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DURABILITY PERFORMANCE OF STRUCTURAL CONCRETE MADE WITH COARSE RECYCLED CONCRETE AGGREGATES

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ABSTRACT

There is often a poor perception of the durability of concrete made with recycled concrete aggregates (RCA), as well as concerns regarding performance variability and contamination of the source material. Additional research regarding the addition of RCA in structural concrete is therefore required to more clearly determine the limits of its suitability.

The influence of RCA on the mechanical properties of concrete has been well investigated; the effect on durability however, is less well understood. Chloride ions can be particularly detrimental to the durability of reinforced concrete and BS 8500 currently allows RCA in strength classes up to C40/50 for structures unlikely to be exposed to de-icing salts and marine environments during their design life. This research investigated the effect of coarse RCA in combination with supplementary cementitious materials on the resistance to chloride ingress of concrete in terms of surface resistivity, sorptivity and rapid chloride migration testing. Compressive cube testing was conducted to determine compliance with characteristic and target mean strengths.

The results indicate that a higher replacement of natural aggregates with RCA causes a reduction in the resistance to water and chloride ingress, possibly due to the higher water absorption characteristics of the RCA. PFA and GGBS reduced the rate of water and chloride ingress compared to Portland cement concretes for all coarse RCA increments tested.

Keywords: Recycled concrete aggregates (RCA), durability, chloride ingress, corrosion.

1 Introduction

Recycled aggregates (RA) have become an increasingly popular construction material to replace virgin aggregates since the beginning of the 1980's. Approximately 13.5 and 18.8 million tonnes of hard demolition arisings became available in the UK in 2013 and 2014 respectively (NFDC, 2015). UK government statistics suggest that low amounts of demolition waste are now sent to landfill, and that the recycling target of 70% by 2020 for the demolition and construction industry has already been achieved (DEFRA, 2015). The increase in recycling of demolition materials in recent years has been accelerated by government strategies and industry best practice guidance (BERR, 2008; WRAP, 2009; WRAP 2015).

Recycled concrete aggregates (RCA) are mainly utilised in general fill, road base/sub-base materials and low-grade concrete, as the quality of these aggregates are generally of less importance (WRAP, 2008). A recent study has shown that the sustainability benefits of RCA are soon diminished when the material has to be transported long distances, and virgin aggregates become the preferred option (Georgopoulos and Minson, 2014). It is important to improve the general perception of RCA so that it can be incorporated into a wider variety of applications, including structural concrete.

It is a general perception that the inclusion of RCA requires an increased cement content to compensate for the lower quality of aggregates (Georgopoulos and Minson, 2014; Agrela *et al*, 2013). In recent years pilot schemes, and also major construction projects globally, have included RCA without the need for additional cement by incorporating supplementary cementitious materials (SCMs) (Messari-Becker *et al*, 2014; Filho *et al*, 2013). These case studies have found that the carbon footprint and environmental impact of projects could be significantly reduced, which has led to the need for research to better understand the effects of these aggregates.

The European standard for concrete specification provides recommendations for coarse RCA (d ≥ 4mm) in Annex E, *'Type A aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%'* (BSI, 2013). This limit can be increased to 50% if no reinforcing steel or embedded metal is present. If the source of the RCA is unknown or does not conform to the criteria of Type A aggregates (>95% concrete products, unbound aggregate and natural stone) (BSI, 2002a) then the replacement allowance for the majority of exposure classes, including chlorides, reduces to 0%. The UK standard for the specification of concrete allows crushed concrete aggregate (CCA) in concrete up to strength class C40/50, except when the structure is likely to be exposed to chlorides. The standard also states that *'these aggregates may be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment'* which is an ambiguous statement as no performance criteria or limits are included (BSI, 2015a,b).

A review of research work has highlighted a general consensus that RCA has a detrimental effect on the mechanical properties of concrete (WRAP, 2007; Ajdukiewicz and Kliszczewicz, 2002). The extent largely depends upon the replacement quantity, and the quality of the original concrete. Some studies have shown that RCA can be successfully incorporated at 30% for structural applications, without impacting the compressive strength (Limbachiya *et al*, 2000; Exteberria *et al*, 2007).

The effect on durability is less well understood and requires further investigation, particularly when the RCA concrete is exposed to aggressive chloride environments, increasing the risk of corrosion to steel reinforcement. Recent research suggests water and chloride permeability increases proportionally with RCA content due to the increased water absorption of the aggregates (Lofty and Al-Fayez, 2015; Bravo *et al*, 2015; Soares *et al*, 2014; Pedro *et al*, 2014; Kwan *et al*, 2012). However, it has been shown that SCMs can significantly improve the durability performance of concrete made with RCA, due to the reduced porosity of the cement matrix and interfacial transition zones of aggregates (Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). Some SCMs can also increase the chloride binding capacity of concrete which reduces the free chloride content within the pores (Bapat, 2013). A wider variety of RCA sources, water/cement ratios and cement combinations requires investigation to improve our understanding of the trade-off between cement and aggregate sources.

The aim of this study was to examine one source of RCA with different cement combinations and its resistance to water and chloride ingress. The compressive strength was tested to determine compliance with the characteristic and target mean strength.

2 RCA composition

RCA from a commercial recycling facility in Plymouth, UK, from mixed sources of concrete, was crushed to a 40mm down product including 0-4mm fines. The fines content and larger aggregates (>20mm) were sieved out to leave coarse RCA conforming to Type A recycled aggregates suitable for concrete production (BSI, 2013). RCA samples were analysed for cement content, alkali content and chloride content testing to BS 1881:124 (BSI, 2015c). The results are summarised in Table 1.

Given that the age, composition and source of the concrete were unknown, some assumptions were made regarding the original mix design. A concrete density of 2400kg/m³ was assumed, thus the data in Table 1 suggests a cement content between 265kg/m³ to 310kg/m³ in the original concrete(s), which may be representative of structural concrete. This however is not a sufficient indicator of the quality of the original concrete. An alkali content of up to 0.4% can be beneficial for strength development of concrete but quantities higher than 0.6% can cause expansive reactions of the aggregate (Neville, 2011). In this case the alkali content is lower than 0.6% and unlikely to cause contamination problems in the new concrete.

The chloride levels of the RCA are relatively low and are comparable to readings taken from non-contaminated reinforced concrete structures. This therefore indicates that the concrete structures that the RCA was obtained from were not exposed to severe chloride environments. It is generally accepted that a threshold level of chloride below 0.4% by weight of cement represents a low risk of corrosion initiation. (Concrete Society, 2004).

Table 1 - Laboratory analysis of RCA

Cement content (%) by mass of dried sample	Sample 01	11.1
	Sample 02	12.8
Alkali content (%) by mass of dried sample	Sample 01	K_2O – 0.12 Na_2O – 0.02
	Sample 02	K_2O – 0.19 Na_2O – 0.03
Chloride content (%) (acid soluble) by mass of dried sample	Sample 01	0.03
	Sample 02	0.02
	Sample 03	0.01

3 Methodology

A C28/35 concrete was cast as part of an initial testing programme to determine the effect of RCA on the durability performance of concrete. The BRE mix design method (BRE, 1997) was adopted for the design of concrete mixes to achieve characteristic and target mean strengths of 35MPa and 49MPa respectively. Portland cement (CEM I) and GGBS (50% - CEM III/A) concrete mixes were tested at a water-binder ratio of 0.5, and PFA (30% - CEM IIB-V) mixes at a ratio of 0.4, with a reduced water content for PFA mixes following the recommendations in the BRE mix design method (BSI, 2013). The water-binder ratios were chosen to comply with the recommendations for XD3/XS3 exposure classes in Table A.4 of BS8500-1 (BSI, 2015a). Coarse RCA was incorporated at 20%, 40% and 60% to replace natural coarse aggregates (rounded quartzite river gravel) by mass. An additional cement content was added to compensate for the inclusion of coarse RCA (10kg/m³ per 20% RCA) following the recommendations for crushed aggregates in the BRE mix design method. Table 2 details the test methods adopted to investigate the effect of coarse RCA on the durability properties of concrete.

Table 2 - Test methods

Test	Justification
Compressive cube strength (BSI, 2009)	To determine compliance of mixes with characteristic and target mean strengths and to analyse the effect of coarse RCA on compressive strength.
Surface resistivity (AASHTO, 2015)	To determine the effect of coarse RCA on electrical resistivity of concrete, to provide an indication of its ability to resist chloride ion penetration.
Absorption by capillary action (BSI, 2002b)	To determine the effect of coarse RCA on the sorptivity of concrete with no external pressures applied. This is the key transport mechanism of water and chloride ingress when concrete is in a dry state.
Rapid Chloride Migration (NordTest, 1999)	To determine the effect of coarse RCA on the chloride migration coefficient in concrete. The results cannot be directly compared to natural diffusion tests, however provides a rapid indication of durability performance.

Statistical analysis of the results was undertaken using t-tests to determine the effect on sample means when coarse RCA and SCMs were added. Probabilities were calculated based on a detrimental effect on performance by 10% when compared to the control concrete for each cement combination.

4 Analysis of Results

4.1 Compressive strength

Tests were conducted on 100mm cube samples at 7, 28 and 56 days. The results show that the inclusion of coarse RCA does have an increasing detrimental effect on compressive strength at both 28 and 56 days for all cement combinations tested, except for 20% RCA in Portland cement concrete (Figures 1 and 2 respectively). The target mean strengths (49MPa) for Portland cement and PFA concretes were met for lower levels of RCA inclusion (up to 40%), however was not achieved for any of the GGBS concretes at 28 days. In all cases the characteristic strength (35MPa) at 28 days was easily achieved.

A left-tailed t-test was used to determine if the addition of coarse RCA had a detrimental effect (10% decrease) on sample means. A high probability (p>0.733) was obtained for coarse RCA contents above 20% in the PFA concrete at 28 days. A lower probability was observed in Portland cement and GGBS concretes at 28 days (p<0.384 and p<0.135 respectively). The highest probability calculated for the concrete to decrease below the 28 day characteristic strength of 35MPa was p=0.006.

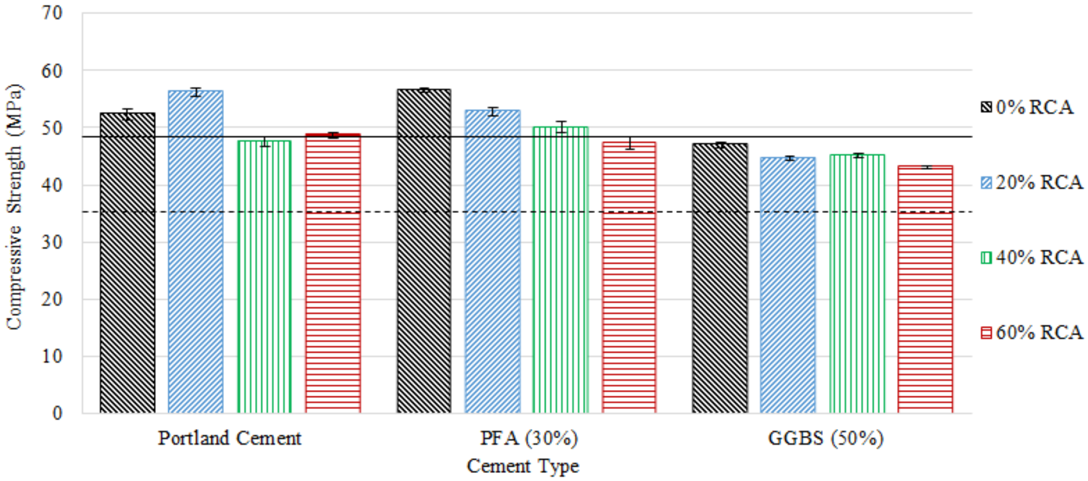

Figure 1 - 28 day compressive cube strength

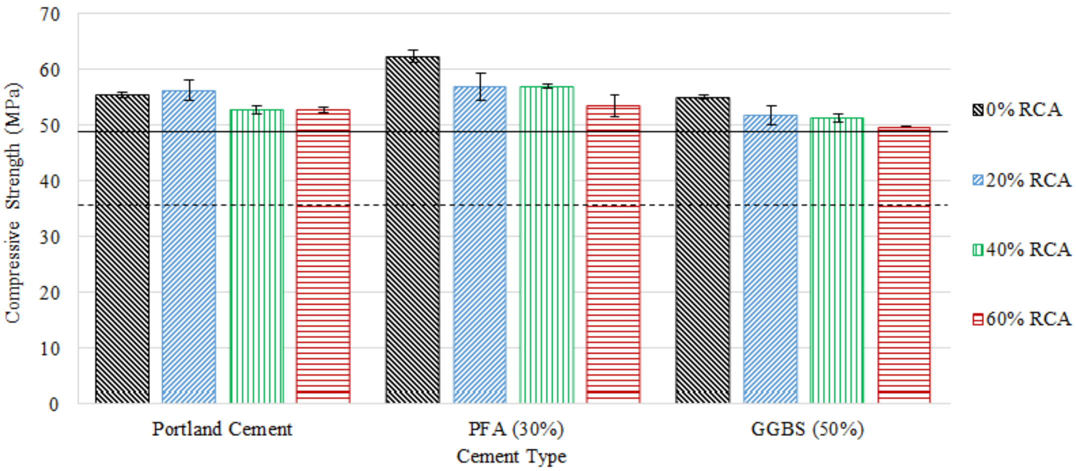

Figure 2 - 56 day compressive cube strength

4.2 *Surface resistivity*

The surface resistivity of cylindrical specimens (200mm x 100mm diameter) was measured at 28 days; a relatively quick method for assessing the microstructure and subsequent transport properties of concrete (Angst and Elsener, 2014). The results of surface resistivity testing are commonly interpreted following recommendations in Tables 3 and 4. A lower resistivity indicates a more porous concrete microstructure as it allows a higher current to pass between the probes at the surface. The results of the surface resistivity test are shown in Figure 3.

Table 3 - Interpretation of Wenner probe readings (Concrete Society, 2004)

Resistivity (kΩcm)	Interpretation
>20	Low corrosion rate
10-20	Low to moderate corrosion rate
5-10	High corrosion rate
<5	Very high corrosion rate

Table 4 - Interpretation of Wenner probe readings (AASHTO, 2015)

Resistivity (kΩcm)	Interpretation
<12	High chloride ion penetration
12-21	Moderate chloride ion penetration
21-37	Low chloride ion penetration
37-254	Very low chloride ion penetration
>254	Negligible chloride ion penetration

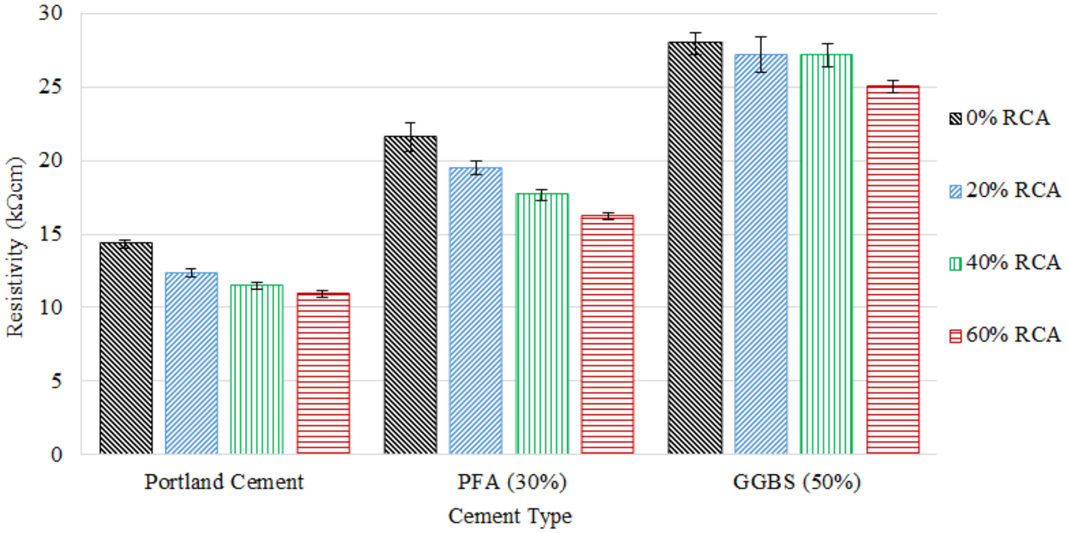

Figure 3 – Concrete surface resistivity at 28 days

The results show that the Portland cement concrete has the lowest surface resistivity followed by PFA and GGBS concretes respectively. The addition of coarse RCA had an increasing detrimental effect on the surface resistivity of the concrete, however all mixes tested remained within the low to moderate chloride ion penetration/corrosion rate range, even with up to 60% coarse RCA content. Statistical analysis showed a particularly high probability ($p>0.929$) that the surface resistivity would decrease by more than 10% when more than 20% coarse RCA content is included in the Portland cement and PFA concretes. A much lower probability was calculated for the GGBS concrete ($p<0.290$) with up to 60% coarse RCA content.

4.3 Absorption by capillary action

Kropp *et al* (1995) describe sorptivity as the *'transport of liquids into porous solids due to surface tension acting in capillaries'*. The sorptivity is influenced by the characteristics of the liquid and solid material it is in contact with, particularly the radius, tortuosity and continuity of the capillaries. The concrete specimens (50mm x 100mm diameter slices) were sealed on all sides except the surface to be exposed to the water; therefore the capillary suction phenomenon is considered to be in non-steady state as no evaporation of liquid can take place. Cumulative absorption was measured at 28 and 120 days (Figures 4 and 5 respectively) and the sorption coefficient determined from the gradients (Table 5). Higher sorption coefficients were observed at 120 days compared to the 28 day readings for all cement combinations tested.

Low probabilities ($p<0.047$) were calculated for the total cumulative absorption (kg/m^2) to increase by more than 10%, when coarse RCA was included up to 60% for the 28 day readings. In contrast, higher probabilities of increased absorption ($p>0.563$) were observed at 120 days for the same effect. This suggests that the inclusion of RCA had a more detrimental effect on sorption at later ages. Statistical analysis of the data also showed that the inclusion PFA and GGBS reduced the probability ($p<0.008$) of a significant detrimental effect on the concrete.

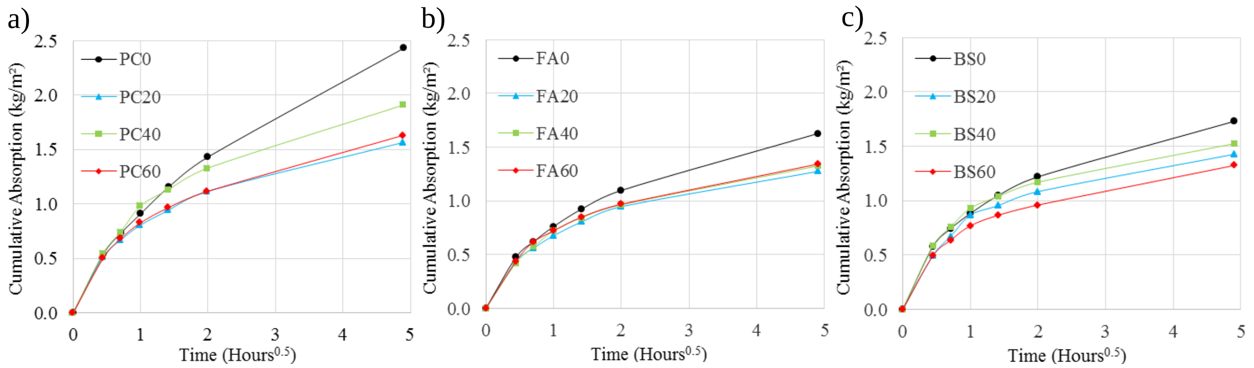

Figure 4 – Cumulative absorption at 28 days for a) Portland cement, b) PFA, c) GGBS concrete

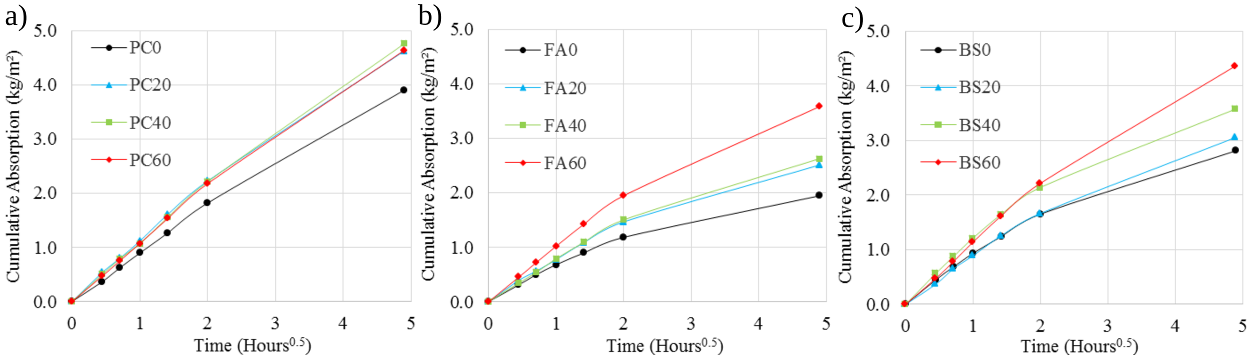

Figure 5 – Cumulative absorption at 120 days for a) Portland cement, b) PFA, c) GGBS concrete

Table 5 - Sorption Coefficients for all concretes tested

	Portland Cement				PFA				GGBS			
RCA Content (%)	0	20	40	60	0	20	40	60	0	20	40	60
28 Day Sorption Coefficient (kg/m².h$^{0.5}$))	0.50	0.32	0.39	0.33	0.33	0.26	0.27	0.27	0.35	0.29	0.31	0.27
120 Day Sorption Coefficient (kg/m².h$^{0.5}$))	0.80	0.94	0.97	0.95	0.40	0.51	0.54	0.73	0.57	0.62	0.73	0.89

4.4 Rapid chloride migration

Migration of chloride ions occurs when an electric field is applied across a concrete specimen (50mm x 100mm diameter slice), causing the negatively charged chloride ions to move towards the anode (Claisse, 2014). The non-steady state migration coefficients have been calculated from average penetration depths and are shown in Figure 6.

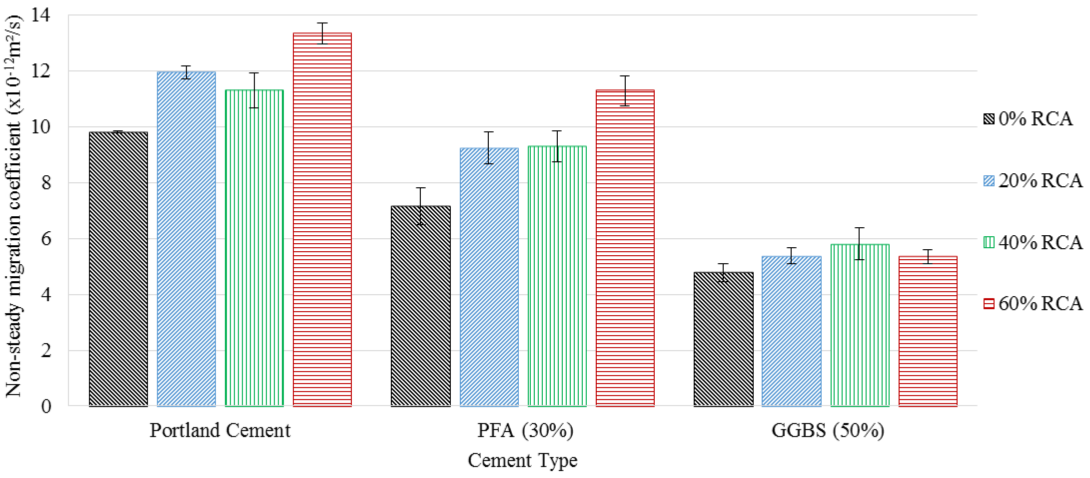

Figure 6 - Rapid chloride migration at 28 days

The results show that the inclusion of coarse RCA content generally had an increasing detrimental effect on the migration coefficient of concrete. Statistical analysis showed a particularly high probability ($p>0.727$) that the migration coefficient would increase by more than 10% when more than 20% coarse RCA content was included in the Portland cement and PFA concretes. A slightly lower probability was calculated for the GGBS concrete ($p<0.588$) with up to 60% coarse RCA inclusion. Statistical analysis of the data also showed that the inclusion of PFA and GGBS reduced the probability ($p<0.043$) of a significant detrimental effect on the concrete.

5 Discussion

5.1 Compressive strength

The statistical tests for 28 day results provide strong evidence that coarse RCA is detrimental to the compressive strength of concrete at higher increments than 20% in PFA and Portland cement concretes, similar to the findings of other published research work (Exteberria *et al*, 2007; Ajdukiewicz and Kliszczewicz, 2002; Limbachiya *et al*, 2000). The particularly low probability of RCA causing a detrimental effect on compressive strength in GGBS concretes suggests that it is the most suitable replacement material. In this case, the extremely high probability for all concretes to achieve the 28 day characteristic strength suggests that the BRE method of mix design is suitable for designing concrete of sufficient strength with coarse RCA up to 60%. Figure 2 shows that the target mean strengths for all concretes was achieved after 56 days; this is particularly important for the concrete containing GGBS and higher levels of RCA inclusion (>40%). The benefits of SCM's are also demonstrated in Figures 1 and 2 with the continuing development of concrete strength due to pozzolanic and latent hydraulic effects.

5.2 Surface resistivity

Figure 3 shows that as the coarse RCA content increased the concrete surface resistivity in all cement combinations tested reduced, probably due to the RCA concrete having a more porous and open microstructure, as suggested by the higher water absorption of the aggregates (Pedro *et al*, 2014; Kwan *et al*, 2012). The inclusion of both PFA and GGBS increased the surface resistivity of concrete; however, the statistical analysis suggests that GGBS is more beneficial in reducing the porous microstructure of concrete and hence increasing resistivity. It should be noted that a reduced water-binder ratio for the PFA concretes would also contribute to an increased surface resistivity.

5.3 Absorption by capillary action

The inclusion of both PFA and GGBS had a beneficial effect on the sorption coefficient of the concrete for all increments of coarse RCA tested, possibly due to the reduced porosity of the cement matrix (Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). The difference in probability values between 28 and 120 days suggests that the inclusion of RCA had a more detrimental effect on sorption at later ages. This is possibly due to the hydration process of the cement paste which has reduced the size and continuity of the capillaries in the concrete. The natural aggregate and RCA then becomes the more dominant pathway for the water ingress rather than the surrounding cement paste. Hydration of the cement paste also caused an increase in cumulative absorption due to increased surface tension effects of the smaller pores. The increased water absorption of the RCA therefore contributes to the increase in absorption by capillary action of the concrete. This finding is in agreement with the work of other published research in this field (Lofty and Al-Fayez, 2015; Bravo *et al*, 2015; Soares *et al*, 2014).

5.4 Rapid chloride migration

The results show that the migration coefficient can be reduced with the inclusion of both PFA and GGBS for all increments of coarse RCA tested, in agreement with other published work, and is possibly due to the reduced porosity of the cement matrix (Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). The probability values calculated for Portland cement, PFA and GGBS concretes suggest that GGBS is the more suitable replacement material for reducing the detrimental effect on the migration coefficient. This is possibly due to the combined effect of reduced porosity and the chloride binding capacity of the cement paste when a high quantity of GGBS is included within the mix (Bapat, 2013).

6 Conclusions

The results show that the inclusion of RCA has a slightly detrimental effect on the compressive strength of concrete. Statistical analysis of the results showed that for the concrete mixes tested in this study, the BRE method of mix design is suitable for designing concrete of sufficient strength with coarse RCA up to 60%. In all cases the characteristic strength was exceeded at 28 days. The benefits of SCMs on compressive strength are usually seen at later ages due to pozzolanic and latent hydraulic effects.

The results of the tests to investigate the effect of coarse RCA on the surface resistivity, resistance to water and chloride ingress of concrete has highlighted that RCA contents, even as low as 20%, have a detrimental effect on the durability of concrete. However, statistical analysis has highlighted that the addition of PFA (30%) and GGBS (50%) can significantly increase the surface resistivity and resistance to chloride migration whilst reducing water absorption of the RCA concrete for all replacement levels tested (up to 60%) which is in agreement with other published work in this field. The GGBS concrete performed better than the PFA and Portland cement concretes in all the test methods due to the combined effect of reduced porosity of the cement matrix and the chloride binding capacity.

These findings suggest that RCA could be a viable option for new structural concrete, even when the structure is likely to be exposed to chlorides during its service life, provided that a suitable level of SCM is incorporated. This conclusion is valid, provided that: a reliable and consistent source of RCA is obtained with no known sources of contamination or deleterious materials present; and the durability recommendations for minimum cement content, maximum water-cement ratio and minimum cover to reinforcing steel are met (BSI, 2015a).

7 Acknowledgements

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