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SHOULD DURABILITY BE A BARRIER TO THE USE OF CRUSHED CONCRETE AGGREGATE IN STRUCTURAL CONCRETE?

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ABSTRACT:. Applications involving crushed concrete aggregate (CCA), or recycled concrete aggregate (RCA), are growing, as interest continues to increase in the sustainable sourcing of materials. For CCA to be fully used in structural concrete however, it's influence on the mechanical and durability properties of the resultant concrete is required. The electrical resistivity and water absorption by capillary action of CEM I and CEM III/A concretes were hence investigated to determine the effects on concrete microstructure and water ingress. Findings show that incorporating coarse CCA has generally a detrimental effect on the microstructure and water ingress of structural concrete. However, this can be mostly overcome through the inclusion of GGBS, hence allowing higher proportions of coarse CCA to be incorporated. Limiting the GGBS and coarse CCA content to 50% and 60% respectively is advised, hence minimising the risk of any significant deterioration of mechanical and durability performance. Results suggest that CCA CEM III/A concrete could be a suitable option for structural concrete, provided that a reliable and consistent source of CCA can be obtained.

Keywords: Crushed concrete aggregates (CCA), recycled concrete aggregate (RCA), durability, performance, microstructure, supplementary cementitious materials, ggbs.

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INTRODUCTION

Crushed concrete aggregates (CCA), formerly referred to as recycled concrete aggregates (RCA) have become increasingly popular to replace virgin aggregates since the 1980's, particularly with a more recent impetus towards sustainable sourcing of materials [1; 2]. Approximately 13.6, 18.8 and 21.2 million tonnes of hard demolition arisings were produced in the UK in 2013, 2014 and 2015 respectively, and the quantity is predicted to continue to increase annually [3]. In the UK, a high proportion of hard demolition arisings are utilised as general fill, sub-base material or within low grade concretes, as the quality requirements for aggregates in these applications are generally lower [4; 5]. The use of CCA for structural applications is currently limited due to uncertainty regarding performance; recycled aggregate producers however, are continually looking to improve the quality and performance of CCA to allow specification in higher value applications [4; 6]. The UK's Waste and Resources Action Programme (WRAP) provides a framework of quality controls for the production of CCA for use in structural concrete, and all aggregates must conform to the European standard for aggregates in concrete [7; 8].

Furthermore, the abundance of natural aggregates (NA) in the UK, does not incentivise designers and contractors to include CCA as a replacement material in structural concrete applications. Certain situations however, may arise where CCA may be a suitable replacement material such as: a specific project/client requirement, improved project sustainability credentials, a good quality, consistent source of CCA is available on site, and/or where there is a short supply of NA [9]. This study investigates the effects of three sources of coarse CCA from known structural elements on the durability performance of structural concrete. The presentation of results concentrates on the microstructure and water ingress; the resistance to chloride ingress is published elsewhere, together with SEM anaylis and results of the CCA [10, 11].

BACKGROUND TO CCA

Specification of CCA in structural concrete

The European standard for concrete specification states that a Type A coarse aggregate (>95% concrete product; 4/20mm), from a known source, may be incorporated into structural concrete up to 30% replacement by mass in low risk exposure classes only, including: XC1-4, XF1, XA1 and XD1 [8]. The British Standard is further limited and permits the inclusion of coarse CCA, up to 20% replacement by mass, in concrete up to strength class C40/50, except when the structure is to be exposed to chlorides [12; 13]. The British 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 ambiguous as no performance criteria or limits are included to determine suitability. This highlights the importance of further research of coarse CCA, to understand the effects on the mechanical and durability properties, if a more robust framework for coarse CCA is to become a possibility.

Effect of coarse CCA on concrete properties

The effect of coarse CCA on the mechanical properties of structural concrete has been investigated in recent studies [15; 16; 17]. The effect of CCA on long-term durability performance however, is less well established, particularly in relation to water and chloride ion ingress. The majority of published research on the effect of coarse CCA on concrete durability has focused on rapid migration and water absorption test methods to determine acceptable levels of replacement of NA. The general consensus is that 25-30% coarse CCA can be successfully incorporated without detrimentally affecting the transport properties of concrete. The detrimental effect is generally attributed to the increased water absorption of the coarse CCA [18 ; 19; 20; 21; 22; 23].

Studies of the effects of coarse CCA on structural concrete have shown that CCA content, as low as 20% and 40% for CEM I and CEM III/A concretes respectively, had a significant detrimental effect on the durability performance [24; 25]. Statistical analysis also established that the inclusion of SCMs improved the resistance of concrete to water and chloride ion ingress. A CEM III/A structural concrete incorporating 60% coarse CCA outperformed the control CEM I concrete for all durability test methods adopted.

METHODOLOGY

The effect of coarse CCA on the compressive cube strength and durability of structural concrete was investigated. Forty different CEM I and CEM III/A concretes were produced to achieve a characteristic ($f_{c,cube}$) and target mean strength of 45MPa and 59MPa respectively by the BRE mix design method [26]. The concretes were produced in accordance with BS 1881-125 and all specimens were cured in water at a temperature of (20±2°C) until testing. The constituents for each mix are summarised in Table 1. The water-binder ratio of 0.5 and the cement content were selected to comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 [12]. Three sources of coarse CCA (4/20mm) of known composition were incorporated at 30%, 60% and 100% to replace the coarse NA by mass and will be referred to here as sources A, B and C. GGBS was incorporated at 36%, 50% and 65% to replace CEM I by mass, to produce a range of CEM III/A concretes. No admixtures were included and no additional cement was added to compensate for the inclusion of CCA.

The concrete mixes are coded by the numeric GGBS content, followed by A, B or C for the relevant CCA source and the numeric CCA content. For example, a mix denoted as 36A-60 refers to a concrete produced with 36% GGBS and CCA source A at 60%.

Table 1 - Mix design constituents for control batches

	Mix Design			
Constituents	CEM I	CEM III/A (36%)	CEM III/A (50%)	CEM III/A (65%)
Water-binder ratio	0.5	0.5	0.5	0.5
Cement (kg/m³)	390	250	195	136
GGBS (kg/m³)	-	140	195	254
Water (kg/m³)	195	195	195	195
Sand (kg/m³)	653	653	653	653
Coarse 10/20mm (kg/m³)	775	775	775	775
Coarse 4/10mm (kg/m³)	387	387	387	387

Concrete cubes and cylinders were cast according to the test methodology detailed in Table 2. The methods were chosen to investigate the effect of different sources of coarse CCA on the microstructure of structural concrete and its ability to resist water ingress. Compressive strength testing was undertaken to determine compliance with characteristic ($f_{c,cube}$) and target mean strengths.

Table 2 - Test method justification

Test	Standard	Justification
Compressive cube strength	BS EN 12390-3 (BSI, 2009a)	To determine compliance of mixes with the characteristic ($f_{c,cube}$) and target mean strength, to analyse the effect of coarse CCA on compressive strength and to determine the suitability of the BRE mix design method to produce structural CCA concrete.
Surface resistivity	AASHTO T358-15 (AASHTO, 2015)	To determine the effect of coarse CCA on the microstructure of concrete, indicated by the electrical surface resistivity.
Absorption by capillary action	BS EN 13057 (BSI, 2002)	To determine the effect of coarse CCA 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.

Statistical analysis was undertaken using t-tests to determine the effect on sample means when coarse CCA sources A, B and C were added based on a 10% decrease in performance. A 10% decrease in performance is considered to be significant as this is greater than any expected human or batch reproducibility error. The results of concrete produced with CCA were compared against the results of the control concrete for each binder type to calculate a probability of a significant detrimental effect. The results from the three sources were also compared. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect.

Aggregate Properties

The European standard for concrete specification states that a quality source of CCA, of known composition, should be obtained to produce sustainable structural concrete. This is to prevent possible contamination and reduce any detrimental effects [27]. Further aggregate and concrete testing was conducted for each CCA source to determine the original concrete compostition and characteristics.

Three sources of CCA were obtained from selected components of reinforced concrete structures from two demolition sites in the East and West Midlands, UK (Table 3). Larger sections of reinforced concrete beams, footings and floor slabs were separated by the contractor on site and brought to the laboratory to be processed. The steel reinforcement was removed and a primary jaw crusher reduced the CCA to a 40mm down product. The resultant material was sieved into 4/10mm and 10/20mm size increments, conforming to a ‘Type A’ aggregate suitable for concrete production [27]. Obtaining sources of CCA in this manner is not necessarily a typical approach for current demolition practices; it was however important for this study as the material characteristics and original constituents could be better quantified.

Table 3 – CCA sources obtained

Source	Site location in UK	Structural Component
A	Royal Mail Sorting Office, Bishop Road, Coventry	Reinforced concrete beam (internal)
B	Moseley site (Office/Factory), Derby Road, Loughborough	Reinforced concrete footing and column base
C		Reinforced concrete slab (ground floor)

The water absorption and particle density of the natural aggregates (NA - rounded quartzite river gravel) and CCA are summarised in Table 5. The particle densities of the three sources of CCA are lower than that of NA for both coarse size increments tested, indicating a lower density microstructure. The water absorption of CCA ranged between 6 and 10 times greater than the NA. A higher water content was added during mixing to account for the short-term water absorption of coarse CCA in accordance with the BRE mix design method [26].

CCA samples from each source were analysed for cement, alkali and chloride contents in accordance with BS 1881-124 [28] (Table 4) and were found to be within acceptable limits and hence unlikely to cause contamination problems in the new concrete [29; 30]. The cement content is highest for source B, followed by A and C.

Table 4 - Laboratory analysis of CCA

Source	Cement content [%]	Alkali content [%]	Chloride content [%] by mass of dried sample/cement
A	12.2	K_2O – 0.07 Na_2O – 0.07	<0.01/0.08
B	17.1	K_2O – 0.09 Na_2O – 0.15	<0.01/0.06
C	10.6	K_2O – 0.05 Na_2O – 0.08	0.03/0.28

The compressive strength results of the cored specimens are shown in Table 5. The three sources of CCA provide a wide range of equivalent in-situ compressive strengths. Source A had the lowest compressive strength, followed by sources B and C respectively; therefore it may be expected that source A will have the largest detrimental effect on the resultant compressive strength of concrete.

Table 5 provides a summary of the characteristics of the coarse CCA sources. It can be seen that little correlation exists between the water absorption, particle density, and the equivalent in-situ results. Little correlation also exists between the cement content and equivalent in-situ strength (Tables 4 and 5). The higher water absorption, higher estimated water-cement ratio, complex lithology and evidence of microcracking suggests that source B may have the greatest detrimental effect on the mechanical and durability performance of structural concrete. Source A and C have similar compositions, with source A having a higher estimated cement content, an observed better grading of coarse aggregates and no evidence of microcracking.

Table 5 – Summary of coarse CCA characteristics

Source	24 hour water absorption [%]		SSD particle density [Mg/m³]		Contaminants	$f_{ck,is}$ [MPa]
	10/20	4/10	10/20	4/10		
A	4.81	6.80	2.40	2.30	None	17.6
B	6.75	8.33	2.35	2.31	None	25.6
C	5.30	6.41	2.33	2.27	None	33.4

ANALYSIS OF RESULTS

Compressive strength

Tests were conducted on 100mm cube samples at 28 and 91 days. The results confirm that the inclusion of coarse CCA has an increasingly detrimental effect on compressive strength at all ages for CEM I and CEM III/A concretes (Figures 1 and 2 respectively). The characteristic strength of 44MPa (indicated by the horizontal line) at 28 days was achieved by 24 of the 40 concrete mixes. Concretes with higher quantities of CCA and GGBS generally had lower strengths, with source B having the greatest detrimental effect, followed by sources C and A respectively. Concretes containing 100% coarse CCA only achieved the characteristic strength for mixes 0A, 36A and 0C. The characteristic strength was met for CEM III/A concretes (up to 50% replacement) produced with coarse CCA contents up to 60% for sources A and C. In comparison a reduced coarse CCA content of 30% could be used for the same binder type when source B is utilised.

The results at 91 days (Figure 2) show the latent hydraulic effect of GGBS with many of the CEM III/A concretes produced with higher quantities of GGBS having sufficient strength. At this later age, 37 of the 40 concretes achieved the characteristic strength of 44MPa. Only concretes 50B, 65B and 65C made with 100% coarse CCA content did not achieve the characteristic strength. These concretes have a confidence level of 0.997, 0.066 and 0.849 of achieving the characteristic strength respectively (when a human and batch reproducibility error above 10% is considered significant), which highlights that the 65B-100 concrete has the highest risk of non-compliance.

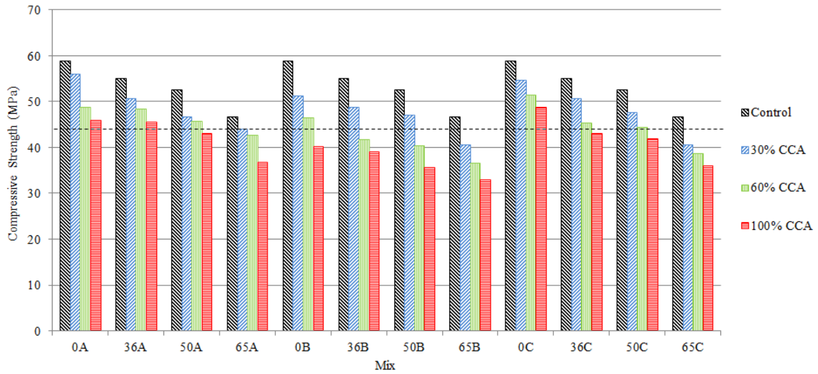

Figure 1 - Compressive strength at 28 days

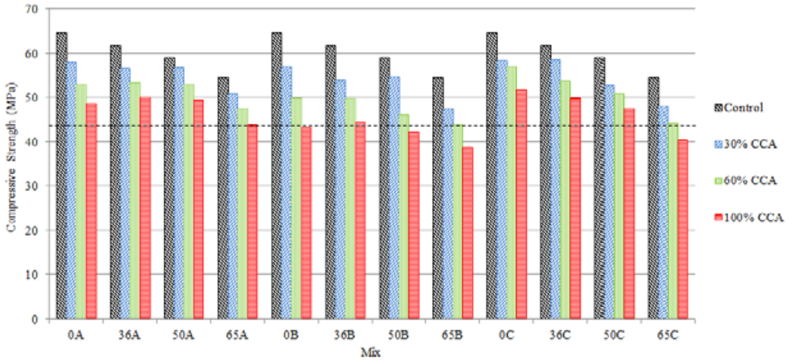

Figure 2 - Compressive strength at 91 days

Surface resistivity

The surface electrical resistivity of cylindrical specimens (200mm x 100mm diameter) was measured at 28, 56 and 91 days. Figure 3 show that the surface resistivity reduced with increasing CCA content at 28 days. Similar trends were observed for concretes at 56 and 91 days, but are omitted for clarity. All CEM III/A concretes produced with up to 100% CCA content had a higher surface resistivity than the control CEM I concretes at all ages. At 28 days, 26 of the 40 concrete mixes were above 20kΩcm, which both interpretations acknowledge as being related to low corrosion rate/chloride ion penetration [31; 30]. The concretes below this threshold consisted of all the CEM I concretes, 36B-60, 36A-100, 36B-100 and 36-C100. The surface resistivity continues to increase for the CEM III/A concretes above the 20kΩcm threshold with only the 36A-100 and 36B-100 batches not achieving this by 56 days. At 91 days only the CEM I concretes have surface resistivities lower than 20kΩcm. The data highlights that source B predominantly was the worst performing source of coarse CCA, followed by sources A and C respectively.

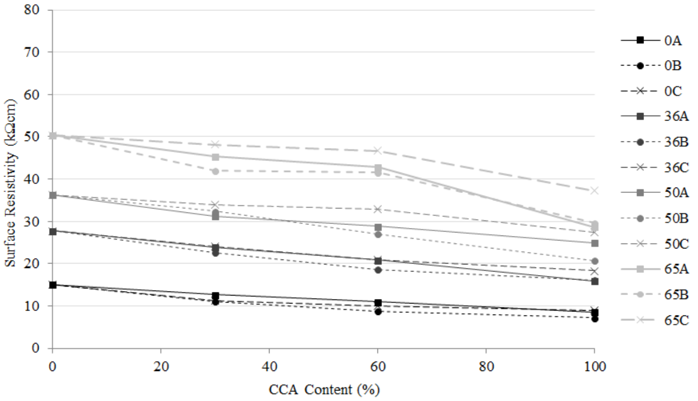

Figure 3 - Surface resistivity at 28 days

Figure 4 show the beneficial latent hydraulic effects of GGBS in CEM III/A concretes as the surface resistivity continues to increase with time for concretes produced with coarse CCA from source B. Similar trends were observed for sources A and C, but are again omitted for clarity. Source B concretes produced with 65% GGBS content, along with 36B-0, 50B-0, 50B-30 and 50B-60 concretes at 91 days, achieved above 37kΩcm, which is acknowledged as being related to a very low chloride ion penetration [31].

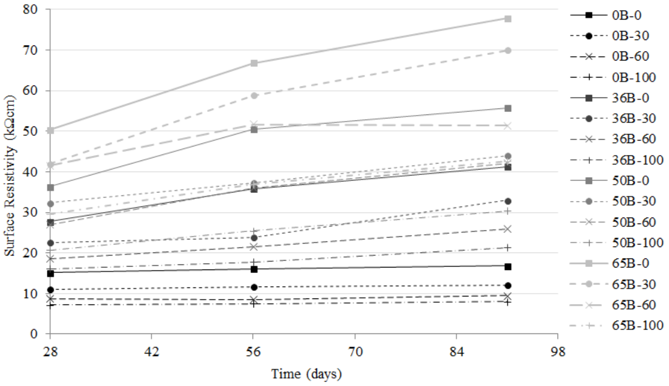

Figure 4 - Surface resistivity for source B concretes

Absorption by capillary action

The 24 hour sorption coefficient of cylindrical specimens (60mm x 100mm diameter) was measured at 28, 56 and 91 days (Figures 5 to 7). Figures 9 and 10 show that the 24 hour sorption coefficient generally increased with increasing coarse CCA content at 28 and 91 days. A similar trend was observed for concretes at 56 days. This trend was more evident at 91 days for all concrete types tested. At 28 and 91 days there was no clear trend of sorption coefficient with a particular source of coarse CCA; source A and B however had a detrimental effect on performance compared to source C CCA for CEM I concretes at 91 days ($P>0.847$). CEM III/A concretes produced with up to 100% CCA content had a lower 24 hour sorption coefficient than the control CEM I concretes at 91 days ($P>0.936$), except for the 50C-100 concrete, the probability of this concrete having a detrimental effect of 10% compared to the control CEM I concrete however was significantly low ($P<0.021$). At 28 days, the probability of CEM III/A concretes produced with up to 100% CCA content having a detrimental effect on the 24 hour sorption coefficient compared to the control CEM I concretes was significantly higher ($0.938<P<0.999$).

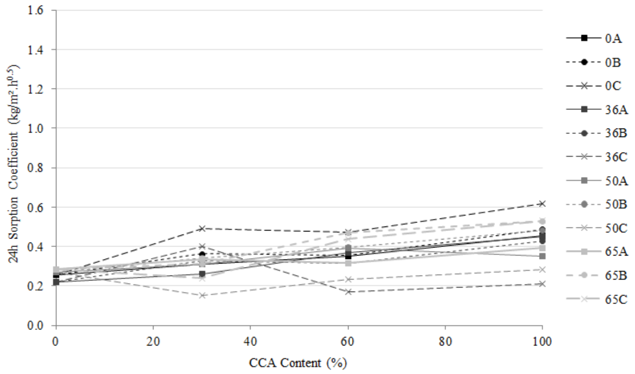

Figure 5 – 24hr Sorption coefficient at 28 days

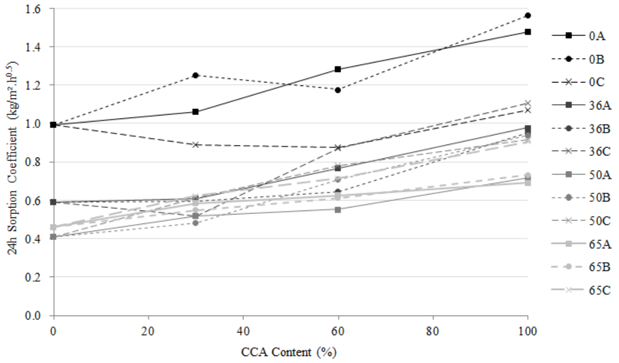

Figure 6 – 24hr Sorption coefficient at 91 days

Figure 7 shows that the sorption coefficient generally increases with time for concretes produced with coarse CCA from source B. Similar trends were observed for sources A and C. The beneficial latent hydraulic effects of GGBS in CEM III/A concretes can be observed as the sorption coefficient remains lower than CEM I concretes at 56 and 91 days. The CEM III/A concretes produced with higher quantities of coarse CCA content generally had higher sorption coefficients at all ages. At 56 and 91 days CEM III/A concretes produced with up to 100% coarse CCA from source B had lower sorption coefficients than the CEM I control concrete. Similar effects were observed for CCA sources A and C, except for the 36C-100 concrete.

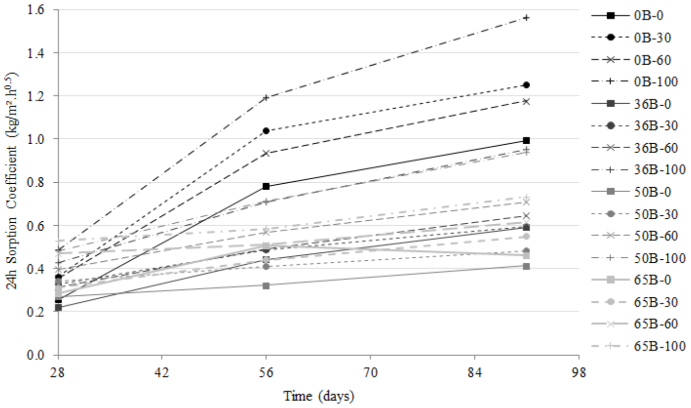

Figure 7 – 24hr Sorptivity coefficients for source B concretes

DISCUSSION

The characteristic strength ($f_{c,cube}$) of 44MPa at 28 days was achieved by 24 of the 40 concrete mixes (Figure 1). CEM III/A concretes (up to 50% GGBS replacement) produced with coarse CCA contents up to 60% for sources A and C, and 30% for source B, achieved the characteristic strength. In comparison 37 of the 40 concretes achieved the characteristic strength by 91 days (Figure 2), with only the 65B-100 concrete having a statistically high probability of non-compliance. Therefore if the characteristic strength at 28 days is of particular importance (as is usually the case in the construction industry) then it is recommended that the GGBS and coarse CCA content be restricted to 50% and 30% respectively. If a different approach is adopted whereby the long term 91 day compressive cube strength performance is assessed, then higher quantities of coarse CCA content can be utilised, producing a more sustainable structural concrete. In this case the coarse CCA content may be increased to 60% without significantly increasing the risk of not achieving the characteristic strength, which is higher than previously reported values of 25-50% [14; 15; 16; 17].

The results of surface resistivity testing showed the beneficial latent hydraulic effects of GGBS as all CEM III/A concretes produced with up to 100% CCA content had a higher surface resistivity by a factor of 3 to 4 than the control CEM I concretes at all ages (Figures 3 and 4), which indicates a less porous microstructure related to a low corrosion rate/chloride ion penetration [31; 30]. This finding is in agreement with other published research on the beneficial effects of SCMs [31]. At 91 days only the CEM I concretes had surface resistivities lower than 20kΩcm, which increases the risk of a reduced durability performance compared to CEM III/A concretes. A strong correlation was observed between surface resistivity (Figure 4), in agreement with other published research [32] which indicates that the surface resistivity readings can be used to assess the bulk microstructure of the concrete.

The beneficial latent hydraulic effect of GGBS was also observed in the test for absorption by capillary action, however was only evident at later ages (Figure 6). CEM III/A concretes produced with up to 100% CCA content had a lower 24 hour sorption coefficient by a factor 1.1 to 2.2 than the control CEM I concretes at 91 days, except for the 50C-100 concrete which was found to have a low probability of a significant detrimental effect in comparison ($P<0.021$).

The results of these durability tests have shown the importance of analysing concrete at both early and later ages (28 and 91 days) to better understand the effects of coarse CCA on structural concrete. The inclusion of coarse CCA generally reduced the surface and resistivity and increased the 24 hour sorption coefficient of concrete for all binder types tested. This is most likely due to the increased water absorption of the coarse CCA itself [18; 19; 20; 21; 23]. The magnitude of results between CEM I and CEM III/A concretes has shown that up to 100% coarse CCA, irrespective of CCA source, can be incorporated into structural CEM III/A concrete and have a better durability performance than that of control CEM I concrete, which is a higher than the previously reported values of 25-50% [19; 21; 22; 23] and a positive finding for the wider implementation of coarse CCA to produce sustainable structural concrete [10, 11]. BS8500 provides guidance for cover depth and concrete mix design proportions based on the chosen binder type and expected environmental conditions [14, 18]. The guidance suggests that the cover depth for CEM III/A concretes may be reduced to provide equivalent performance with CEM I concretes. If, however, a different approach is adopted whereby the cover depth is kept similar to that of CEM I concretes then the risk of structural degredation regarding durability performance of CEM III/A CCA concretes is further reduced.

Taking all the results together, the source B CCA was the worst performing aggregate, followed by sources A and C respectively. This however, was not the case for every individual test and concrete type, which again highlights some issues with the variability of performance for even the same source of CCA of known structural elements. The aggregate and concrete testing of CCA sources sought to characterise the CCA sources to be able to predict their effect on mechanical and durability performance. It was found that little correlation existed between the results of water absorption/particle density, chemical analysis, and the equivalent in-situ strength; however the information as a whole provided some indication that source B may perform worse than sources A and C due to a higher water absorption, higher estimated water-cement ratio, complex lithology and evidence of microcracking. It is recommended that sources of coarse CCA be tested in a similar manner before inclusion within structural concrete to be able to foresee any potential risks to mechanical and durability performance.

CONCLUSIONS

To conclude, the results show that the inclusion of coarse CCA generally has a detrimental effect on the microstructure and water ingress of structural concrete. The detrimental effects can be largely overcome through the use of GGBS to produce CEM III/A concretes, allowing higher proportions of coarse CCA to be utilised. Based upon the analysis of results, the following recommendations are made:

1. Replacement of GGBS and coarse CCA be limited to 50% and 30% respectively in cases where compliance with the 28 day characteristic strength is of particular importance. If this criterion can be relaxed and the

mechanical performance of CEM III/A concretes tested at later ages for conformity, then higher quantities of coarse CCA may be implemented up to 60% to produce a sustainable structural concrete.

2. CEM III/A concretes produced with up to 100% coarse CCA, irrespective of CCA source, have been shown to outperform control CEM I concrete with NA in durability performance tests. If the cover depth of CEM III/A concretes can be increased, similar to that of CEM I concretes, then the risk of potential durability performance issues could be further reduced.

The findings of this study have highlighted that sustainable structural CEM III/A concrete can be a viable option for future responsibly sourced projects, provided that a reliable and consistent source of CCA can be obtained. This is a positive outcome for the wider implementation of coarse CCA into structural concrete applications. The authors have also previously published results on the incorporation of fine crushed concrete aggregate on the durability of structural concrete [33], as well as other durability properties [24; 10; 11; 25].

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