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Characterization of Vibration Effects on the Internal Structure and Strength of Regular and High Strength Recycled Concrete

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ABSTRACT

There is a need for more in depth understanding of the consolidation effect of concrete on its durability, especially in tropical climates. During placement of fresh concrete in molds vibration is required to prevent quality problems such as honeycombs and desegregation. Nevertheless, precise monitoring of concrete vibration time has been avoided by construction professionals. This results in concrete durability reduction of appropriately designed concrete due to variation in aggregate settlement, air void content and change in water to cement ratio. In this study, the effects of vibration time on concrete strength, aggregate segregation, and physical properties were experimentally investigated on regular and high strength recycled concrete. The optimum vibration times are to be determined as a tool for construction professionals to address concrete consolidation issues associated with improper vibration time. The study reports on the test results of regular and high strength recycled concrete with a vibrating table and a rod vibrator for varying vibration times. The result of vibration on the internal structure is also studied as aggregate packing greatly affects concrete durability. It was concluded that an ideal vibration time period for recycled concrete should be based on a combination of concrete properties affecting durability instead of a specific property as vibration of concrete significantly affects concrete strength, porosity, density, viscosity, aggregate segregation, and consolidation. Ideal vibration period for recycled regular and high strength concrete provided the best combination of compressive and splitting tensile strengths, consolidation of aggregate particles, aggregate packing, and air void content to enhance the overall durability of material.

Keywords: Regular strength concrete, high strength concrete, recycled concrete, vibration, consolidation, segregation, durability.

1.0 INTRODUCTION

Durability of concrete is the quality survival of the material in the living environmental conditions for the duration of its design life. Each phase of the concrete—aggregates, hydrated cement paste, interfacial transition zone (ITZ)—can be adjusted through the design or manufacturing process to enhance durability and prevent material degeneration.

The compressive strength of concrete can increase with vibration by about 3% to 5% for each percent of air removed. Vibration consolidates concrete in two stages: 1) by moving the concrete particles and 2) by removing the entrapped air. Vibration settles concrete by subjecting the individual particles to a rapid succession of impulses causing differential motion where each particle moves independently of the other (Neville, 2011; Safawi *et al.*, 2005). As the concrete particles consolidate, the trapped air is forced to the surface thus allowing the concrete to flow into corners, around rebar and flush against the form face. This eliminates voids (honeycombing) and brings paste to the surface to assist in the finishing.

Vibration of fresh concrete reduces its internal shear strength, and enables concrete to momentarily liquefy to facilitate the consolidation process. When the vibration stops, the liquid flow subsides. As concrete flows better with vibration the mix can contain less water and provide greater strength for the finished product. The concrete is not fully consolidated until both vibration stages of moving the particles and removing the trapped air are complete. Over-vibration for most concrete mixes create the problem of segregation in which the denser aggregates settle to the bottom while the lighter cement paste moves upward creating less overall uniformity, and more heterogeneity amongst aggregates. However, if the vibration time is too short, some of the smaller air bubbles will not have enough time to move to the surface (Arslan *et al.*, 2011; Hughes, 1972; Safawi *et al.*, 2005).

An adequately vibrated mix will contain optimal packing of particles as entrapped air is removed, and it consolidates maximizing its strength, density, and durability. However, inadequate concrete vibration and under-consolidation reduces its density resulting in an increased permeability and consequently less resistance to deterioration. Other important characteristics like rebar bond capacity and appearance will be affected.

Over consolidated concrete encounter laitance, a phenomenon when the upper weaker layer segregates and forms the potential plane of weakness leading to possible and premature failure of the concrete structure during the design life.

Varying both the natural components of concrete andmethod of placement creates a change in the material properties (strength, porosity, density, viscosity, durability, and workability). Immediately after placement, concrete can contain about 20% entrapped air (Safawi *et al.*, 2005). The amount of vibration required varies according to the properties of individual components, the type of mix, its slump, the placement method, form size, and the amount of reinforcing steel amongst other properties.

Arslan *et al.* (2011) determined that as the water to cement (w/c) ratio increased, the extended vibration time negatively affected the strength of ordinary concrete due to increase fluidity and the segregation of course aggregates. The author also concluded that a suitable vibration time for ordinary concrete was at 60s vibrations per minute (VPM), since the vibration times longer or less than approximately 60s, decreases compressive strength. The compressive strengths of samples subjected to 240s vibration times were approximately 36% lower than those of 60s vibration time depending on w/c ratios. Contrary to regular strength concrete, Arslan *et al.* determined the suitable vibration time for high strength concrete to be shorter at a value was 30s due to the addition of superplasticizer and the higher fluidity. In their study, Arslan *et al.* used a high dosage super plasticizer for obtaining workable mixture and fine pozzolanic admixture such as micro silica that would permit fluidity in the concrete mixes.

Other researchers (Date *et al.*, 2012), investigated the mix parameter and the mixing method on the productivity of concrete. The method used was a two-stage mixing method where water was divided into two portions and each portion is added and mixed with cement at different times. In the mixing, the surface of sand was kept at an appropriate moist state during the first mixing. In the next process (second mixing), the surrounding sand was covered by cement paste of a low w/c ratio. The interface of cement paste and sand showed sufficient adhesion to reduce the transition zone. An increased sand percentage caused increase in the plastic viscosity and prevented dynamic segregation caused by displacement of the aggregate. The compactability by vibration also improved. As a result, the concrete with two stage mixing method enhanced desirable properties such as less bleeding, higher strength and higher resistance to segregation. This method proved to be effective for improvement of compressive strength, durability of hardening concrete and also the pumpability of fresh concrete.

Crawley (1953) observed the effect of high-frequency (13,000 vpm) and moderate-frequency (6800 vpm) vibration on concrete ranging from 12.7mm to 101.6mm slump, containing 152.4mm coarse aggregate, and having nominal air contents of 3, 6, and 9% in that portion of the mix smaller than the 38 mm sieve. Cores drilled from hardened specimens of the concrete with 6% air content were examined micrometrically for the amount and distribution of air and coarse aggregate. The high-frequency vibrator was found to cause more rapid loss of entrained air than the moderate-frequency vibrator. However, either vibrator could cause a 50% loss in air from a nominal 3% air-content concrete in 30 sec. The rate at which air was lost generally increased with slump, but not to a marked degree. The high-frequency vibrator had more effect in causing movement, and escape of air, while the moderate-frequency vibrator caused more movement and segregation of the coarse aggregate.

Petrou *et al.* (2000a) monitored the settlement of aggregates and studied the rheological properties of concrete utilizing nuclear medicine techniques. Results demonstrated that vibration reduced both the yield stress and the viscosity of the concrete. The concrete yield stress approached zero when subjected to vibration at an almost instantaneous rate. The authors also determined that as the concrete yield stress approached zero, the concrete may continue to behave as a Bingham plastic and the effect of vibration on the yield stress and the viscosity is more pronounced near the vibrator. Additionally, further studies demonstrated that the aggregates migrated horizontally toward the vibrator and that aggregates only settle while the concrete is being vibrated (Petrou *et al.*, 2000a; Petrou *et al.*, 2000b).

The use of coarse recycled aggregates as full or partial replacement of natural aggregates has been explored by many researchers (Duan & Poon, 2014). Historically, recycled concrete aggregates have been used in civil engineering applications since the 1970’s. Recycled aggregates can be used in the construction of road bases, foundations, reinforced and prestressed concrete (Limbachiya *et al.*, 2000; McNeil & Kang, 2013). Other researchers (Çakır, 2014; Dilbas *et al.*, 2014; Duan & Poon, 2014) investigated the mechanical and physical properties of recycled aggregates. Various percentage replacements were used and they conducted compressive strength, tensile splitting strength, water absorption, flexural and durability tests. Their focus was solely based on the effects of using recycled aggregates and making a comparison to conventional concrete by implementing the aforementioned experimental tests. All cube and prism samples were compacted using a vibrating table. Similar compaction methods were utilized by other authors but there was no discussion on the effects of compaction using the recycled aggregates (Duan & Poon, 2014).

In this study, the effects of vibration time were investigated on regular and high strength recycled concrete for improved durability. The strength increase of the concrete was not obtained through the use of superplastizers, which allowed for an investigation of consolidation considering solely the increase in the w/c ratio. Post vibration, the internal structure of the concrete was examined and correlated with material strength and durability.

2.0 METHODOLOGY

The procedure involved development of recycled regular strength concrete (RRSC) and recycled high strength concrete (RHSC) that were tested in both fresh and hardened states after specific vibration intervals. Slump tests, splitting tensile test, compressive test, segregation analysis, and method of slices were carried out on the concrete. Details of the tests are provided below.

The porosity and density for the samples were determined and regular strength concrete (RSC) and high strength concrete (HSC) parent mixes were developed using the American Concrete Institute (ACI) standard (see Table 1). To control impurities in the recycled mix for these experiments, the recycled aggregates were crushed from the parent concrete after 28 days. The same mix design was adopted for the recycled concrete using an optimal recycled coarse aggregate of 30% by mass replacement to regular coarse aggregate. Sieve analysis of the aggregates were conducted according to ASTM C33/C33M standard. Type 1 Ordinary Portland Cement was used in the mix design with water to cement ratio for the regular and high strength mixes of 0.45 and 0.39 respectively. A sieve analysis was performed for coarse and fine aggregates to ensure aggregates were within specification gradation ranges. Specimens were cured in the lab. The wet and dry weights of each sample were measured to allow for density and porosity calculations.

Table 1. Concrete mix design

Concrete Strength	W/C	A/C	CA/FA
Regular	0.45	4.57	1.2
High	0.39	3.77	1.3

Recycled aggregates were soaked in water for 24 hours and left to air dry to surface dry conditions before being used as coarse aggregate replacement. This method allowed for the omission of superplasticizer. Dry components were blended in the mixer for three minutes prior to the addition of the water, then all the components were blended for an additional three minutes.

Slump tests were performed prior to specimen vibration. The slump test was performed to check the workability of freshly made concrete, and therefore the ease with which concrete flows. It was also used as an indicator to identify any improperly mixed concrete batch.

Vibrations were performed at various intervals in a range of 0s to 180s with 10s intervals up until 60s. A large laboratory vibration table was used to consolidate specimens for compression and tensile tests, and a vibration rod of 8000 to 10000 vibrations per minute (vpm) and amplitude 0.5 to 1 mm was utilized for the method of slices.

An Engineering Laboratory Equipment (ELE) Compression Testing machine was utilized for the compression and tensile tests after 28 days. Compression tests were loaded axially, while the tensile tests were loaded diametrically. To allow the uniform distribution of this applied load and to reduce the magnitude of the high compressive stresses near the points of application of this load, strips of plywood were placed between tensile test specimens and loading platens of the testing machine. Both tests were performed in load control at a rate of 120 kN/min. Cylindrical moulds measured 100mm diameter and 200mm length. Five specimens were tested and averaged for the compression and four for the split tensile tests. The compressive strength of the specimens was determined as compressive load at failure, *F* divided by cross sectional area, *A*. The concrete splitting tensile strength was determine using $T = 2F/\pi DL$ where *D* and *L* are specimen diameter and length respectively.

The method of slices was adopted from (Rols *et al.*, 1999; Safawi *et al.*, 2004). The form was made of plywood of smooth interiors with dimensions 150mm x 150mm x 300mm. All sides were pasted with silicon bond and bolted together to prevent leakage. One side of the form was loosely tightened so that it could be taken off easily. After vibration by the rod vibrator at half the form depth for the required time, the open end of the specimen was closed and laid horizontally. The loosely bonded sidewall was carefully pried open and the fresh concrete in the form was divided into five equal parts by using metal slides. Guides were created at the sides of the formwork to ensure vertical insertion. Metal slides were inserted through the guides into the fresh concrete at a 60mm separation interval as shown in Fig. 1. The concrete from the individual portions were poured into individual trays and the mass of each section was recorded. Two sieves of 5mm and 13mm were aligned, one on the other, and used to collect the course aggregates as the concrete from each tray was washed with regular flowing tap water. The aggregates retained in the sieves were wiped using a cloth until a Saturated Surface Dry (SSD) condition was obtained, and the mass was recorded. The percentage of coarse aggregates at each level, *i*, was calculated as a weight ratio of coarse aggregate retained in each tray to the concrete retained in each tray (G_i/C_i). Whereas $(G/C)_{ave}$ was the weight ratio of total coarse aggregate to total concrete. A heterogeneity constant, *K*, was determined as $K = x_i - 1$, where $x_i = G_iC_i/GC_{ave}$.

Fig. 1. Photo of method of slices apparatus with metal slides inserted

Pore volume was determined using the fluid saturation method on 100mm x 200mm cylindrical specimens. The diameters and lengths of each specimen were measured and the bulk volumes were calculated as cross-sectional area times height. Thereafter, the dry weights of each specimen were measured. The specimens were then submerged in a water bath for 60 minutes to allow for full saturation and immediately after, the saturated weights were measured. Finally, the specimen porosity and density were determined.

Hardened cylinder specimens were sliced at 50mm intervals after consolidation and an internal visual inspection was conducted for coarse aggregate content and placement, air voids, and honeycombing.

3.0 RESULTS AND DISCUSSION

Table 2 shows the results of the design compressive strength and slump cone tests performed on the specimen. The regular strength mixes contain more water than the high strength mixes as visible in the increased slump. Although the recycled aggregates were soaked for 24 hours, the recycled mixes were still drier than the regular aggregate counterpart. A previous experiment by the authors demonstrated that the regular concrete maximum strengths occurred at vibrations of 60s and 120s for RSC and HSC respectively, hence the control RSC and HSC were vibrated at these optimum times only.

Results for the maximum compression and indirect tensile tests for the 100mm x 200mm cylindrical RRSC and RHSC specimens are also provided in Table 2. The addition of the 30% recycled aggregates under ideal conditions resulted in increased strengths of 20.6% and 10.3% respectively. These increases can be due to the lower w/c ratio or the varied shape of the recycled aggregates due to crushing. Crushed aggregates have higher internal friction and less workability due to poor shape.

Table 2. Concrete strength and slump test results

Concrete	Compressive Strength MPa	Slump mm
RSC	37.8	15
HSC	48.7	10
RRSC	45.6	10
RHSC	53.7	5

The compressive and tensile strength curves for RRSC and RHSC with varied vibration times are given in Figs. 2 and 3 respectively. The average points for the specimens are bounded by maximum and minimum values. The RRSC compression results shows a gradual increase in strength with vibration time until 60s after which there is a general strength reduction, whereas the tensile curve shows more variation in the first 50s with a peak strength at 50s followed by a general decline. The RHSC shows variation for both compressive and tensile results for the initial 50-60s. Although the maximum compressive value occurred at 30s, considering both figures a more ideal consolidation period (ICP) occurred between 60-90s. The ideal times for durability are a combination of the concrete strengths, segregation results, and visual inspections, which are discussed below. Unlike the decrease in time for HSC compared to RSC as observed by (Arslan *et al.*, 2011), no superplasticizer was added to the mix and a greater vibration time was needed for proper consolidation of the drier mix. There was also a greater rate of decrease in strength of the RHSC compared to the RRSC past the ICP. Compressive strength of RRSC and RHSC were 26.3% and 52% greater at the ICP than at the lowest observed strength solely through consolidation. Rearrangement of aggregate particles, and removal of air through consolidation caused consistent strength increase for both RRSC and RHSC. Inspection of the photographed sliced RRSC specimens shown in Fig. 4 to Fig. 7 further solidifies the point that ideal consolidation for durability should be based on a combination of concrete properties, and not necessarily the best specific property obtained at a vibration point.

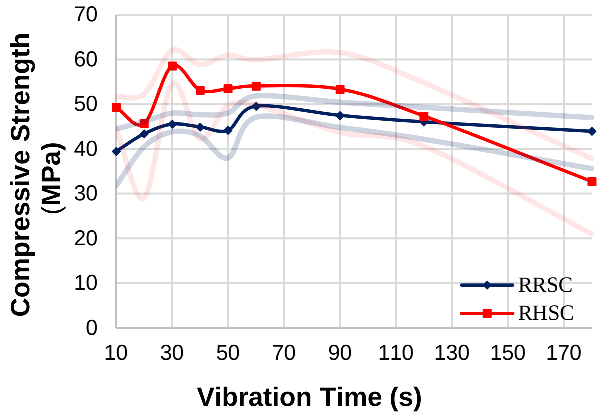

Fig. 2. Variation of compressive strength and tensile strength with vibration time for RRSC

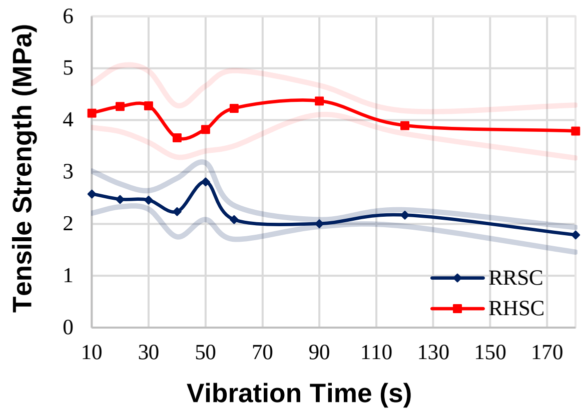

Fig. 3. Variation of compressive strength and tensile strength with vibration time for RHSC

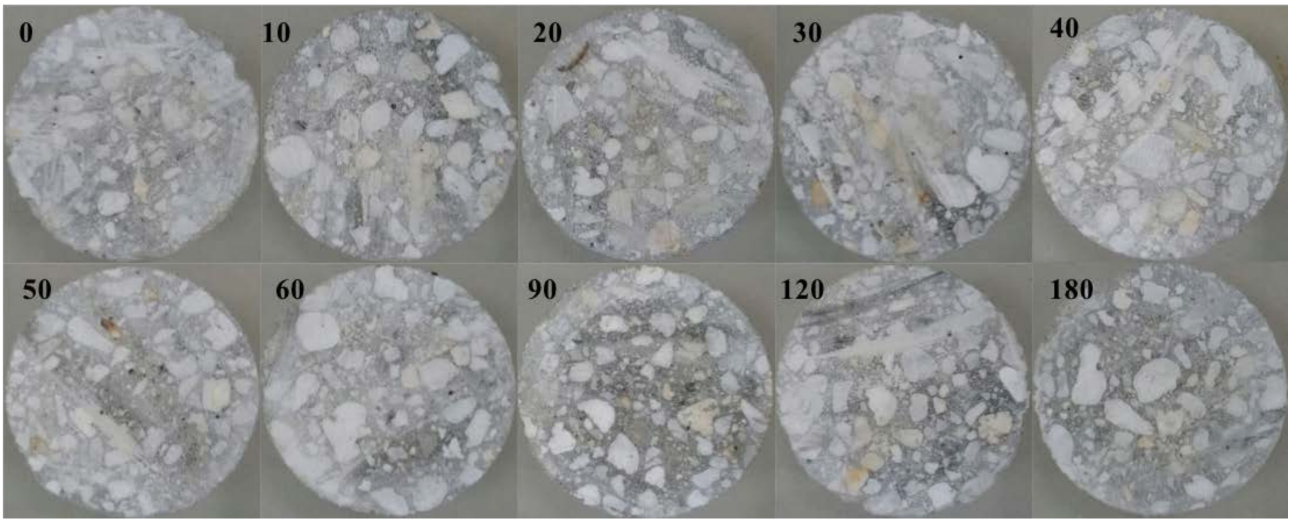

Fig. 4. First layer (top) of aggregate distribution in hardened RRSC specimen

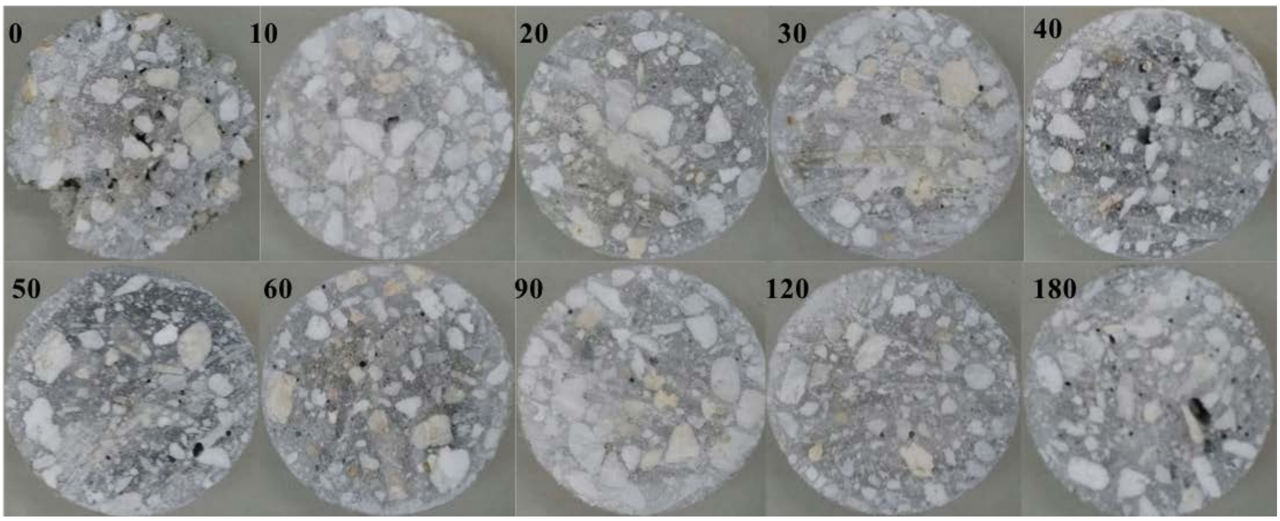

Fig. 5. Second layer of aggregate distribution in hardened RRSC specimen

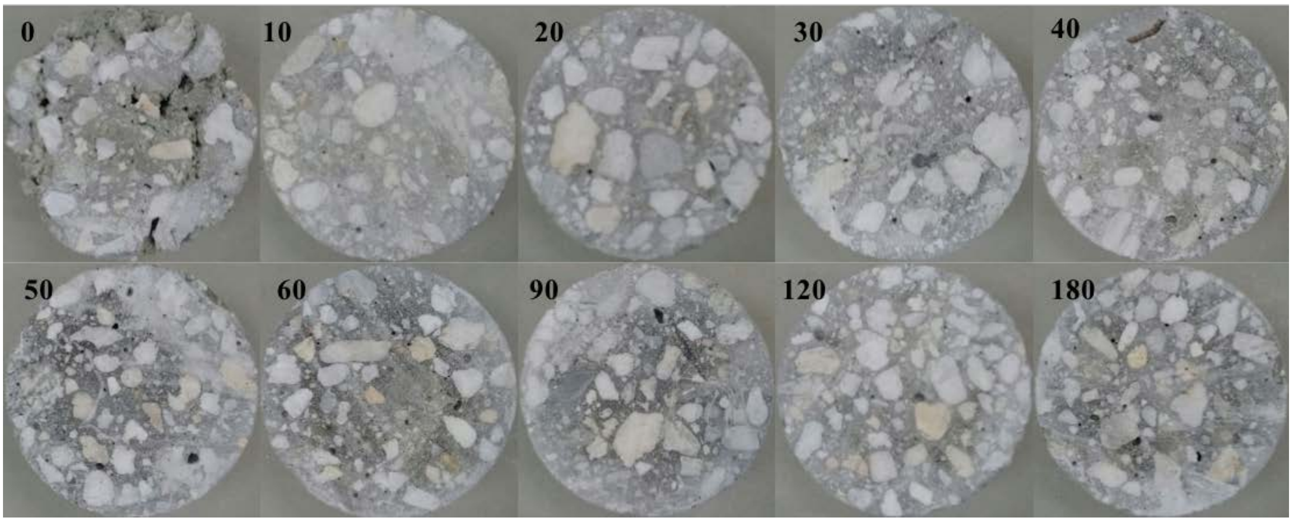

Fig. 6. Third layer of aggregate distribution in hardened RRSC specimen

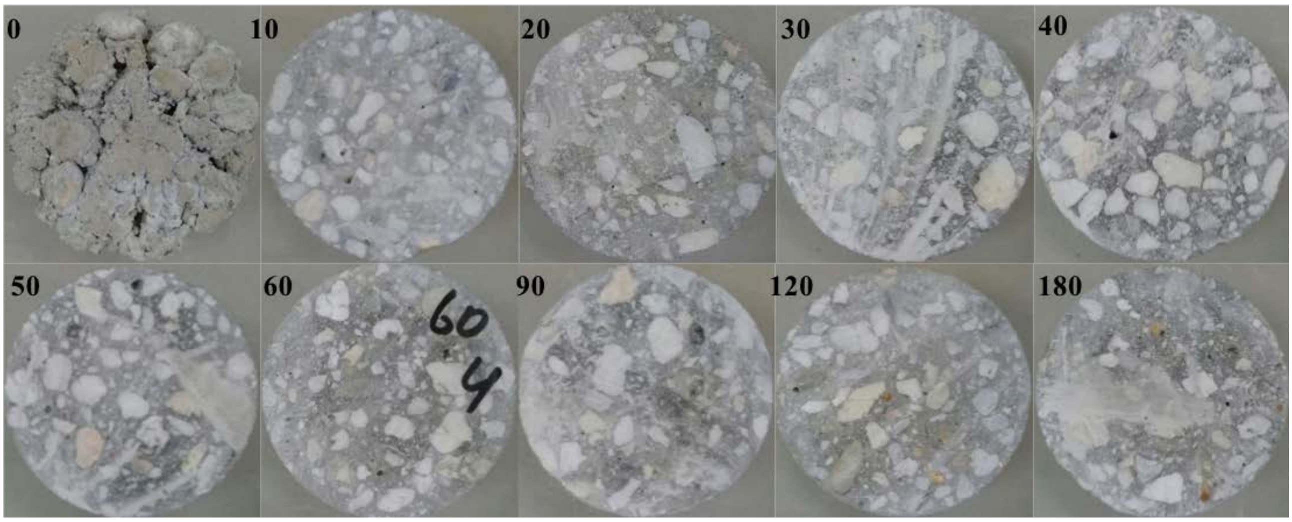

Fig. 7. Fourth layer (bottom) of aggregate distribution in hardened RRSC specimen

Figure 4 shows the top layer under varied vibration times and Fig. 7 shows the bottom layer. For 0 vibration time, honeycombing is observed in the first layer, and the specimen deteriorates further through the fourth layer. A 10s vibration time clearly demonstrates the importance of consolidation on aggregate arrangement. At the ICP of 60s, the air void in most layers were reduced and increased above and below the ICP. Additionally, the ICP produced a more homogeneous blend of coarse aggregate across each specimen layer compared to other vibration times. This is especially important for durability as the ITZ often proves to be the weakest region and area of cracking. Wall effect, where there is less efficient smaller particle arrangement around coarser particles, increases void content and bleed water in the surrounding coarse aggregates can connect to each other and form a continuous water path through the concrete (percolation) with higher aggregate concentration. This creates an open path for chemical attack in the material and accelerated deterioration (Alexander & Mindess, 2005). Insufficient consolidation has higher porosity and transport coefficients associated with permeability and ion diffusivity, especially around aggregate particles (Halamickova *et al.*, 1995).

Post ICP, the expectation was for a general decrease in larger coarse aggregates compared to before ICP in the first layer and an opposite trend was expected in the fourth layer, where over consolidation would increase the overall quantity of course aggregates post ICP. However, the low slump reduced the workability and increased viscosity of the mix and less coarse aggregate movement across layers were readily visible.

To further investigate aggregate segregation, the results from the heterogeneity constant, *K* are shown in Figs. 8 and 9 for the RRSC and RHSC specimens. The K value determines the degree of variation of the heterogeneous distribution of the coarse aggregates within the suspension. The lower the constant the more homogenous the distribution of coarse aggregates, whereas a higher *K* value indicates significant segregation and increased

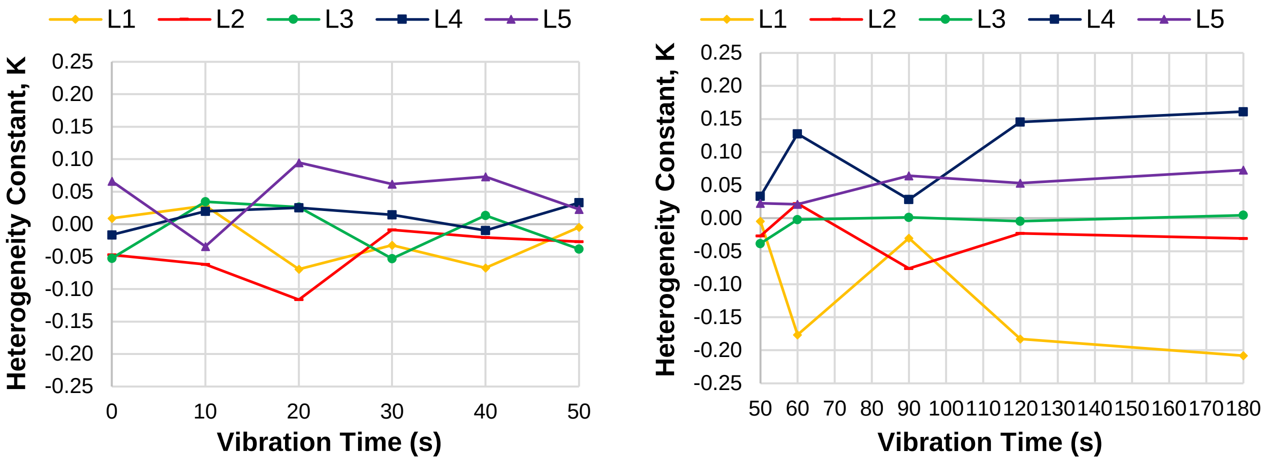

Fig. 8. Variation of K values with vibration time for RRSC

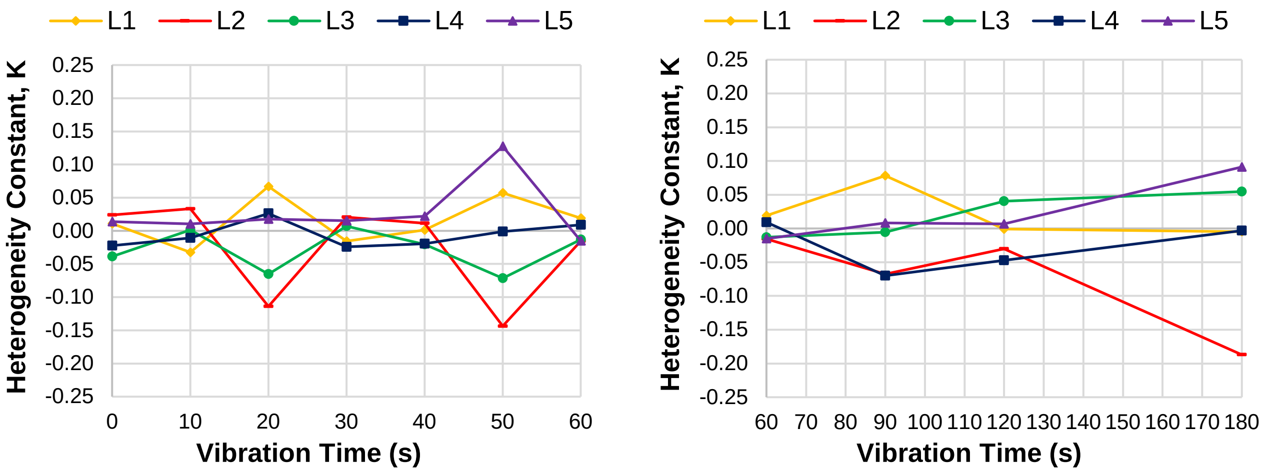

Fig. 9. Variation of K values with vibration time for RHSC

heterogeneity compared to the overall mix design. Moreover, a positive value indicates a greater density of coarse aggregate is present in the section due to mass compared to a lower value that would indicate a reduction in coarse aggregate quantity. Figure 8 shows there is less variation around the ICP and a greater segregation observed post ICP compared to pre ICP. As the material is over consolidated more segregation is observed.

Additionally, the top two layers contain less aggregate by mass than the bottom two layers and the middle layer somewhat vacillates around the global average coarse aggregate content. Also, up until the vibration time investigated, the mass of coarse aggregate in the fourth layer increased significantly. A similar trend is observed in Fig. 9 with ICP between 60-90s.

As the concrete vibration time was increased from 0s to the ICP, the distribution of the coarse aggregates approached a homogenous blend. However, as the vibration time exceeded the ICP, the coarse aggregates segregated resulting in higher *K* values. For the RRSC the middle layer had the most homogenous distribution of coarse aggregates as well as the lowest consistent *K* value throughout. The low flowability of the mix reduced the expected segregation of aggregates.

Throughout the two cases, the RRSC concrete showed the most segregation while the RHSC showed the least. As previously demonstrated the segregation tendency were closely associated to the flowability and viscosity of the RRSC and the RHSC. The higher the w/c ratio, the greater the flowability, the lower the viscosity of concrete, and the higher the segregation tendency. Therefore, the RRSC had a greater *K* value than the RHSC under vibration, therefore achieving the homogeneity condition faster due to a higher w/c ratio. The greater the water to cement ratio the more likely the coarse aggregates would settle to the bottom layer as the vibration time increased.

4.0 CONCLUSIONS

Both direct and indirect factors that affect durability must be considered to enhance concrete design.

Understanding the effects of vibration on regular and high strength concrete is important because it affects concrete properties like strength, porosity, density, viscosity and aggregate segregation that directly and indirectly affect concrete durability.

In this study the effects of vibration on the internal structure of recycled regular and high strength concrete were assessed via segregation profiles, heterogeneity constants, compressive strengths, splitting tensile strengths and visual inspection. Results demonstrate that durability due to vibration is better determined by an examination of a variety of concrete properties as the best result of only one experiment may not provide the most durable material, especially when using recycled aggregates. The ideal consolidation period obtained for RRSC and RHSC were 50-60s and 60-90s respectively for maximum strength, lower permeability and improved durability.

The vibration process attempts to fluidize the concrete, thereby removing all the air voids within the internal structure, which increases the concrete density and lowers its porosity. The longer the vibration time, the longer the concrete is fluidized. Increasing the w/c ratio will increase the chances for the heavier aggregates to settle downwards, over-consolidate, and reduce in overall strength. Since packing affects penetrability through pores as a result of its size, distribution and connectivity, the ideal consolidation period will have enhanced durability against chemical attack.

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