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The influence of aggregate grading on concrete potential durability and penetrability

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ABSTRACT: Aggregate grading is guided by the aim of achieving the greatest possible aggregate packing density in a concrete mixture. However, little consideration is given to the direct influence of aggregate grading on concrete properties, including durability. This research aimed at enhancing understanding of how grading influences potential concrete durability. The research involved laboratory experiments on concretes made with different binary blended aggregates, each containing a fine and a coarse aggregate constituent. Each of the binary blends had a different particle size distribution but the same packing density. Fine aggregates varied, according to fineness modulus (FM), within a range from 1.5 to 3.0, and coefficient of uniformity (Cu), within a range of 3.3 to 6.8. Coarse aggregates were varied to achieve either a gap or a continuous grading in the binary blend, and were characterised by FM. The concrete specimens were tested using the South African Durability Index test methods to characterise potential durability. In the tested ranges, a change in FM resulted in a maximum difference in water sorptivity index (WSI) of 1.33 mm/h0.5 and chloride conductivity index (CCI) of 0.31 mS/cm. Change in Cu resulted in a maximum difference in oxygen permeability index (OPI) of 0.30. A correlation coefficient smaller than 0.3 was found for the relationship between FM and OPI and between Cu and both WSI and CCI. These relationships were deemed not to be meaningful, statistically or practically. For all of the durability indexes, the binary blend with gap grading resulted in better performance than with continuous grading: OPI increased by 0.45, WSI decreased by 1.14 mm/h0.5 and CCI decreased by 0.16 mS/cm, on average. Nevertheless, these effects, as well as those derived from variation of fine aggregates, were relatively small compared to the changes observed in other research, resulting from variation in water/binder ratio and binder type and content. It was thus concluded that, within the range of aggregate properties studied, aggregate grading per se, while important for plastic properties and compactibility of concrete, has a minimal influence on potential durability, and will therefore generally not be a primary consideration in durability-focused concrete mix design. This does not detract from the significance of aggregate type – it speaks only of the aggregate grading for a given aggregate type

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Aggregate grading is guided by the aim of achieving the greatest possible aggregate packing density in a concrete mixture. However, little consideration is given to the direct influence of aggregate grading on concrete properties, including durability. This research aimed at enhancing understanding of how grading influences potential concrete durability. The research involved laboratory experiments on concretes made with different binary blended aggregates, each containing a fine and a coarse aggregate constituent. Each of the binary blends had a different particle size distribution but the same packing density. Fine aggregates varied, according to fineness modulus (FM), within a range from 1.5 to 3.0, and coefficient of uniformity (C_u), within a range of 3.3 to 6.8. Coarse aggregates were varied to achieve either a gap or a continuous grading in the binary blend, and were characterised by FM. The concrete specimens were tested using the South African Durability Index test methods to characterise potential durability. In the tested ranges, a change in FM resulted in a maximum difference in water sorptivity index (WSI) of 1.33 mm/$h^{0.5}$ and chloride conductivity index (CCI) of 0.31 mS/cm. Change in C_u resulted in a maximum difference in oxygen permeability index (OPI) of 0.30. A correlation coefficient smaller than 0.3 was found for the relationship between FM and OPI and between C_u and both WSI and CCI. These relationships were deemed not to be meaningful, statistically or practically. For all of the durability indexes, the binary blend with gap grading resulted in better performance than with continuous grading: OPI increased by 0.45, WSI decreased by 1.14 mm/$h^{0.5}$ and CCI decreased by 0.16 mS/cm, on average. Nevertheless, these effects, as well as those derived from variation of fine aggregates, were relatively small compared to the changes observed in other research, resulting from variation in water/binder ratio and binder type and content. It was thus concluded that, within the range of aggregate properties studied, aggregate grading per se, while important for plastic properties and compactibility of concrete, has a minimal influence on potential durability, and will therefore generally not be a primary consideration in durability-focused concrete mix design. This does not detract from the significance of aggregate type – it speaks only of the aggregate grading for a given aggregate type.

1 INTRODUCTION

Concrete is generally perceived as being an inherently durable material. However, many concrete structures need substantial repair and maintenance during their service life, with resultant costs to the economy reaching 3 – 5 % of gross national product in some countries (Alexander, Mackechnie & Ballim, 1999). Durability is therefore critical in concrete design and specification. Aggregates constitute between 60 and 80 % by volume of typical concretes, and can have a profound influence on the physical properties, including durability, of hardened concrete.

Mix proportioning guidelines laid out in the Cement and Concrete Institute Method in South Africa (Addis & Goodman, 2009), as well as the ACI Standard 211.1-91 (American Concrete Institute, 1999), aim at achieving the greatest possible aggregate packing density for a combination of given coarse and fine aggregates. This is done to:-

a. Minimise the cost of concrete production by maximising the volume of cheaper aggregate and minimising the volume of expensive cement;
b. Reduce the environmental impact of concrete, as cement is associated with significant carbon emissions;
c. Maximise workability. It has been found that in most applications, aggregates with greater (but not always the greatest) packing density give better workability (de Larrard, 1999; Johansen & Andersen, 1991);
d. Reduce shrinkage and creep deformation. Cement paste is the component of concrete which undergoes these deformations. Thus by reducing the paste component, the amount of creep and shrinkage deformation is reduced (Fennis et al., 2012).

However, research suggests that greatest packing density may not necessarily give the best strength and durability properties. There are conflicting mechanisms at play. With increasing volume fraction of the stronger and less permeable aggregate, by way of the dilution effect, improved strength and durability can be expected (Alexander & Mindess, 2005). Furthermore, greater tortuosity of the flow path of a permeating agent – achieved through greater aggregate content - would also contribute to improved durability. On the other hand, the interfacial transition zone (ITZ) can lead to reduced strength and durability with increased aggregate packing density. The ITZ is a region of greater porosity which forms at the paste-aggregate interface of aggregate particles, extending into the paste some 30 to 50 µm (Bentz, et al., 1992; Scrivener & Gartner, 1987; Bentur & Cohen, 1987). In isolation of each other, the ITZs of individual particles have a limited influence. However, with increased aggregate packing density, a percolation effect occurs, whereby the ITZs begin to overlap. The percolation effect results in connected regions of greater porosity, and at a point, a flow path through the concrete develops (Scrivener & Nemati, 1995; Winslow et al. 1993). With these effects, it can therefore be expected that the greatest packing density is not always optimum for strength and durability, suggesting that the selection of aggregate grading may need to be conducted with consideration of more than just its effects on packing density.

Similar to aggregate packing density, aggregate grading may influence durability. For example, aggregates of the same packing density but different gradings may influence durability through mechanisms of tortuosity and the ITZ. A concrete made with an aggregate with a greater amount of larger particles will be less tortuous than one of the same aggregate volume fraction but a smaller average particle size. Furthermore, larger aggregate particles tend to produce a larger ITZ.

This research further investigated the influence of aggregate grading on potential concrete durability, independently of aggregate packing density.

2 METHODOLOGY

The influence of aggregate grading on potential concrete durability was investigated through laboratory experiments. Crushed greywacke aggregate was used because of its availability in coarse and fine aggregate sizes. Thus, the effects that may have arisen from differences in particle shape and material properties were avoided. Binary blends of the coarse and fine aggregates were created to have different particle size distributions (PSDs) but the same packing density. This was done by using coarse and fine aggregates of different PSD's in predetermined volume fractions.

2.1 Fine aggregate

Fine aggregate grading was characterised by fineness modulus (FM) and coefficient of uniformity (Cu). FM is obtained by adding the total percentage of material retained on each of the standard sieve sizes, excluding the 75 μm sieve, and dividing the total by 100. Cu, as given by Equation 1, is the ratio of the diameter of the aggregate particle for which 60 percent of the aggregate, by mass, is smaller than (D_{60}), to the diameter of the particle for which 10 percent of the aggregate is smaller than (D_{10}). FM describes the average particle size and Cu gives an indication of the uniformity of the aggregate grading, which is represented by the gradient of the grading curve. These are illustrated in Figures 1 and 2.

$$Cu = \frac{D_{60}}{D_{10}} \qquad (1)$$

Nine different fine aggregate combinations were tested, with FM varying between 1.5 and 3.0, and Cu varying between 3.3 and 6.8 - see Table 1. These ranges are within the practical limits for aggregates used in concrete production. It is possible to vary FM whilst holding Cu constant. However, this requires going beyond the limits of nominal aggregate particle sizes recommended for inclusion in concrete.

Table 1: Fine aggregate grading properties

Aggregate	FM	Cu	ϕ*
F1	1.5	4.3	0.596
F2	2	3.3	0.571
F3	2	4.4	0.611
F4	2.05	6	0.61
F5	2.25	3.8	0.585
F6	2.3	6.8	0.587
F7	2.5	5.6	0.607
F8	2.55	5.9	0.581
F9	3	5.2	0.581
C1	8.37	-	0.486
C2	9.03	-	0.458

'F' – Fine aggregate; 'C' – Coarse aggregate

* See Equation 2

2.2 Coarse aggregate

Two coarse aggregates were used. One had FM = 8.37 which, when mixed with the fine aggregate, gave binary blends with a continuous grading, and the other with FM = 9.03 which gave binary blends with a gap grading (C2). See Table 1.

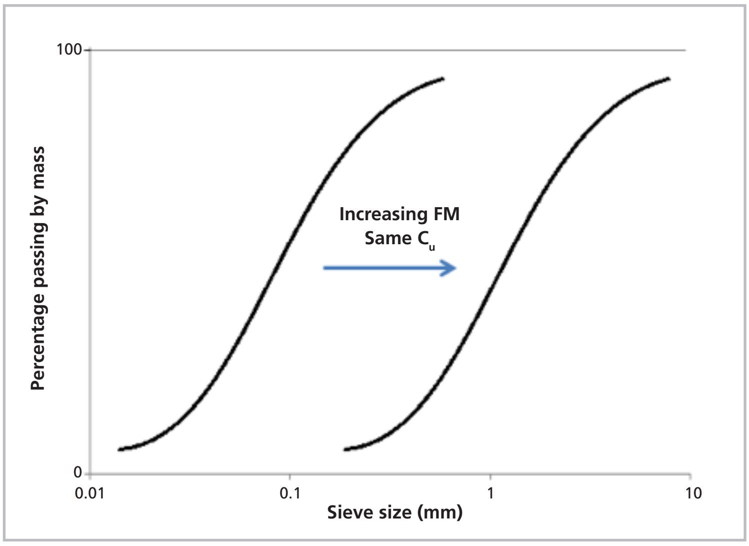

Figure 1: Grading curve depicting a change in FM

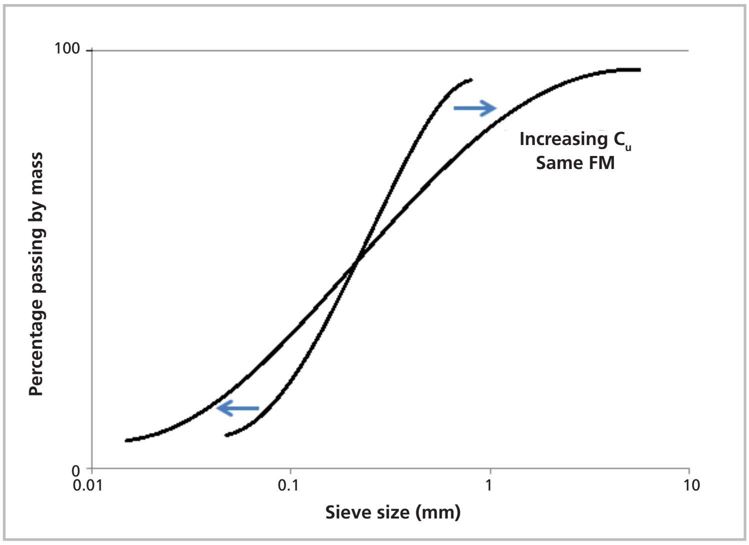

Figure 2: Grading curve depicting a change in Cu

2.3 Binary blend

The packing density of the binary blends of coarse and fine aggregates was held constant by adjusting the volume fraction of the coarse and fine constituents. The required volume fractions were calculated using the modified-Toufar packing model, which is represented by Equations 2 below (Goltermann et al., 1997).

$$\varphi = \frac{1}{\frac{y_1}{\varphi_1} + \frac{y_2}{\varphi_2} - y_2\left(\frac{1}{\varphi_2} - 1\right)k_d k_s} \qquad (2)$$

$$k_d = \frac{d_2 - d_1}{d_2 + d_1}$$

$$k_s = 0.8165x \qquad \text{if } x < 0.4753$$

$$k_s = 1 - \frac{1 + 4x}{(1 + x)^4} \qquad \text{if } x \geq 0.4753$$

$$x = \frac{y_1 \varphi_2}{y_2 \varphi_1 (1 - \varphi_2)}$$

Where:

y_1/φ_1 bulk volume of fine particles with y_1 being the fine aggregate volume fraction, and φ_1 the packing density of the fine aggregate.

y_2/φ_2 bulk volume of coarse particles with y_2 being the coarse aggregate volume fraction, and φ_2 the packing density of the coarse aggregate.

$y_2 = (\frac{1}{\varphi_2} - 1)$ void volume between coarse particles.

d_1 & d_2 characteristic diameter (or average particle diameter) of fine and coarse aggregate particles respectively, which, for an aggregate used in concrete, is the particle diameter for which 36.8 % of the particles are greater than that size (Johansen & Andersen, 1991).

k_d factor that accounts for the effects of diameter ratio, given above.

k_s a statistical factor given above.

Water/cement ratio and water content were kept constant throughout. CEM II-B/M (LS) cement of strength class 42.5N was used. Chryso Optima 175 (a high-range water reducing admixture based on polycarboxylate and modified phosphonate) was added to achieve a slump between 50 and 100 mm. A mean quantity of superplasticiser equal to 0.48 percent of the cement mass was used for continuously-graded aggregates. For gap-graded aggregates, the mean was 0.69 percent. This was unexpected, since gap-graded aggregates tend to overcome the internal friction caused by intermediate sized particles which results in reduced workability (Alexander & Mindess, 2005). The concrete mix designs are provided in Table 2.

The South African durability indexes, (oxygen permeability (OPI), water sorptivity (WSI) and chloride conductivity (CCI) indexes), were used to characterise the potential durability of the concrete. These tests, particularly the OPI and CCI tests, have been found to give accurate reflections of the concrete durability properties and yield results with strong correlation to other internationally accepted methods (Torrent & Fernandez Luco, 2007; Romer & Fernandez Luco, 2005). Compressive strength tests were conducted for quality control to ensure that sample preparation, including batching, mixing and curing, had been done correctly and consistently throughout.

Laboratory test specimens were prepared in accordance with the specifications of the Concrete Durability Index Testing Manual (Alexander, Ballim & Mackechnie, 2010). The samples for all durability index tests were 30 mm thick slices of 70 mm diameter cores cut from 100 mm cubes. A core was cut perpendicular to the cast face of a cube, through to the opposing face, and the slices were taken 5 mm from each end of the core. For the durability index tests, four 100 mm cubes from each mix were cast and cured in a water bath at 23 °C for 28 days. Thereafter, the cubes were cored and cut and the test samples were placed in an oven at 50 °C for 7 days.

3 RESULTS

Correlation and regression analyses were employed to determine whether FM and C_u had a meaningful effect on the measured parameters. This involved the calculation of the correlation coefficient r. The correlation coefficient ranges from -1 to 1 and describes a linear relationship, where negative values indicate an inversely proportional relationship and positive values describe a directly proportional relationship. Values close to -1 or 1 indicate that data points are clustered around a definite line (i.e. there is a strong relationship between the two variables), whilst a value close to zero indicates a large scatter.

Table 2: Mix designs for laboratory experiments (per m^3)

Mix	Water	w/b	CEM II B 42.5	y_1	Sand	13 mm Stone	19 mm Stone	Superplasticiser		Slump
	kg	-	kg		kg	kg	kg	l/m^3	% of cement mass	mm
C1F1	200	0.55	364	0.34	598	585	585	2.77	0.8	75
C1F2	200	0.55	364	0.37	646	561	561	2.00	0.6	85
C1F3	200	0.55	364	0.34	608	580	580	2.31	0.7	70
C1F4	200	0.55	364	0.35	610	579	579	2.15	0.6	95
C1F5	200	0.55	364	0.37	649	559	559	1.54	0.4	90
C1F6	200	0.55	364	0.37	648	560	560	1.31	0.4	80
C1F7	200	0.55	364	0.36	637	566	566	0.92	0.3	65
C1F8	200	0.55	364	0.38	670	549	549	0.77	0.2	85
C1F9	200	0.55	364	0.42	769	520	520	1.15	0.3	90
C2F1	200	0.55	364	0.40	699	-	1069	4.15	1.2	70
C2F2	200	0.55	364	0.45	790	-	979	2.69	0.8	90
C2F3	200	0.55	364	0.40	702	-	1066	1.77	0.5	95
C2F4	200	0.55	364	0.40	704	-	1064	2.69	0.8	90
C2F5	200	0.55	364	0.44	777	-	991	2.08	0.6	80
C2F6	200	0.55	364	0.44	773	-	995	2.08	0.6	80
C2F7	200	0.55	364	0.42	741	-	1027	1.46	0.4	70
C2F8	200	0.55	364	0.46	813	-	955	2.38	0.7	80
C2F9	200	0.55	364	0.60	1061	-	707	2.00	0.6	70

R^2 (which is the same as r^2) is the coefficient of determination, which specifically indicates the goodness of fit of the fitted linear relationship. Since it was necessary to know whether a change in the controlled variable resulted in an increase or decrease in test parameters, it was beneficial to use r rather than R^2. The correlation coefficients are given in Table 3.

Table 3: Correlation coefficients (r)

Aggregate grading	OPI		WSI		CCI	
	FM	C_u	FM	C_u	FM	C_u
Continuous	-0.171	-0.472	-0.186	0.004	0.488	0.147
Gap	0.067	-0.198	-0.342	0.144	0.033	0.283

Cohen (1988) suggests that |r| < 0.3 indicates little correlation. With a low correlation, there is little relationship between the variables of interest, which means that a regression analysis is not of value. The correlation analysis was therefore used as an indicator of whether or not to perform a regression analysis. For cases in which regression analysis was performed, the regression coefficient, β, described the magnitude of the effect that the aggregate grading had on the measured parameter.

3.1 Oxygen permeability index

The scatter-plot in Figure 3 presents the OPI results. Correlations between Cu and OPI, in concretes with continuously graded binary aggregate blends, gave r = -0.472. With β = -0.086, an increase in Cu of 3.5 units - the greatest range tested in this research and which is practically possible within the limits of FM and fines content requirements specified in design codes - caused a decrease in OPI of 0.3 units. It is hypothesised that this was caused by the increase in D_{60} which, by attracting a greater level of localised bleeding at the aggregate surface, causes a greater porosity in the ITZ. However, there is little meaningful correlation between the same two parameters in concretes with a gap grading. There is also little meaningful correlation between OPI and FM.

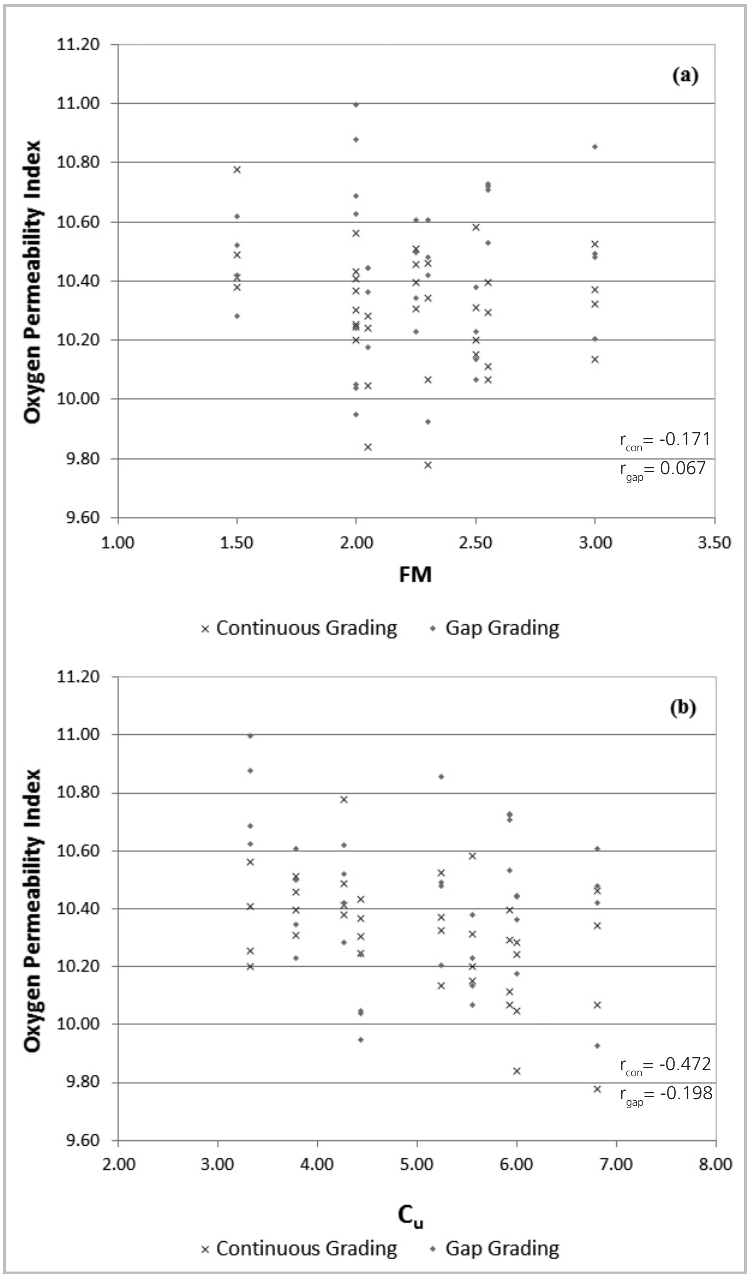

Figure 3: Scatter plot showing the influence of FM (a) and C_u (b) on OPI at different aggregate gradings

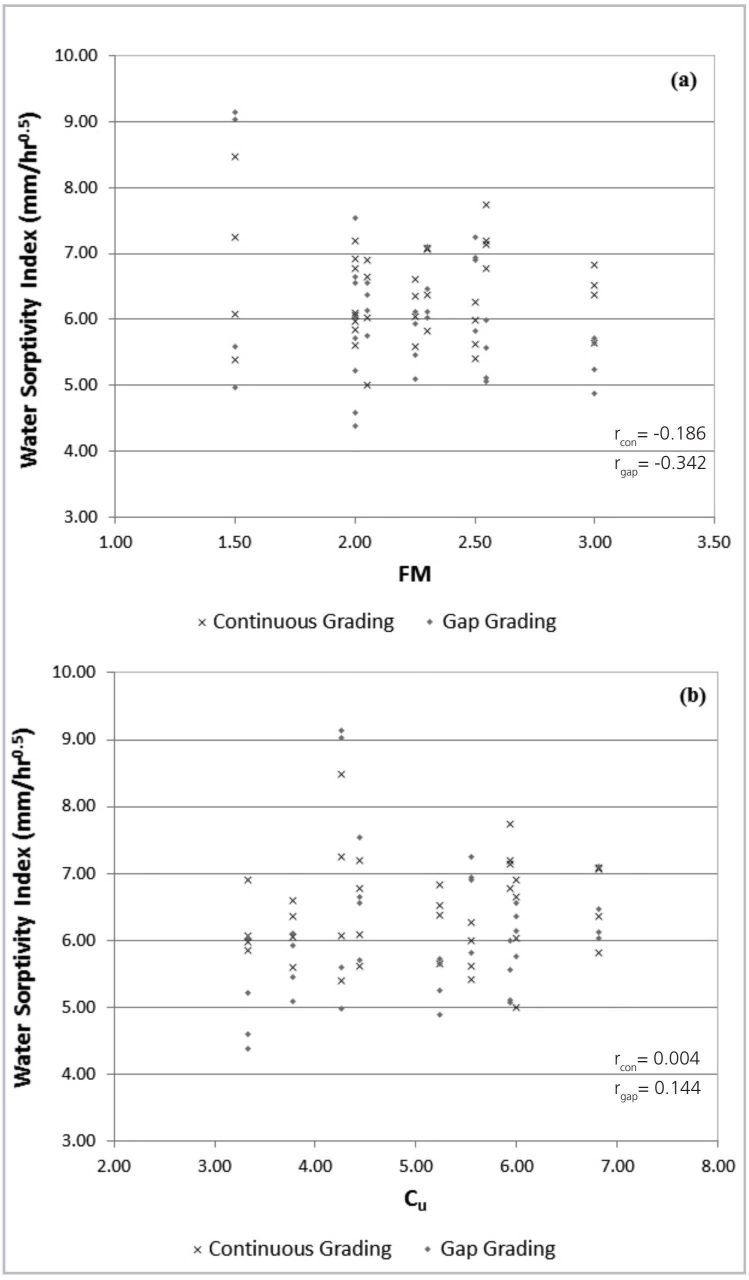

Figure 4: Scatter plot showing the influence of FM (a) and C_u (b) on WSI at different aggregate gradings

3.2 Water sorptivity index

The scatter-plot in Figure 4 presents the WSI results. Correlations between FM and WSI gave r = -0.342 in concretes with gap grading. With β = -0.885, an increase in FM of 1.5 units – which is the range between the upper and lower values tested and around the greatest range that may be achieved whilst within the limits for fines contents and upper FM value specified by design codes - caused a decrease in WSI of 1.33 mm/hr$^{0.5}$. This was explained by the relationship between FM and the volume of the total aggregate that was constituted by fine aggregates (y_1) whereby, in order to maintain constant packing density, as FM increased, so did y_1. As a result, there was a greater proportion of particles of 75 μm and smaller, which refines the pore structure, particularly in the region of the ITZ. However, there is little correlation between the same two parameters in concretes with a continuous grading. There is also little meaningful correlation between WSI and C_u.

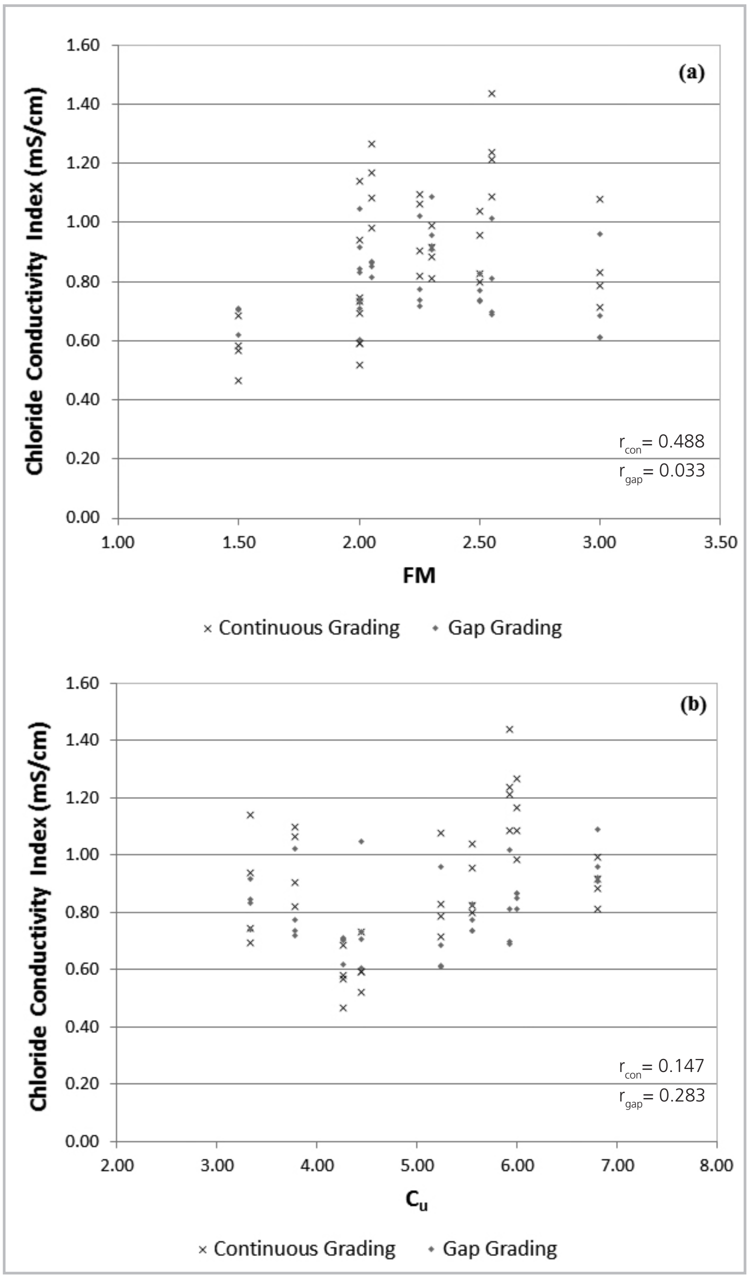

Figure 5: Scatter plot showing the influence of FM (a) and C_u (b) on CCI at different aggregate gradings

3.3 Chloride conductivity index

The scatter-plot in Figure 5 presents the CCI results. Correlations between FM and CCI, in concretes with continuous grading, gave r = 0.488. With β = 0.206, an increase in FM of 1.5 units – which is the range between the upper and lower values tested and around the greatest range that may be achieved whilst within the limits for fines contents and upper FM value specified by design codes - gave an increase in CCI of 0.31 mS/cm. It was hypothesised that this was a result of the increase in the average particle size. The larger particles would cause greater amounts of localised bleeding at the aggregate particle surfaces, resulting in greater porosity in the ITZ. Furthermore, with a greater average aggregate particle size, there is less tortuosity which allows for easier passage of a penetrating substance. However, there is little meaningful correlation between the same two parameters in concretes with a gap grading. There is also little meaningful correlation between CCI and C_u.

4 DISCUSSION

To gain an idea of the significance of the observed changes in the concrete caused by the variations in aggregate grading, the results were compared with observations in other research resulting from changes in water/binder ratio and binder type and content (Heiyantuduwa, 2008). This comparison is presented in Table 4.

4.1 Fine aggregate

In each of the durability indexes, the aggregate gradings studied had less influence than what has been observed for changes in binder type and content and, in particular, changes in water/binder ratio. The correlation between FM and OPI is not meaningful, by Cohen's (1988) measure. Similarly, there is no meaningful correlation between C_u and both WSI and CCI. An increase in FM led to improved performance as measured by the WSI, but poorer performance as measured by the CCI. Together the minimal influence of both FM and C_u, and the variable effects of FM, suggest that the grading of fine aggregate, at least by the studied characteristics of FM and C_u, is not a strong determinant of concrete durability performance. In cases where more meaningful effects were observed, these are hypothesized to be attributed to changes arising in the ITZ. Scanning electron microscopy (SEM) analysis, similar to that carried out by Elsharief et al. (2003), would be useful inconfirming this.

Table 4: Comparison of experimental findings: typical influences observed for change in w/b ratio and binder type and content as found by Heiyantuduwa (2008) (indicative only)

Property	Range	Increase (%)	OPI	WSI (mm/hr$^{0.5}$)	CCI (mS/cm)
Change in w/b ratio	0.2	50	-1.0	+5.5	+0.7
Change in binder type and content*	-	-	+0.5	+3.5	+1.2
Fineness modulus †	1.5	100	-	-2.03	+0.47
Coefficient of uniformity †	3.5	106	-0.3	-	-
Grading	Continuous to Gap	-	+0.45	-1.14	-0.16

These values are magnitude only
†Where no value is given, there was no meaningful effect found

4.2 Overall binary aggregate grading

As shown in Figures 3, 4, 5, and Table 4, binary aggregate blends with an overall gap grading yielded better performance than those with continuous grading across all durability indexes.

This observation may be explained as follows: The greater distribution of particles in coarse aggregate C1 (the coarse aggregate that gave rise to binary blend with a continuous grading) gave it a greater particle packing efficiency than C2, which was more uniformly graded. Thus, to achieve the same overall packing density in aggregate blends, a greater proportion of fine aggregate had to be blended with C2 than with C1. This meant that for each fine aggregate, y_1 for coarse aggregate C2 was greater than y_1 for coarse aggregate C1, with a correspondingly greater amount of fine material, specifically sub-75 µm material, which refined the pore structure and yielded less particle friction, thus improving consolidation. Penetrability was thus reduced, as shown by improved durability index values.

Notwithstanding this, the improvement in potential durability, resulting from the change from continuous grading to gap grading is between 55 and 79 % less than that which results from a change in water/binder ratio from 0.6 to 0.4, as observed by Heiyantuduwa (2008). Binder type and content has also been observed to have a much greater influence on potential durability than that observed for overall grading of the binary blend of coarse and fine aggregate. Thus, in durability focused concrete design, consideration should be given to the water/binder ratio and binder type and content ahead of aggregate grading, provided the grading is suitable to achieve a compactable concrete.

In Table 3, continuously graded aggregates exhibited two regression coefficients greater than 0.45 in magnitude (-0.472 and 0.488) whilst there was only one regression coefficient greater than 0.30 (0.342) recorded for gap graded aggregates. It is therefore, evident that the potential durability performance of gap graded binary blends is generally less sensitive than continuously graded blends to changes in aggregate grading. This is of benefit in construction where changes in aggregate grading will occur.

The observed relationship between aggregate grading and the required amount of superplasticiser poses further consideration. The higher demand for superplasticiser observed with gap graded aggregate suggests that a gap graded aggregate yields a less workable mix. This was unexpected, as gap graded aggregates usually overcome particle interference, by omitting some intermediate particle sizes, thereby improving workability (Alexander & Mindess, 2005). It is possible that this was a result of the shape of the aggregate. The test aggregates were formed entirely of crushed aggregates. The consequent angularity of the aggregate particles may have limited the potential of the gap graded aggregates to overcome particle interference.

This observation suggests that the overall grading does not have a direct, independent link with workability. Since workability has been found to be linked to potential durability parameters – sorptivity in particular – it is reaffirmed that overall aggregate grading has a limited influence on potential durability (Ballim et al., 2009; Kropp & Alexander, 2002). Furthermore, it also suggests that overall aggregate grading may not need to be considered in concrete mix design when trying to optimise workability.

5 CONCLUSIONS

From the discussed research, the following points can be noted about the effects of aggregate grading:

1. The grading of fine aggregate, as characterised by the fineness modulus (FM) ranging from 1.5 to 3.0 and coefficient of uniformity (C_u) ranging from 3.3 to 6.8, has little or limited influence on concrete potential durability. Since these parameters comprehensively characterise fine aggregate grading and the ranges are at practical limits, it is concluded that fine aggregate grading is not of primary concern in optimising concrete durability, other than through influences it may have on overall aggregate packing density, water requirement, and workability. Further research, including tests that measure penetrability over a greater time frame, may be useful in conclusively showing the absence of any meaningful relationship.
2. A binary blend of coarse and fine aggregates that has gap grading gives better potential durability than overall continuously graded aggregates. In the present tests, this was ascribed to the greater content of fine aggregate material in the gap graded mixes.
3. Gap grading is less sensitive to changes in grading than continuous grading. This is a benefit since it means that changes in grading, inevitable during the course of a construction contract, are less likely to adversely affect the potential durability of the concrete.
4. In general, aggregate grading has a much smaller influence on concrete potential durability than water/binder ratio and binder type and content.
5. The influence of aggregate grading on concrete workability is not independent. Particle shape appears to determine the influence that grading has on workability. Further research into the relationship between these three properties would be useful.

However, an important caveat is necessary. While the effects of aggregate grading and the nature of the grading are minor at most, and often only background, this is not to say that different aggregate types may not have an important influence on durability properties. Data to hand from other work indicate that aggregate type may play a larger role. What the observations do say is that, for a given and consistent aggregate source, changes in aggregate grading have minor influence on the potential durability of the concrete, other factors being equal.

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