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A trade-off concept for lightweight concrete in chloride environments

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ABSTRACT

The aim of this study was to investigate the influence of supplementary cementing materials (SCM's) on the initial surface absorption (ISA), sorptivity and chloride penetrability to ASTM C1202 and NT Build 492 of lightweight aggregate based concretes (LWAC), and to compare these properties to those of normal-weight aggregate based concretes (NWAC).

The lightweight aggregate (LWA) was Lytag, a fly ash based aggregate, which was pelletised during manufacture. Three normal-weight aggregates (NWA) were investigated, including, natural river gravel, jurassic oolitic limestone and crushed dolomitic limestone. The SCM's used were fly ash (FA), ground granulated blastfurnace slag (GGBS), limestone (LS), silica fume (SF), and metakaolin (MK). CEM I replacement was undertaken on a percentage mass basis. Experimental work focused on concrete mixes with a fixed water/binder ratio of 0.50 and a constant total binder content of 330kg/m^3.

28-day results indicate that with respect to aggregate influence, for CEM I only concrete, reduced concrete performance is obtained when replacing normal-weight aggregate with lightweight on a like-for-like basis. These negative effects can be reduced however, by good cement addition specification, as was found in the majority of the concretes in this study. These benefits include, to varying degrees, enhanced compressive strength, and increased resistance to water permeation and chloride ion penetration.

A trade-off between aggregate type and binder combination is therefore desirable, to enable enhanced concrete chloride ion resistance.

Keywords: lightweight, normal-weight, supplementary cementing materials, chloride, durability, trade-off

1. Introduction

Aggregates are the most commonly used material in the United Kingdom (UK) construction industry (MPA, 2015). In 2014, total production amounted to 170 million tonne. Concrete can be made with aggregate that are obtained from a range of sources (MPA, 2015). They can be obtained from: naturally occurring process or from extraction from the earth, these are termed natural aggregates (also termed primary aggregates); they can be derived from derived from other industrial processes that they are manufactured and these are commonly referred to as manufactured aggregates (commonly referred to as secondary aggregates) or; they can originated from demolition and construction waste materials, giving rise to the term recycled aggregates. The two former aggregate types form this basis of this paper with the later not discussed in any further detail.

Concerns are growing in the UK, over potential aggregate shortages as the economy achieves full recovery (MPA, 2015). This in turn is resulting in the ever increasing trend of the use of these non-primary aggregates in concrete construction. In this respect the UK construction industry is leading the way in Europe, where, in 2014, secondary and recycled aggregates accounted for 29% of the total UK aggregate market. This was over two times greater than the European average, over the same period (MPA, 2015). Thereafter, primary aggregates accounted for the remaining 72% of material usage.

LWAC has existed since ancient times. The essential characteristics of these aggregates are their high porosities and low apparent specific densities (Chandra and Berntsson, 2002; Neville, 1995). Kayali

(2008), noted that these aggregates possess unique characteristics that make them suitable for application in high strength and high performance concrete. A number of researchers have studied the microstructure of the Initial Transition Zone (ITZ) between lightweight aggregate and cement paste. Their findings suggest that densification of the ITZ microstructure occurs as a result of lightweight aggregate absorbing water from the cement paste. They report that this gives rise to enhanced bond along the surface of aggregates and cement paste (Swamy and Lambert, 1981; Holmes et al., 1984; Zhang and Gjorv, 1990; Breton et al., 1993; Chia and Zhang, 2001 & 2002; Elsharief et al., 2005; Lo et al., 2008). However, Wasserman and Bentur (1997 and 1996), studying ITZ around lightweight sintered fly ash aggregate, observed a decrease in the quality of the ITZ with increased absorption of aggregates.

Lytag is a well-known lightweight aggregate that is used in these applications. They have been successfully manufactured from fly ash since the 1960s. Research by Dhir et al., (2001), established that the chloride diffusion indices of concrete containing pelletised sintered fly ash LWA with absorption of 15.1%, were approximately 40% greater than those of their highest absorption NWAC. On the other hand, Kayali (2008) observed improved performance to that of reference concretes, when using sintered non-pelletised, fly ash aggregate in high strength concrete. This he attributed to the presence of a strong interfacial zone being obtained between his rough surface aggregates and the cement paste.

The fly ash aggregate reported here, have been manufactured using sintering with subsequently palletisation. In this paper, the performance of concrete made from this type of LWAC is examined and compared with conventional NWAC. The concrete mix designs were performed, such that, they were yield corrected to obtain the required constant water/cement (w/c) / Water/binder (w/b) ratio of 0.50.

2. Experimental Details

2.1 Materials

A single sourced CEM I 42.5N cement conforming to BS EN 197-1 was utilised. In addition, five SCM were examined in this work: (i) Fly Ash (FA); (ii) Ground Granulated Blastfurnace Slag (GGBS); (iii) Limestone (LS); (iv) Silica Fume (SF) and; (v) Metakaolin (MK). The key characteristics of these addition materials are given in Table 1.

Table 1. Properties of cement and addition materials

Property Measured	PC	FA	GGBS	LS	SF	MK
Fineness (m^2/kg)	414†	367†	460†	1550§	22400§	13025§
Loss on Ignition, %	1.74	6.02	0.90	42.84	2.49	0.97
Particle Density, g/cm³	3.14	2.25	2.89	2.63	2.20	2.49
† Tested by Blaine fineness method	§ Tested by nitrogen adsorption BET method					

Natural sand conforming to BS EN 12620 (BSI, 2002), was used as aggregate in all mixes and its properties along with the properties of the course aggregates, are presented in Table 2.

Twenty-four concrete mixes were proportioned for a single w/c ratio of 0.50, total cement content of 330 kg/m^3 and single water content of 165 kg/m^3. These are designed in accordance with the BRE method for designing normal concrete mixes (BRE, 1997). The mix design was to achieve a consistence conforming to the S2 slump class in BS 8500-1 (BSI, 2006). Table 3 gives the standard CEM I mix design for both aggregate types. Table 4 outlines the SCM's expressed as a percentage of the total cement content.

The test specimens were cast in moulds and, cured under damp hessian and polythene sheeting to maintain a high humidity (> 95%) for 24 hours. The specimens were then de-moulded, marked for identification and cured in water at 20°C ± 2°C, in accordance with BS EN 12390-2, until time of testing (BSI, 2000).

Table 2. Properties of aggregates

Property Measured	Natural Sand	Carboniferous Limestone	Natural Gravel	Jurassic Oolitic Limestone	Lytag[†]
		Aggregate A	Aggregate B	Aggregate C	Aggregate D
	0/4mm	Average[#]	Average[#]	Average[#]	4/14mm
Shape, visual inspection	Round	Irregular and Angular	Round	Irregular and Angular	Spherical
SSD Density[§], kg/m^3	2600	2750	2600	2710	1600
LBD Density[$], kg/m^3	1680	1440	1520	1400	830
CBD Density[*], kg/m^3	1800	1540	1610	1495	915
Water Absorption, %	0.5	0.8	1.9	4.0	21.5
Loss on Ignition, %	3.5	37.2	3.5	40.9	6.3

[#] Average of 4/10mm and 10/20mm aggregates

[†] Sintered Fly Ash Lightweight Aggregate

[§] Saturated surface dry density

[$] Loose bulk density

* Compacted bulk density

Table 3. Mix proportions of normal and light-weight aggregate concretes

w/c or w/b Ratio	Mix Constituent Proportions[*], kg/m^3					
	Free Water	Cement	Aggregates, mm			SP, %[§]
			Natural Sand	Normal-weight Aggregate		
			0/4	4/10	10/20	
0.50	165	330	655	417	833	All mixes
				Lightweight Aggregate (Lytag)		
				4/14		
0.50	165	330	675	755		All mixes

[*] Yield corrected for each mix design (cement and aggregate type)

[§] Percentage by weight of cement or cement and addition

Table 4. CEM I and binary cement combinations breakdown

Composition of main constituents, %						Total, %
PC	FA	GGBS	LS	SF	MK	
100	-	-	-	-	-	100
65	35	-	-	-	-	100
45	-	55	-	-	-	100
80	-	-	20	-	-	100
90	-	-	-	10	-	100
90	-	-	-	-	10	100

2.2 Experimental Methods

2.2.1 Compressive strength

Compressive strength was measured in accordance with BS EN 12390-3 (BSI, 2002), with two 100mm cubes in fully water saturated condition tested at 28-days.

2.2.2 Initial surface absorption (ISA-10)

This test was conducted in accordance with British Standard BS 1881: Part 208 (BSI, 1996). Initial surface absorption testing was undertaken with the results of each concrete when subjected to a head of water for 10, 30 and 60 minutes. However, the results after the initial 10 minutes exposure (ISA-10), are only reported.

2.2.3 Sorptivity

The capillary rise test was used to measure sorptivity of concrete due to capillary suction, to ASTM C1585-04. 100mm diameter and approximately 50mm length concrete discs were cut from a cylinder of 100mm diameter × 300mm length utilized and pre-treated as per the ISA test procedure. Thereafter, these specimens were coated with a wax sealing material and plastic sheeting to ensure sorptivity could only occur through the one open face. Prior to being positioned in a shallow tank of water (≈20ºC), the initial mass of the specimens was recorded. During testing the samples were rested on rods to allow free access of water to the base of each specimen. The quantity of absorbed water was measured by weighing the specimens to the nearest 0.1g at 1, 5, 10, 20, 40, 60 minute intervals and, thereafter, every 60 minutes up to 6 hours from commencement of the test. This allowed the accumulative water absorption (i) to be determined.

2.2.4 Rapid chloride permeability

Rapid chloride permeability testing (RCPT) was performed in accordance with ASTM C 1202 (ASTM, 2007).

2.2.5 Rapid chloride migration

Rapid chloride migration testing (RCMT), was performed in accordance with Nordic test method (NT BUILD 492, 1999).

3. Results

As shown in Tables 3 and 4, it is of importance to note that, in the case of the LWACs, their mix designs varied when compared to the three NWACs. This characteristic is of importance when comparing the performance of these concretes on an equal w/b ratio basis.

3.1 Compressive strength

The compressive strength of concretes made with Aggregates A to D at 28-days is illustrated in Table 5. The trends in strength of each concrete were as expected, with respect to cement and aggregate types. Concretes containing SCM's developed reduced compressive strength, in all instances, when compared to their reference CEM I concrete's. Fly ash and GGBS blended with CEM I resulted in the greatest reduction in strength at 28-days. Thereafter, aggregate type was found to impact on the compressive strength of concrete. When assessing extremes in measurements across aggregate types, the greatest reductions in 28-day strength, was observed in the instance of the lightweight aggregate.

Table 5. 28-day compressive cube strength

Combination Type, %	28-Day Compressive Cube Strength, N/mm^2				% of CEM I Strength			
	Aggregate Type							
	A	B	C	D	A	B	C	D
CEM I	57.5	52.0	46.0	44.5	100	100	100	100
FA 35	41.0	33.0	31.5	30.0	71	63	68	67
GGBS 55	51.5	41.5	40.0	35.5	90	80	87	80
LS 20	45.0	42.5	38.5	34.5	78	82	84	78
SF 10	63.0	58.5	53.0	48.5	110	113	115	109
MK 10	62.0	57.0	49.5	45.0	108	110	108	101

3.2 Initial surface absorption (ISA-10) and sorptivity

Illustrated in Figures 1 and 2, the ISA-10 and sorptivity measurements were found to vary for a given concrete. Improved concrete performance, as measured by reduced water penetration, was observed when SCM's were added to the matrix. This is in comparison to their reference CEM I concrete. The exception was observed with the inclusion of LS at the 20% replacement level, where reductions in resistance to water uptake were observed, as indicated by increased measured values.

This research established that as course aggregate quality decreased, as dictate by the incorporation of aggregates with increasing water absorption characteristics, concrete performance decreased. This results, in increased measurement of permeation properties of concrete with respect to their reference CEM I concretes.

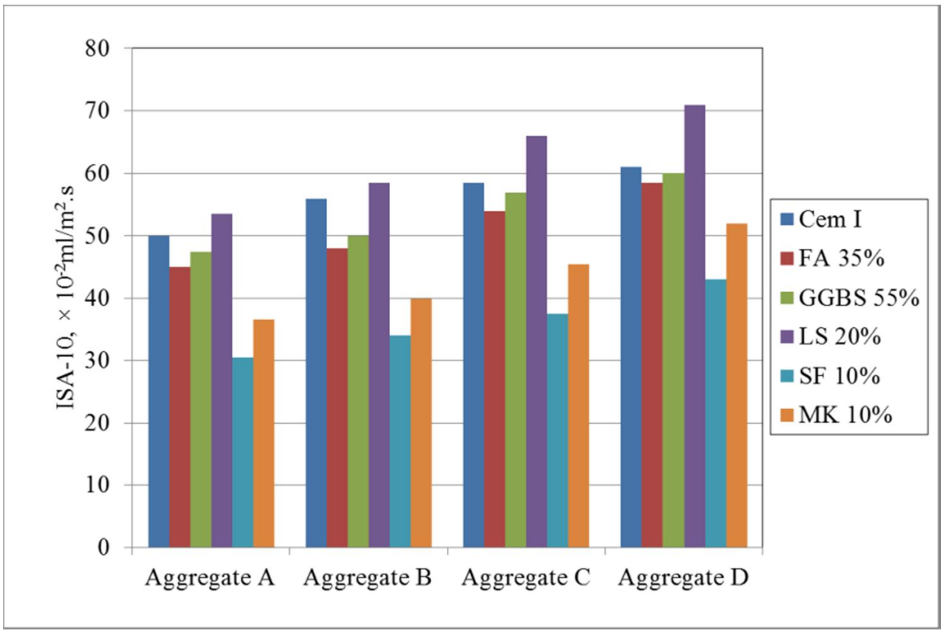

Fig. 1. ISA-10 measurement of concretes

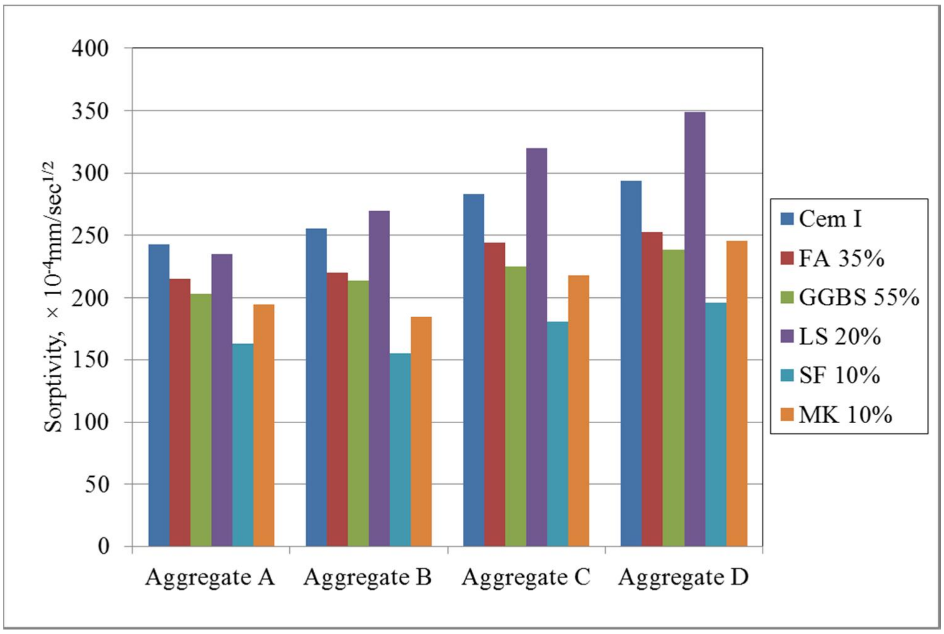

Fig. 2. Sorptivity measurements of concretes

3.3 Rapid chloride permeability and rapid chloride migration

As illustrated in Figures 3 and 4, upon investigating the influence of aggregate type on chloride ingress of concrete, it was found that aggregates of increasing water absorption result in concretes with reduced resistance to chloride ion ingress. This research did establish that that aggregate type is of lesser significance than cement type. Subsequently an aggregate/cement combination trade-off concept is proposed in the discussion section of this paper. It was established how after careful selection of the binary cement combination, a concrete containing the highest absorption aggregate (21.5%), can attain equal or greater resistance to chloride ion ingress.

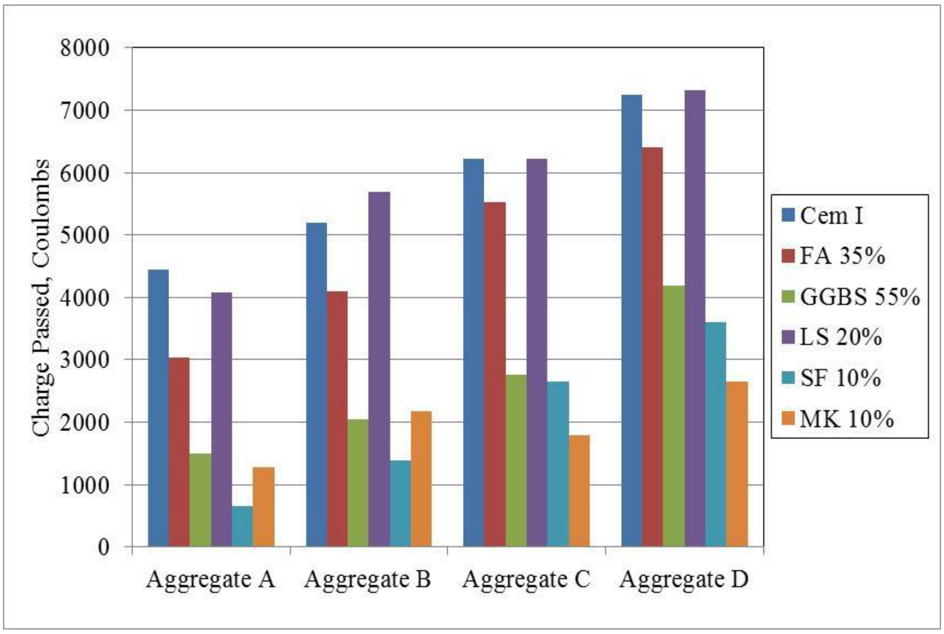

Fig. 3. Aggregate effect on chloride charge passed

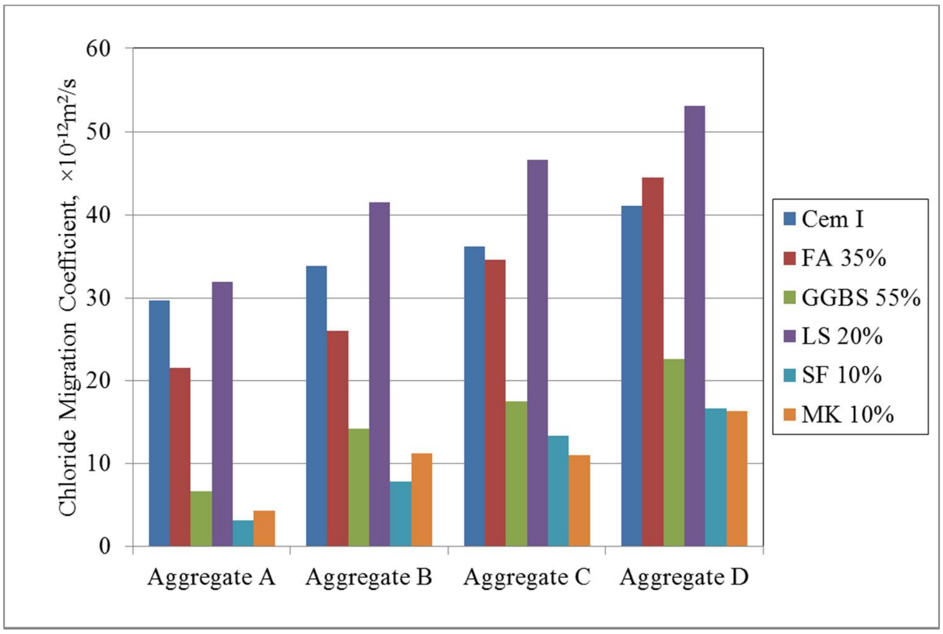

Fig. 4. Aggregate effect on chloride migration coefficient

4. Discussion

Although not quantified in this research, it is reasonable to expect that aggregate characteristics such as shape, size and texture will have an influence on the chloride ion ingress resistance of concrete. These aggregate properties are known to contribute to aggregate/cement paste bond strengths whilst also resulting in effects to the initial transition zone (ITZ) of concrete. A number of researchers have studied the microstructure of the Initial Transition Zone (ITZ) between lightweight aggregate and cement paste. As outlined at the outset of this paper, their findings suggest that densification of the ITZ microstructure occurs as a result of lightweight aggregate absorbing water from the cement paste and that this gives rise to enhanced bond along the surface of aggregates and cement paste. However, from the current study it was observed that, irrespective of the cement combination type, compressive strengths, water permeability and chloride ingress of concrete decreased as the water absorption of the aggregate decreased.

Table 5 demonstrated the compressive strength, up to 28-days, of all the concretes. The LWAC's were found to give rise to the lowest strength. With the exception of the PC65%/FA35% combination, the Aggregate D concretes were found to have the lowest gain in strength with respect to their reference CEM I concretes. Observations across each concrete combination type, established that the range differences in compressive strengths were 6% to 10%. Thereafter, the data revealed that reductions in strength, due to the inclusion of aggregates of greater water absorption, are offset by the inclusion of certain SCM's. Illustrated in Table 5, in the case of the Aggregate D type concretes, reductions in strength of the Aggregate D CEM I concrete, to that of the Aggregate A CEM I concrete, to that of the Aggregate D PC90%/SF10% concrete, was found to decreased from 33% to 16% respectively. As a result, without considering the effects of aggregate shape, it is concluded that aggregates of reduced water absorption, give rise to greater in compressive strengths.

Water penetrability of the concretes followed similar trends in results to that of compressive strength. These are presented in Figures 2 to 3. The results indicated that for a concrete with aggregate of increased absorption characteristics, the corresponding concretes water permeability increases. Across all aggregate types, the PC80%/LS20% concretes were found to result in the greater uptake of water. These concretes were found to possess the greatest percentage increase in permeation at 18 ($\times 10^{-2}$ml/m^2.s) for the ISA-10 measurement and 114 ($\times 10^{-4}$mm/sec$^{1/2}$) difference observed across Aggregate A to Aggregate D concretes. Differences in the remaining concrete types were found to range from between 60% to 70% and 30% to 45% of these values, for each test type.

Figures 3 to 4 outline the chloride penetrability data of each concrete. In general, these results were found to be consistent with those obtained by the ISA-10 and sorptivity tests. The electric charge passed through the NWCA and LWCA concretes were in the same order of magnitude. With the exception of the PC80%/LS20% concretes, across all concrete types, the ability of concrete to resist chloride ion penetration increased with the introduction of SCM's. An anomaly in these results is observed with respect to the PC65%/FA35%, Aggregate D concrete, when tested to NT Build 492.

This research demonstrates the possibility of offsetting the adverse properties of high water absorption aggregate, with the inclusion of addition material. In fact, these results demonstrate that, irrespective of the total CEM I replacement content or aggregate type, improved resistance to chloride ion ingress can be achieved to the reference CEM I concrete. In the case of the PC45%/GGBS55%, PC90%/SF10% and PC90%/MK10% concretes, they were all found to provide enhanced resistance to that of the reference CEM I concrete. On comparison of compressive strength, irrespective of aggregate type, it appears that the quality of the mortar matrix and not compressive strength is significant in controlling permeability of concrete.

Whilst aggregate type influences the chloride ingress resistance of concrete, it has being demonstrated that cement combination type plays an important role in controlling this process. The has given rise to the theory that a trade-off concept, between aggregate type and a particular cement combination, could be adopted in achieving a specific concrete chloride ingress resistance. The consequences of this would be a greater shift towards a more sustainable approach in aggregate specification for chloride environments. This approach is illustrated in Figures 5 and 6, which indicate that, by using a concrete which consists of 100% primary materials (CEM I and natural Aggregate A), a specific chloride ingress resistance can be achieved.

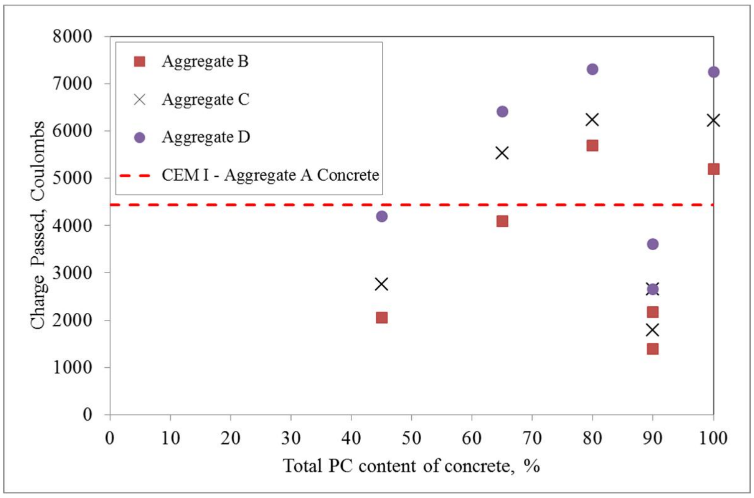

Fig. 5. Aggregate effect on chloride charge passed

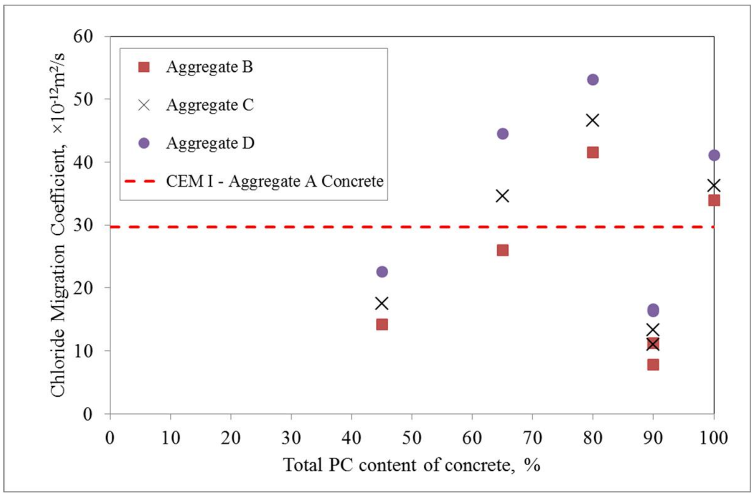

Fig. 6. Aggregate effect on chloride migration coefficient

5. Conclusions

When comparing the results presented in this paper it is noted that their mix designs varied. Notwithstanding this, for these mix designs, the following conclusions may be drawn:

- Aggregate type influenced the compressive strength and the water and chloride ion permeability of the concrete. As a result, it is concluded that aggregates of reduced water absorption and greater densities give rise to greater compressive strengths.
- Irrespective of aggregate type, the quality of the mortar matrix is significant in controlling the permeability of concrete.
- A correlation exists between water permeability and chloride ion ingress of concrete.
- With the exception of the LS concretes, it was demonstrated that by replacing CEM I with SCM's, a progressive offsetting of the negative aggregate effects imparted on concrete from aggregates of inferior quality (as measured by increasing absorption characteristics) can be achieved.
- A trade-off concept was proposed, and the potential suitability of applying this theory in concrete chloride design was discussed. This established that, on applying a particular binary cement

combination with an aggregate of greater absorption (21.5%), it is possible to attain equal or greater resistance to chloride ion ingress. As a result, although limited in its scope, these findings would imply that there is further potential to exploit the usage of different aggregate types with respect to the specification of concrete in chloride environments.

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