Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on microstructure and water ingress

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HIGHLIGHTS

- Coarse CCA generally has a detrimental effect on structural concrete.
- This can largely be overcome with the use of GGBS to produce CEM III/A concretes.
- Sustainable structural concrete is found to be a viable option for future projects.
- Up to 50% and 60% GGBS and coarse CCA respectively may be incorporated.

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ABSTRACT

The use of crushed concrete aggregate (CCA), formerly referred to as recycled concrete aggregate (RCA) is increasing, particularly with a recent push towards sustainable sourcing of materials. Further research is required to understand the effect of coarse CCA on the mechanical properties and durability performance of structural concrete. The electrical resistivity, water absorption by capillary action and SEM analysis of CEM I and CEM III/A concretes were investigated to determine the effects on concrete microstructure and water ingress, together with compliance of characteristic (f\text{c, }\text{cube}) and target mean compressive strengths. The results show that for the three coarse CCA sources tested, the inclusion of coarse CCA generally has a detrimental effect on the microstructure and water ingress of structural concrete. These can be largely overcome through the incorporation of GGBS to produce CEM III/A concretes, allowing higher proportions of coarse CCA to be incorporated. We conclude that the GGBS and coarse CCA content be limited to 50% and 60% respectively, as this reduces the risk of a significant reduction of compressive cube strength and durability performance. The findings suggest 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 and significant outcome for the wider implementation of coarse CCA into structural concrete applications.

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1. 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 push towards sustainable sourcing of materials [28,66]. 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 [47]. 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 [6,65]. 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 [6,23]. 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 [31,15].

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.

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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 [37,67,34].

This study investigates the effects of three sources of coarse CCA from known structural elements on the durability performance of structural concrete.

2. Background to CCA

2.1. Specification of CCA in structural concrete

The European standard for concrete specification states that a Type A coarse aggregate (>95% concrete product; 4/20 mm), 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 [16]. The British standard places further limits on the inclusion of coarse CCA, and permits up to 20% replacement by mass, in concrete up to strength class C40/50, except when the structure is to be exposed to chlorides [19,20]. The British standards also state 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 [19,20]. 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.

2.2. 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 [58,9,25,54,51,62,32]. 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 [10,46,52,57,60,68,44]. Quantities up to 75% have been shown to produce structural concrete of adequate quality, however it was noted that higher amounts also increased the variability of durability performance compared to the control concretes [68]. Limbachiya et al. [43] established that a replacement level up to 100% may not have a significant effect on the durability performance of high strength Portland cement (CEM I) concretes, provided the CCA is obtained from a high quality precast concrete source.

Research has shown that the latent hydraulic and pozzolanic properties of supplementary cementitious materials (SCMs) improve the durability performance of CCA concrete. The addition of SCMs reduce the porosity of the cement matrix, improve quality of the interfacial transition zones (ITZ) and increase the chloride binding capacity of concrete [7,38,61,8,4].

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 [29,30]. Statistical analysis also established that the inclusion of SCMs improved the resistance of concrete to water and chloride ion ingress. Dodds et al. [29] established that a CEM III/A structural concrete incorporating 60% coarse CCA outperformed the control CEM I concrete for all durability test methods adopted. The observed beneficial effects of SCM’s is in agreement with other published work in this field [33,59,36,38,39,44,61,8,4]. For example, Berndt [8] found that CEM III/A concrete (with 50% GGBS) was found to perform best when compared against other replacement levels of SCMs, including 50% fly ash, 70% GGBS and a tertiary blend of 25% fly ash and 25% GGBS.

2.3. Key transport properties of concrete

The durability of reinforced concrete is primarily influenced by its microstructure – the connectivity, continuity, tortuosity and radius of its pores – as this determines how gases, liquids and other substances penetrate the concrete cover to reinforcement [40,50]. Water and chloride ions can ingress concrete through a combination of transport mechanisms, namely absorption by capillary action, diffusion and permeation [64]. Absorption by capillary action and diffusion relate to the transport of liquids and ions by surface tension effects and concentration gradients respectively; they are the dominant mechanisms in higher risk exposure classes (under the cyclic wetting and drying of reinforced concrete – denoted XD3 and XS3) [16]. Diffusion is a much slower process as the movement of ions occurs in the pore solution of saturated concrete, whereas absorption by capillary action occurs in a dry or semi-dry state and is considered the fastest transport mechanism [40].

Taking measurements of surface resistivity is a well-established and relatively quick method of assessing the microstructure and subsequent transport properties of concretes, where a lower surface resistivity relates to a more porous concrete [24]. The results of surface resistivity are commonly interpreted following the recommendations in Table 1; no recommendations currently exist for bulk resistivity testing. Recent research has shown that strong correlations exist between electrical resistivity (both surface and bulk), water penetration, rapid chloride migration coefficients and diffusion coefficients [49,45,56,53]. Some variability in electrical resistivity results can occur due to the inhomogeneity of concrete, location/presence of coarse aggregates, probe spacing and specimen size therefore care should be taken when interpreting results [35,3].

The transport of liquid in concrete predominantly occurs through the pores of the cement matrix; however aggregates also play an important role. The specific gravity of aggregates (or particle density) can be a good indicator of their water absorption properties and subsequent quality of ITZ between the cement matrix and aggregates, which can accelerate or decrease the rate of ingress of fluids [48,55]. Aggregates with increased water absorption can

| Table 1 | Interpretation of four-point Wenner probe readings [1,26]. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Concrete Society Technical Report 60 | AASHTO T358 | Resistivity \([\text{[d}\Omega \cdot \text{cm}]) | Interpretation | Resistivity \([\text{[d}\Omega \cdot \text{cm}]) | Interpretation |
| <5 | Very high corrosion rate | <12 | High chloride ion penetration |
| 5–10 | High corrosion rate | 12–21 | Moderate chloride ion penetration |
| 10–20 | Low to moderate corrosion rate | 21–37 | Low chloride ion penetration |
| >20 | Low corrosion rate | 37–254 | Very low chloride ion penetration |
| – | – | >254 | Negligible chloride ion penetration |
reduce the ability of cement paste to adhere to the surface of aggregates, and in turn the quality of the ITZ [46,10,60,52,41]. Research has shown that a strong correlation exists between the water absorption and oven-dried density of coarse CCA which could be used as a prediction model to determine the quality of CCA [57]. Microscopic imaging techniques such as scanning electron microscopy (SEM) and X-ray microtomography can help analyse the microstructure of concrete. Some researchers have used these techniques to analyse the cement matrix, aggregates and ITZ quality of concretes, confirming that CCA itself has an increased porosity and has a detrimental effect on the ITZ, primarily due to the release of air from CCA as water is absorbed during the early curing process which creates additional voids [42,63].

3. 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 44 MPa and 58 MPa respectively by the BRE mix design method [22]. The concretes were produced in accordance with BS 1881–125 [17] and all specimens were cured in water at a temperature of $(20 \pm 2 \, ^\circ C)$ until testing. The constituents for each mix are summarised in Table 2. The free water-binder ratio and the cement content were selected to comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 [19]. Three sources of coarse CCA (4/20 mm) of known composition were incorporated at 30%, 60% and 100% to replace the coarse NA by mass, and will be referred to as sources A, B and C (more detail provided in Section 4). 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%.

Concrete cubes (100mm³) and cylinders (200 mm × 100 mmØ) were cast according to the test methodology detailed in Table 3. The test 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.

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 respective 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.

4. 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 [16]. Further aggregate and concrete testing, as detailed in Table 4, was conducted for each CCA source to determine the original concrete composition 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 5). 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

| Constituents | Mix design |
|--------------|------------|
| Free water-binder ratio | 0.5 | 0.5 | 0.5 | 0.5 |
| Cement (kg/m³) | 390 | 230 | 195 | 136 |
| GGBS (kg/m³) | – | 140 | 195 | 254 |
| Water (kg/m³) | 195 | 195 | 195 | 195 |
| Sand (kg/m³) | 653 | 653 | 653 | 653 |
| Coarse 10/20 mm (kg/m³) | 775 | 775 | 775 | 775 |
| Coarse 4/10 mm (kg/m³) | 387 | 387 | 387 | 387 |

| Test | Standard | Justification |
|------|----------|---------------|
| Compressive cube strength | BS EN 12390-3 [12] | 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 concrete which were produced to match commonly adopted practices in the UK construction industry for quality control purposes |
| Surface resistivity | AASHTO T358-15 [11] | To determine the effect of coarse CCA on the microstructure of concrete, indicated by the electrical surface resistivity |
| Bulk resistivity | N/A | To determine the effect of coarse CCA on the microstructure of concrete, indicated by the electrical bulk resistivity |
| Absorption by capillary action | BS EN 13057 [11] | 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 |
| SEM analysis | N/A | To provide microscopic imagery of the new cement matrix, the cement matrix of the adhered mortar of the coarse CCA and the quality of the interfacial transition zones between coarse aggregates and cement paste |
reduced the CCA to a 40 mm down product. The resultant material was sieved into 4/10 mm and 10/20 mm size increments, conforming to a 'Type A' aggregate suitable for concrete production [15,16]. 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.

The water absorption and particle density of the NA (rounded quartzite river gravel) and CCA are summarised in Table 6. 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 [22]. The water absorption of coarse CCA at 24 h in other studies has been reported to be between 3.6% and 11.6%, dependent on the original source of concrete [10,46,52,68,38,44,61,84]. The CCA sources in this study fall within the expected range, with the original source of concrete [10,46,52,60,68,38,44,61,8,4]. The cement content is highest for source B, followed by A and C.

The compressive strength results of the cored specimens are shown in Table 8. 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. The key findings of the petrographic analysis are summarised in Table 9 [5].

It should be noted that the values estimated in petrographic analysis are based upon point-counting of mix constituents across thin sections; care should be taken when interpreting this information.

Table 6

| Source | Size (mm) | Water absorption | Particle density |
|--------|-----------|------------------|-----------------|
|        | 30 min [%] | 24 h [%] | SSD [mg/m^3] |
| NA     | 10/20 | 0.63 | 0.90 | 2.59 |
|        | 4/10  | 1.07 | 1.16 | 2.57 |
|        | 0/4   | 0.42 | 0.54 | 2.61 |
| A      | 10/20 | 4.72 | 4.81 | 2.40 |
|        | 4/10  | 6.50 | 6.80 | 2.30 |
|        | 0/4   | 8.15 | 8.33 | 2.31 |
| B      | 10/20 | 6.18 | 6.75 | 2.35 |
|        | 4/10  | 8.15 | 8.33 | 2.31 |
| C      | 10/20 | 4.85 | 5.30 | 2.33 |
|        | 4/10  | 6.08 | 6.41 | 2.27 |

5. Analysis of results

5.1. Compressive strength

Tests were conducted on 100 mm 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 (Figs. 1 and 2 respectively). The characteristic strength of 44 MPa (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 con-
Table 8
Determination of equivalent in-situ characteristic strength from cored specimens.

| Source | Compressive strength of cored specimen [MPa] | Coefficient of variation [%] | Correction factor \(|K_{0.5,svy}|\) | Corrected compressive strength [MPa] | Equivalent in-situ characteristic strength \(|f_{c,k,svy}|\) [MPa] |
|--------|---------------------------------------------|----------------------------|-----------------------|-----------------------------------|-------------------------------|
| A      | 24.3                                        | 7.56                       | 1.012                 | 24.6                              | 17.6                          |
| B      | 32.4                                        | 4.61                       | 1.007                 | 32.6                              | 25.6                          |
| C      | 40.3                                        | 4.12                       | 1.002                 | 40.4                              | 33.4                          |

Table 9
Key findings of petrographic analysis.

| Source | Key findings |
|--------|--------------|
| A      | - The concrete is produced with quartz dominated gravel typical of the Midlands and South East of England (average size 10 mm – well graded), quartz sand and Portland cement - No evidence of cement replacements or admixtures - Estimated water-cement ratio, slump and 28 day strength are 0.51, 10–30 mm and 40 MPa respectively - Estimated cement content is 365 kg/m³, 15.2% of total weight of concrete - There is no obvious segregation, excessive voids, honeycombing or visible microcracking - Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs - Phenolphthalein indicator solution suggests maximum carbonation from the surface is 7 mm |
| B      | - The concrete is produced with river gravel with complex lithology typical of the Midlands (Quartz, Chert, Limestone, Ironstone) - Average size 12.5 mm), quartz sand and Portland cement - No evidence of cement replacements or admixtures - Estimated water-cement ratio, slump and 28 day strength are 0.55, 0–10 mm and 36 MPa respectively - Estimated cement content is 262 kg/m³, 10.6% of total weight of concrete. - There is no obvious segregation, excessive voids or honeycomb ing. Some microcracking exists, however they are not considered significant - Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs - Phenolphthalein indicator solution suggests maximum carbonation from the surface is 5 mm |
| C      | - The concrete is produced with quartz dominated river gravel typical of the Midlands (average size 12.5 mm), quartz sand and Portland cement - No evidence of cement replacements or admixtures - Estimated water-cement ratio, slump and 28 day strength are 0.49, 0–10 mm and 41 MPa respectively - Estimated cement content is 317 kg/m³, 13.0% of total weight of concrete - There is no obvious segregation, excessive voids or honeycomb ing. Some microcracking exists, however they are not considered significant - Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs - Phenolphthalein indicator solution suggests carbonation depth varies significantly. This is often typical of concrete that has been damp for long periods |

Table 10
Summary of coarse CCA characteristics.

| Source | 24 h water absorption [%] | SSD particle density [mg/m³] | Contaminants | \(f_{c,k}\) [MPa] | Key notes of petrographic analysis |
|--------|---------------------------|-----------------------------|--------------|-----------------|-----------------------------------|
|        | 10/20                     | 10/20                       |              |                 |                                   |
| A      | 4.81                      | 6.80                        | 2.40         | 2.30            | None                              |
| B      | 6.75                      | 8.33                        | 2.35         | 2.31            | None                              |
| C      | 5.30                      | 6.41                        | 2.33         | 2.27            | None                              |

The surface and bulk electrical resistivity of cylindrical specimens (200 mm x 100 mm diameter) was measured at 28, 56 and 91 days (Figs. 3–6). Figs. 3 and 4 show that the surface and bulk 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 and bulk resistivity than the control CEM I concretes at all ages. At 28 days, 26 of the 40 concrete mixes were above 20 kΩ cm, which both interpretations acknowledge as being related to low corrosion rate/chloride ion penetration. The concrete 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 20 kΩ cm 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 20 kΩ cm. The data in Figs. 3 and 4 highlights that source B predominantly was the worst performing source of coarse CCA, followed by sources A and C respectively.

A statistically significant detrimental effect in surface resistivity (indicated by a 10% decrease in sample means) was observed when CCA sources A and B were used in concretes produced with a GGBS content greater than 50% and a CCA content greater than 60%, when compared with a concrete produced with source C 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.
(P > 0.758). A low probability of a detrimental effect was observed for concretes 50C-30, 50C-60, 65A-30, 65C-30 and 65C-60 when compared against the respective control concrete for each binder type (P < 0.214). No statistical analysis could be performed on the bulk resistivity results as only one reading was taken at each time interval.

Figs. 5 and 6 show the beneficial latent hydraulic effects of GGBS in CEM III/A concretes as the surface and bulk 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 37 kΩ cm, which is acknowledged as being related to a very low chloride ion penetration [1].

In addition to the individual trends observed in surface and bulk resistivity results with increasing CCA content and time, a strong correlation was observed between the two test methods as shown in Fig. 7.

5.3. Absorption by capillary action

The 24 h sorption coefficient of cylindrical specimens (60 mm × 100 mm diameter) was measured at 28, 56 and 91 days (Figs. 8–10).
Figs. 8 and 9 show that the 24 h 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 h 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 h sorption coefficient compared to the control CEM I concretes was significantly higher (0.938 < P < 0.999).

Fig. 10 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.

5.4. SEM analysis

Samples of CCA concrete for CEM I and CEM III/A binder types were randomly selected for SEM analysis. The samples were polished, coated with gold palladium and analysed in variable pressure (VP) mode with backscatter to produce high resolution, high magnification images. The areas between the coarse CCA and the new cement matrix were analysed to determine the quality of the ITZ (Fig. 11).

The images show that there was no obvious increased porosity around the ITZ for CEM I concretes, compared to CEM III/A concretes. Instead the quality of ITZ for all concretes appeared to be dependent on the shape, size and arrangement of aggregates in a particular area. This effect can be observed in Fig. 11c where the quality of ITZ is reduced in the area adjacent to the aggregate particle of the coarse CCA. In general, larger and more regular pores were observed in the new cement matrix for CEM I concrete (Fig. 11a) compared to the CEM III/A concretes (Fig. 11b–d). The pores generally reduced with size and frequency as the GGBS content increased. Larger and more regular pores were also observed in the old Portland cement matrix of the coarse CCA; whereas the pore size and distribution of the original aggregates was largely

![Fig. 5. Surface resistivity for source B concretes.](image)

![Fig. 6. Bulk resistivity for source B concretes.](image)
varied across samples and can be observed when comparing Fig. 11c and d.

6. Discussion

The characteristic strength ($f_{c,\text{cube}}$) of 44 MPa at 28 days was achieved by 24 of the 40 concrete mixes (Fig. 1). CEM III/A concretes (up to 50% GGBS replacement level) 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 (Fig. 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% [9,51,62,32]. It is important to note that no superplasticisers were utilised in this study which could further contribute to an increase in compressive strength, and further research is required to quantify this effect.

The results of surface and bulk 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 and bulk resistivity by a factor of 3 to 4 than the control CEM I concretes at all ages (Figs. 3–6), which indicates a less porous microstructure related to a low corrosion rate/chloride ion penetration [1,26]. This finding is in agreement with other published research on the beneficial effects of SCMs [32,59,36,38,39,44,61,8,4]. At 91 days only the CEM I concretes had surface resistivities lower than 20 kΩ cm,
which increases the risk of a reduced durability performance compared to CEM III/A concretes. A strong correlation was observed between surface and bulk resistivity (Fig. 7), in agreement with other published research [49,45,56,53] 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 (Fig. 9). CEM III/A concretes produced with up to 100% CCA content had a lower 24 h 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 bulk resistivity and resulted in an increase in the 24 h sorption coefficient of concrete for all binder types tested. This is most likely due to the increased water absorption of the coarse CCA itself [10,46,52,60,68,44]. The magnitude of difference in the measured results between CEM I and CEM III/A concretes has shown that up to 100% coarse CCA, irrespective of the CCA sources adopted in this study, can be incorporated into structural CEM III/A concrete and have a better durability performance than that of control CEM I concrete, which is higher than the previously reported values of 25–50% [46,60,68,39,44] and a positive finding for the wider implementation of coarse CCA to produce sustainable structural concrete [29,30]. BS8500 provides guidance for cover depth and concrete mix design proportions based on the chosen binder type and
expected environmental exposure conditions [19,20]. 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 for certain exposure conditions, then the risk of structural degradation regarding durability performance of CEM III/A CCA concretes is further reduced.

The SEM analysis of the microstructure of concrete, particularly the quality of ITZ between the new cement matrix and aggregates, revealed no additional voids due to the release of air from course CCA in this case (Fig. 11). This result contradicts previously published work in this field [42,63], and further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes. Larger and a more regular pore structure was observed for the new and old cement matrices of CEM I concretes. The pore structure of the coarse CCA itself was largely varied throughout, which may cause some problems regarding variability in performance when higher quantities are incorporated.

Taking account of all the results together, source B CCA was found to be 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 (Table 4) sought to characterise the CCA sources to be able to predict their effect on compressive cube strength and durability performance. It was found that little correlation existed between the results of water absorption/particle density, equivalent in-situ strength and petrography; 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 [57]. 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. In particular the results of water absorption, chemical analysis and petrographic analysis had a good correlation to potential performance.

7. Conclusions

In summary, 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 conclusions can be drawn:

1. It is recommended that the replacement of CEM I and NA with GGBS and coarse CCA be limited to 50% and 30% respectively in cases where compliance with the 28 day characteristic strength ($f_{c,cube}$) is of particular importance. If this criterion can be relaxed and the compressive cube strength of CEM III/A concretes tested at later ages for conformity, then higher quantities of coarse CCA may be incorporated up to 60% to produce a more sustainable structural concrete. Further research is required to determine the effect of superplasticisers on the acceleration of early strength gain and durability performance.
2. CEM III/A concretes produced with up to 100% coarse CCA, irrespective of the CCA sources adopted in this study, have been shown to outperform control CEM I concrete with 100% NA in durability performance tests. If the cover depth of CEM III/A CCA concretes can be increased, similar to that of CEM I concretes, then the risk of potential durability performance issues can be further reduced. The quantity of coarse CCA should be limited to 60% however, to comply with conclusion one above.

3. The results of SEM analysis contradicted similar previously published work in this field. No additional voids around the ITZ were evident in the case of the three coarse CCA sources tested, suggesting that any observed detrimental effect may be due to other causes. It is recommended that further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes, as this finding may not be a true representation of all coarse CCA sources.

4. It is recommended that when sources of coarse CCA are to be used, they are tested for water absorption, and chemically and petrographically analysed to determine the water ingress, possible contamination and the original concrete composition. These test methods had a good correlation with the compressive cube strength and durability performance of coarse CCA concretes adopted in this study.

The findings of this study have highlighted that sustainable structural CEM III/A concrete can be a viable option for future responsibly sourced projects, providing 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.

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