregation is one of the major impacts of over-vibration of concrete and typically occurs due to
73 inexperience or lack of training of operators (1). The process occurs as the extended vibration of the mix
74 reduces the internal friction and cohesion long enough for gravity to take effect on the coarse aggregate
75 particles, causing them to sink (ibid).

76
77 Segregation can be described as a function of many different factors including vibration time, temperature,
78 internal friction, cohesion and mass of cement and coarse and fine aggregates.

79
80 Neville (3) suggests that differentiation in particle size and specific gravity is the primary cause of
81 segregation, however concedes that the extent of segregation can be controlled in its handling as is
82 proposed to be investigated here. Given this argument, it can be seen that to accurately analyse the effect
83 of vibration time on segregation, all other factors listed above must be controlled. To achieve this a
84 standardised mix design must be developed to be sufficiently repeatable to keep mass, cohesion and

internal friction factors constant. As all testing is carried out at room temperature within a short time frame, the temperature is not expected to be a significant factor.

The degree of segregation in a concrete mix is not easily observed in a newly hardened state, however the effects on hardened state properties can be very severe. Without a good distribution of aggregate throughout the mix the compressive and tensile strength of the concrete are far reduced. The mortar layer that settles on top of the mix is also very susceptible to abrasion forces, meaning the concrete is likely to wear or flake away very quickly. As these risks are not easily observable once the concrete has been cast, it is vital that the relationship between vibration time and segregation be understood as the cost involved in the complete removal and replacement of segregated concrete can be extensive.

Similarly, the effects of under-vibration are just as damaging to hardened state properties but tend to occur within a much narrower timeframe relative to the optimum time of vibration, typically making them of greater concern. Honeycombing is one of the primary effects of under-vibration where the mortar does not adequately flow into the spaces between the coarse aggregate (1).

However, the remaining entrapped air in an under-vibrated mix is more detrimental to concrete strength and is impossible to remove once hardened. The entrapped air as well as decreasing strength, decreases the durability of the concrete by increasing permeability.

From the highly damaging effects of over and under vibration outlined it is clear that further understanding of these principles is essential for engineers and immersion vibrator operators. The optimum compromise between under and over vibration is quantified to ensure that concrete always achieves its maximum potential for strength and durability.

The aim of this study is to show if over-compaction can lead to a reduction in the compressive strength of concrete. The concrete chosen is a normal commonly used concrete.

112

113   **1.1   *Related Studies***

114   The process of consolidation dramatically reduces the internal friction of the concrete mix, temporarily
115   liquefying the mortar and allowing the concrete to reduce to a denser state (1). It has been found in other
116   studies, for example Whiting et al. (6), that for every 5% decrease in degree of consolidation, concrete
117   loses approximately 30% of its compressive strength. It has also been found in previous experiments that
118   over-consolidation tends to have minimal effect on concrete compressive strength (ibid), yet it remains a
119   concern in the commercial zeitgeist. This suggests further research needs to be undertaken to clarify this
120   position, perhaps establishing more direct links and easily measurable guidelines on standard operation.

121

122   Other related studies using vibrating tables such as Arslan et al. (7) have been previously explored with
123   results indicating a vibration time between 35 and 60 seconds yields maximum compaction depending on
124   mix proportions. The same study has also shown that strength reduction begins to occur at typically 60-80
125   seconds (7). It can be seen that the vibration time is significantly in excess of the 5-15 seconds typical
126   compaction time for the internal vibrator currently recommended by Cement, Concrete & Aggregates
127   Australia (5).

128

129   Qualitative limits have been described by Neville (3) such that vibration should continue until air bubbles
130   have ceased coming to the concrete surface, or that vibration completeness can be judged by the surface
131   appearance of the concrete in that it should not be honeycombed nor show an excess of mortar. However
132   as long as economic constraints force operators to finish quickly rather than thoroughly, and the operators
133   fear of under and over vibration remain equal then invariably concrete will continue to be improperly
134   compacted.

135

136   The relationship between concrete vibration time and hardened state properties such as compressive
137   strength and density were recently explored by Daukšys et al. (8) on a shorter scale of zero to twelve
138   seconds and found to be vaguely linear over this time. The addition of super-plasticiser in this case has

meant the change in density and strength of these samples although basically linear is extremely small if not negligible. Another study by Forssblad and Sällström (9) suggests that a 'vibration effort' of 200 to 350 s/m³ of vibration is the optimum for practical application. The study also extends up to a possible 600 s/m³ for some specific situations. When these figures are reduced to volumes equivalent to a Ø100 mm cylinder however the suggested vibration time with a 55-60 mm diameter vibrating head compactor is less than one second. Using the suggested relationship by Forssblad and Sällström (9) of $(D/57)^2$ (where D is the diameter of compacting head) to convert this result to apply to a 28 mm diameter compacting head leads to a suggested vibration time of about four seconds (even using the extreme 600 s/m³ vibration effort). It can be seen then that this relationship breaks down when smaller volume or more technical concrete work is discussed.

Li et al. [10] investigated the interfacial transition zoned in recycled concrete with different mixing approaches. The role of different additives in fresh cement asphalt emulsion paste was investigated in [11]. Long et al. [12] investigated the use of self-compacting concrete as a filling layer in high-speed railway.

It is clear from the review of literature above, there is no maximum limit of compaction time, beyond which concrete strength will deteriorate. The aim of this study is to investigate if such a time limit exists.

2. Methodology

Compressive testing as well as air content and dry density testing are selected as the best candidates to assess objectives 'a' and 'b' as listed in Section 1. The air content and dry density tests allow the correlation of the expected decrease in air content and increase in density with any apparent reduction in strength. As a reduction in air content and increase in density is normally associated with an increase in strength this tends to indicate that strength is reduced due to segregation. This is further correlated by casting one cylinder of each vibration sample to be saw-cut for visual inspection of aggregate distribution. The air content testing is performed to Australian Standards AS1012.4.2 (13) using the 50 mm slump mix concrete to ±5 mm accuracy as per AS1012.2 (14). The dry density of compressive strength samples is also determined to Australian Standards per AS1012.12.1 (15) by the 'Rapid' method. The remaining

objectives are achieved through analysis of test data and cost/benefit analysis is to be undertaken to evaluate whole of life cost implications of incomplete compaction.

The mix design for the concrete to be tested was determined using steps outlined in ACI 211.1-91 (16) and is further refined through multiple trials adjusting the mix to suit slump results. As the experiment proposed to vibrate the samples for an extensive period of time it was also proposed to include a High Range Water Reducer (superplasticiser) to maintain workability of the concrete at the higher vibration time steps shown in Table 1. The time steps chosen were 0, 15, 30, 60, 90, 120 and 180 seconds. These steps were chosen to represent the possible vibration times in the field.

Through this process the following final mix design was developed. The mix design is shown in Table 2. The washed and oven dried 20 mm aggregate used was 1269 kg/m³, washed coarse sand was 761.4 kg/m³, cement was 444 kg/m³, water was 173 kg/m³ (0.36 w/c ratio + 1% of dried aggregate weight), and Brand A HRWR at 2.89 l/m³. The target compressive strength at 28 days was 60 MPa.

This mix was found to have a slump of 60 mm and one cylinder was cast for compression testing.

The cylinder was compressed to failure at an age of 4 days yielding a compressive strength of 33 MPa. This can be estimated to a 28-day compressive strength of 61 MPa using Equation (1) from ACI standards with the assumption of a Type I cement for determining constants 'a' and 'b' per ACI 209.2R-08 (17).

$$\begin{aligned} f_{\text{cmt}} &= \left[\frac{t}{a + bt} \right] f_{\text{cm28}} \\ \therefore f_{\text{cm28}} &= \left[\frac{a + bt}{t} \right] f_{\text{cmt}} \end{aligned} \tag{1}$$

Where:

f_{cm28} = concrete mean compressive cylinder strength at 28 days, MPa;

189 f_{cmt} = concrete mean compressive cylinder strength, 33 MPa used;
 190 a, b = constants used to describe the strength gain developments of the concrete,
 191 a = 4.0 and b = 0.85 used per Table A.4 (17); and
 192 t = age of concrete, 4 days used.

193 Given that an operator in the field is unlikely to remain with a vibrating head in one position for an
 194 extensive time period, the experiments are capped at 3 minutes of continuous vibration in one location. A
 195 selection of vibration times was made within this 3 minute envelope to best represent an even distribution
 196 of results. As the visual inspection samples were less critical it was decided to only cast one cylinder per
 197 time step, but three cylinders per time step for compressive strength testing. Table 1 summarises the
 198 number of samples prepared and the selected vibration time steps.

199
 200 As can be seen the experiment required a total of 35 samples to be tested of which 28 samples were cast
 201 as cylinders. As the vibrating head (13,000 vpm) needs to be inserted into the mix it is natural that the top
 202 of the sample receives slightly more vibration time than the bottom. In an effort to standardise this and
 203 ensure that the selected vibration duration is the average vibration time of the sample, the vibrating head
 204 was inserted and withdrawn from the mix at a rate of ~0.1 m/s (Only slightly faster than the 80 mm/s
 205 recommended by Neville (3). This means that by the time the vibrating head reaches the bottom of the
 206 sample, the top of the sample has received ~2 second of vibration, yielding the correct average value as
 207 can be seen in Fig. 1 using the 15 second time step as an example.

208
 209 To minimise the time that concrete sits idle before being vibrated the testing process was split into four
 210 batches of cylinders as outlined in Table 3. Small individual batches were prepared for air content testing
 211 as the required time to perform each test is unknown. The separate batching of air content samples is
 212 necessary as the time required to test each sample while the mix is fresh becomes cumulatively too
 213 extensive between the first and the last sample. The pattern developed in Table 3 maintains the same idle
 214 time for all corresponding concrete cylinders allowing for an easier and more reliable correlation of results.
 215 It is noted that this does not include the time it takes to transfer the concrete mixture to the cylinders.

216

217 To ensure that each sample is vibrated in the same location (ie the vibrating head is placed as
218 close as possible to the centre mark) a template was considered to be constructed simply from a
219 thin piece of MDF timber. To develop this template for the cylinder the outside diameter of the
220 cylinder was measured and marked on a 150 mm x 150 mm square of MDF along with the centre
221 point. Three locating screws were drilled through the MDF just outside the inscribed circle to
222 hold the template in position. Finally, a hole of 30 mm diameter was to be drilled through the
223 centre mark to allow the Ø28mm vibrating head to pass through. The point where the surface of
224 the concrete is broken by the vibrating head was also to be just visible at this point for vibration
225 timing. A second template was also developed for the air meter using the same method, except
226 the MDF square was to be 250mm x 250mm.

227 Figure 22 shows a diagram of the cylinder template.

228

229

230

231 **2.1 Air Content Metering**

232 Air Content testing was performed in accordance with Australian Standards (13) with a newly calibrated
233 White Meter (Air Meter), shown in Fig. 3. Each Air Content test had its concrete mixed individually due to
234 the time sensitivity of the test. This is due to AS1012.4.2 (13) requiring two tests be performed on each
235 sample and an average of 'apparent air content' taken between these two tests. As part of this process an
236 'Aggregate Correction Factor' was also determined per AS1012.4.2 CL9 (13). As the volume of the air pot
237 is constant, as well as the concrete batch size and proportion of coarse and fine aggregates, the
238 aggregate correction factor is the same for all test cylinders and therefore need only be performed once.
239 Results from Air Content testing were recorded for comparison against dry density and compressive
240 strength results.

241

242   **2.2   Compressive Strength and Dry Density Testing**

243   After all the cylinder samples had been cured in a water bath for 28 days, they were surface dried and
244   measured using digital vernier calipers accurate to 0.01 mm and weighed in accordance with
245   AS1012.12.1:1998 (15). After all measurements were recorded the samples were capped and
246   compressive testing was carried out to Australian Standards (18). Records of all forces applied at failure
247   were tabulated and compressive stress calculated and graphed against air content and dry density.

248

249   **2.3   Visual Inspection of Segregation**

250   To confirm the presence and extent of aggregate segregation within cylinder samples visual inspections
251   were performed. To achieve this, one cylinder per vibration time step was cast to be cut down the
252   cylinder's long axis exposing the position and distribution of coarse aggregate within the sample. To
253   create a clean cut through the sample a diamond blade drop saw was used. Each cylinder was clamped in
254   position on the sliding cutting bed, cut through individually and relabeled for identification. Images were
255   then taken of these samples for later analysis.

256

257   **3.   Results and Discussion**

258

259   **3.1   Density**

260   All batches prepared and tested agreed reasonably well with each other. As shown in Tables 4 and 5, it
261   also appeared that the density demonstrated an approximate asymptotic trend, however it is interesting
262   from the data that all concrete batches appear to have their density converging to 2500 kg/m³ at the 180
263   second time step. This seemed to indicate that by 180 seconds of internal vibration the concrete mix has
264   reached a maximum possible density. From the results a reliable average density could be developed as
265   in Figure 4.

266

267

It can be seen from Tables 4 and 5 and Figure 1 that between the 5 and 15 second vibration times the concrete has achieved roughly between 97.6 and 98.1 percent maximum density. Therefore, from a viewpoint purely looking at concrete density, the five to fifteen second time window appeared to be sufficient for most applications. As expected, the data confirms that there is no decrease in density at any point with extended vibration and this is used to evaluate the concrete strength performance.

3.2 Compressive Strength

All cylinders experienced a conical failure profile as is expected for a compression cylinder. All batches again exhibited a basically asymptotic data trend allowing the average compressive strength graph shown in Figure 5 to be developed.

It can be seen in Tables 6 and 7 and Figure 2 that the average data follows a nearly perfect asymptotic function with no strength decrease evident due to the extended vibration time. This would seem to suggest that there is no influence from segregation on the tested samples.

Considering once again the commercial industry practice of a 5-15 second vibration time envelope, it can be seen that the concrete compressive strength for a similar general purpose mix design ranges between approximately 72 and 85 percent of maximum strength.

3.3 Air Content

Air content testing revealed that the very long vibration time continuously reduced air content at a diminishing rate as seen in Table 8 and Figure 3. Air bubbles released from the concrete mix during vibration ceased to break the surface at the 15 second mark, yet total air content continued to reduce from approximately 1.22% to 0.3% at the 180 second mark. Therefore, a significant portion (35.6% of total air content in sample) of the concrete air content is evacuated by micro air bubbles not so easily visually observed.

Considering the industry guidelines of 5-15 seconds vibration suggested by Cement, Concrete & Aggregates Australia (5), Figure 6 indicates the air content removed is between 34.1% and 53.4% of the total air content. By comparison extending out completely to the 180 second vibration time reduces total air content by 89.7%.

3.4 Visual Inspection

From an inspection of the sawn samples, it was seen that none presented with significant segregation in terms of the vertical distribution of coarse aggregate particles (see Table 9 and Figure 4)

However, in the zero second sample the cement phase of the concrete was in relatively higher quantity towards the base of the sample. This had left the aggregate bound reasonably loosely in the top half of the cylinder.

This was an interesting result for two reasons: First, it appeared that the mechanism of segregation in an un-compacted sample is by the movement of the liquid phase under gravity to the base of the sample while the coarse aggregate remains in place. Second, this un-compacted sample is the most segregated of all the samples. Excluding the possible impacts of compaction dynamics in larger field applications, this would seem to indicate that segregation due to extensive vibration does not play as large a role in general concrete production as indicated in current industry literature per Cement, Concrete & Aggregates Australia (5).

4.0 Discussion

By combining the results from Section 3.1 and 3.3 it appears that while the extended vibration time markedly reduced the sample air content, it had little effect on the overall density. This is not unexpected, as the volume of air within the sample was always expected to be a very small fraction of the total cylinder volume. It does indicate however that concrete durability could potentially benefit from these more extreme vibration times as the air content decreases by between an additional 34.1% and 53.4% over

what it would have within general practice ranges. This additional reduction in air content could improve protection from chloride ion attack in marine structures as well as resist freeze/thaw conditions in harsher climates.

For the 5-15 second vibration time window to apply it can be seen in Section 3.2 that a multiplying factor of approximately 1.4x must be applied to the design compressive strength to ensure that 72%-85% compaction is sufficient. As it was established in Section 3.2 that the concrete strength, developed under standard commercial practice per Cement, Concrete & Aggregates Australia (5), for this mix is 72-85% of maximum, using Cordells Commercial & Industrial Building Cost Guide (19) the financial ramifications of some scenarios can be estimated.

For a basic cost comparison, if a concrete design required a 32 MPa characteristic compressive strength including relevant factors of safety, then by applying the percentage rates developed above the required concrete strength using standard vibrating practice is:

$$\frac{32}{0.72} \leftrightarrow \frac{32}{0.85} \% = 44.4MPa \leftrightarrow 37.7MPa \quad (2)$$

Therefore, as a minimum 40 MPa concrete should be specified, with 50 MPa concrete being required for more critical situations. For a basic slab on ground, the unit rates yield a cost difference of AUD\$13.58 per cubic metre poured. This price difference is the same for other concrete applications such as strip footings and suspended slabs per Cordell (19) and therefore correlates well to being due solely to the increase in characteristic compressive strength. However, maintenance cost was also considered by fatigue analysis as per Figure 8 from ASTM (20) and applying a factor of safety of two.

If such a design had an applied load of 16 MPa compression, a factor of safety of two requires the concrete to be 32 MPa characteristic compressive strength. Applying Figure 8 this implies that the concrete has roughly 10^7 cycles to failure. However, applying the concrete strength percentage reductions from Section 3.2 yields an actual static strength of between 23.04 MPa and 27.2 MPa. Therefore, the

actual cycles to failure can then be estimated to be between 2.45×10^4 and 9.53×10^5 . It can be seen then that the reduction in characteristic compressive strength (assuming this roughly corresponds to the maximum strength) vastly reduces the number of available cycles in the design. The reduced strength concrete approximately reduces the number of cycles to failure to somewhere between 0.245% and 9.53% of what it should theoretically be.

5. Conclusions

From the body of results it has been found in this study that a normal class concrete of similar mix design does not experience strength reduction from excessive internal vibration measured up to 180 seconds. There was also no significant segregation found in any vibrated sample from the images studied. This proves false any notion of over-vibration in similar concretes within the limits employed. As there is no evidence of over-vibration, it follows that the sensitivity of concrete to under vs over vibration is unable to be defined as it is infinite. While this is not quantitatively helpful, it conclusively demonstrates in a qualitative fashion that under vibration is by far more concerning than over vibration. The graph in Figure 2 demonstrated this well due to the near asymptotic data trend.

In terms of economic consequences, if the effects of improper compaction are accounted for in the design phase, then the capital difference is minimal. By comparison, if the implications of the current vibration guidelines are not considered during the design phase, then the whole of life costs can be up to ten times more expensive – with structures requiring regular replacement or modification to remain serviceable. It is also determined that by over designing concrete characteristic compressive strength by 30-40% these risks can be partially addressed. Even if the cost effect is ignored, in a modern age where concrete is used for roads, bridges and buildings among many other structures, constant inspections and maintenance is certainly undesirable. The practical implications on road and traffic networks if 100 year design life bridges were needing replacement after 10 years are staggering.

As discussed in Section 3.2, the range of compressive strength applying current vibration practice is between 72% and 85% for 5 to 15 seconds of vibration. It is proposed that instead of the industry accepted 5-15 second time window for adequate vibration suggested by Cement, Concrete & Aggregates

Australia (5) a new range be proposed in satisfaction of objective 'e' listed in Section 1. This study suggests that 15-30 seconds is a more appropriate window as it narrows the achievable strength to 85 to 92% of maximum. This value agrees well with the previous works mentioned in Section 2 such as that by Arslan et al. (7) which recommend 30 seconds as the optimum vibration time for high performance concrete.

Failing this extended vibration time however, engineers and other design officers need to be aware of the percentage reduction in strength in current practice and adjust their design strengths and factors of safety accordingly. This requirement is an additional 30-40% characteristic compressive strength to counterbalance the loss of strength due to improper compaction with minimal capital cost effect on small projects and maintaining an adequate structure life. To account for the worst result (being 72% of concrete strength), this study suggests an additional 'vibration factor' of 1.4x be applied to compressive strength selection in concrete, as the concrete will have less compressive strength.

Due to all the reasons outlined above, this study has been successful in determining that strength reduction due to over compaction is not a possible outcome when considering practical limits for a normal class concrete. By extension, this study has also demonstrated that the standard practices employed for concrete compaction are not optimised to achieve the most efficient level of concrete compressive strength. It has also been successful in showing there are relevant commercial impacts to this and that the design process should be adjusted as well as the industrial practices.

Acknowledgement

The authors would like to thank the technical staff of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia for their assistance in preparing and executing tests.

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Table 1 - Testing Samples

Duration of Vibration (seconds)	Number of samples tested		
	Compressive Strength	Air Content	Saw-cut for visual inspection
0	3	1	1
15	3	1	1
30	3	1	1
60	3	1	1
90	3	1	1
120	3	1	1
180	3	1	1

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Table 2 - Mix design used in preparing the concrete

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Component	Proportion
20 mm aggregate	1269 kg/m ³
Washed coarse sand	761.4 kg/m ³
Cement	444 kg/m ³
Water	173 l/m ³
High Range Water Reduce (HRWR)	2.89 l/m ³

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Table 3 - Cumulative Time to Vibration

Batch Number	Vibration Time	Cumulative Time to Vibration Start	
	(sec)	(sec)	(mins)
Batch 1-4	0	0	0
	15	0	0
	30	15	0.25
	60	45	0.75
	90	105	1.75
	120	195	3.25
	180	315	5.25

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Table 4 - Sample Measurements and Density

Batch No	Vibration Time	Diameter 1	Diameter 2	Average Diameter	Height	Volume	Weight	Density
	(s)	(mm)	(mm)	(mm)	(mm)	(m ³)	(kg)	(kg/m ³)
1	0	100.52	101.52	101.02	204.3	1.64E-03	3.63	2217.4
1	15	101.70	100.98	101.34	204.5	1.65E-03	4.02	2436.8
1	30	100.67	101.74	101.21	205.7	1.65E-03	4.07	2459.5
1	60	101.15	101.52	101.34	207.4	1.67E-03	4.08	2439.4
1	90	99.69	99.67	99.68	200.6	1.57E-03	3.87	2471.8
1	120	101.62	101.32	101.47	203.8	1.65E-03	4.09	2481.2
1	180	101.07	101.67	101.37	204.6	1.65E-03	4.12	2495.3
3	0	101.63	101.75	101.69	204.5	1.66E-03	3.72	2239.8
3	15	101.17	101.16	101.17	205.0	1.65E-03	4.07	2470.0
3	30	101.55	101.65	101.60	204.5	1.66E-03	4.09	2466.9
3	60	99.30	99.09	99.20	200.0	1.55E-03	3.87	2503.9
3	90	99.65	99.27	99.46	201.0	1.56E-03	3.89	2491.0
3	120	100.24	101.14	100.69	202.3	1.61E-03	4.09	2539.6
3	180	100.86	101.33	101.10	204.0	1.64E-03	4.11	2509.9
4	0	101.26	101.60	101.43	203.5	1.64E-03	3.67	2231.9
4	15	101.42	101.52	101.47	204.5	1.65E-03	4.06	2455.1
4	30	101.49	101.04	101.27	203.0	1.63E-03	4.07	2489.4
4	60	101.94	101.19	101.57	204.5	1.66E-03	4.09	2468.6
4	90	101.78	101.20	101.49	204.0	1.65E-03	4.11	2490.4
4	120	101.60	101.52	101.56	203.0	1.64E-03	4.09	2487.1
4	180	101.71	101.49	101.60	205.0	1.66E-03	4.16	2503.0

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Table 5 - Average Density Calculation

Properties		Vibration Time Steps (s)						
		0	15	30	60	90	120	180
Density B1	(kg/m ³)	2217.4	2436.8	2459.5	2439.4	2471.8	2481.2	2495.3
Density B3	(kg/m ³)	2239.8	N/A	2466.9	2503.9	2491.0	2539.6	2509.9
Density B4	(kg/m ³)	2231.9	2455.1	2489.4	2468.6	2490.4	2487.1	2503.0
Average Density	(kg/m ³)	2229.7	2445.9	2471.9	2470.6	2484.4	2502.7	2502.8

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Table 6 - Compressive Strength Results

Batch No	Vibration Time	Area	Axial Crushing Force	28-day Compressive Strength
	(s)	(mm ²)	(kN)	(MPa)
1	0	8015.02	188.5	23.5
1	15	8065.879	366	45.4
1	30	8044.403	375	46.6
1	60	8065.083	415	51.5
1	90	7803.797	422	54.1
1	120	8086.586	476	58.9
1	180	8070.655	470	58.2
3	0	8121.689	340	41.9
3	15	8038.045	305	37.9
3	30	8107.32	625	77.1
3	60	7728.041	565	73.1
3	90	7769.388	602	77.5
3	120	7962.741	627	78.7
3	180	8026.926	660	82.2
4	0	8080.212	275	34.0
4	15	8086.586	594	73.5
4	30	8053.944	666	82.7
4	60	8101.735	675	83.3
4	90	8089.774	655	81.0
4	120	8100.937	655	80.9
4	180	8107.32	645	79.6

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Table 7 - Average Calculations Table

Properties		Vibration Time Steps (s)						
		0	15	30	60	90	120	180
Compressive Strength B1	(MPa)	23.5	45.4	46.6	51.5	54.1	58.9	58.2
Compressive Strength B3	(MPa)	41.9	N/A	77.1	73.1	77.5	78.7	82.2
Compressive Strength B4	(MPa)	34.0	73.5	82.7	83.3	81.0	80.9	79.6
Average Compressive Strength	(MPa)	33.1	59.4	68.8	69.3	70.8	72.8	73.3

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Table 8 - Air Content

Vibration Time	Measured Air Content (1st Trial)	Measured Air Content (2nd Trial)	Average Air Content	Aggregate Correction Factor	Air Content
(s)	(%)	(%)	(%)	(%)	(%)
0	3.1	3.3	3.2	0.3	2.9
15	1.6	1.7	1.65	0.3	1.35
30	1.2	1.4	1.3	0.3	1
60	1	1	1	0.3	0.7
90	0.9	0.8	0.85	0.3	0.55
120	0.6	0.8	0.7	0.3	0.4
180	0.6	0.6	0.6	0.3	0.3

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Table 9 - Segregation Number Table

Vibration Time	No. Coarse Particles in Sample Top Half	No. Coarse Particles in Sample Bottom Half	Proportion of Aggregate in Lower Half	Segregation Number
0	136	121	0.471	0
15	161	161	0.500	0
30	178	166	0.483	0
60	157	146	0.482	0
90	172	177	0.507	0.007
120	187	162	0.464	0
180	154	167	0.520	0.020

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Figure 1 - Average Sample Vibrations (15 second Example)

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Figure 2 - Vibrating Head Locator Template

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Figure 3 - Air Content Meter

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Figure 4 - Average Density vs Vibration Time

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Figure 5 - Average Compressive Strength vs Vibration Time

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Figure 6 - Air Content vs Vibration Time

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Figure 7 - 180s Sawn Sample

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Figure 8 - Fatigue Strength Curve of Concrete (ASTM (17) p. 138)