# THE EFFECT OF COARSE CRUSHED CONCRETE AGGREGATE ON THE DURABILITY OF STRUCTURAL CONCRETE

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SUMMARY: The use of crushed concrete aggregates (CCA) (formerly referred to as recycled concrete aggregate (RCA)) is increasing, particularly for low-grade applications, where quality is of less importance. In higher value applications, such as structural concrete, further research has been required to understand the effect of coarse CCAs on the mechanical properties and durability performance. This research investigated the effect of coarse CCA in CEM I and CEM III/A structural concretes. The resistance to water and chloride ion ingress in terms of surface resistivity, sorptivity and rapid chloride migration were evaluated in this study, together with compressive strength to determine compliance with characteristic and target mean strengths. From this limited study - which forms part of a wider research project - results indicate that a higher proportion of CCA is detrimental to the resistance to water and chloride ion ingress, possibly due to the higher water absorption characteristics of the aggregates as suggested in literature. The incorporation of GGBS however, significantly improves the durability performance, possibly due to the reduced porosity of the cement matrix, improved quality of the interfacial transition zone (ITZ) between the recycled aggregates and cement matrix and an increased chloride binding effect. From the results it is recommended that a structural CEM III/A concrete incorporating coarse CCA up to 60% may be a viable option for future sustainable construction projects.

KEY WORDS: Crushed concrete aggregate, recycled concrete aggregate, durability, water absorption, chloride ingress

## 1   INTRODUCTION

Recycled aggregates (RA) and crushed concrete aggregates (CCA/RCA) have become an increasingly popular construction material to replace virgin aggregates since the 1980's. Approximately 18.8 and 21.2 million tonnes of hard demolition arisings were produced in the UK in 2014 and 2015 respectively, and the quantity is predicted to continue to increase annually [1]. CCA is primarily specified as low-grade unbound aggregates in general fill, capping layers and as drainage materials, as the quality requirements for aggregates in these applications are generally less [2,3].

The Waste and Resources Action Programme (WRAP), in the UK, provides a framework of quality controls for the production of CCA for use in structural concrete, and all aggregates produced must conform to the

European standard for aggregates in concrete [4,5]. Utilising CCA in lower grade applications has its advantages economically as it enables the inclusion of fine aggregates (0/4mm). This eliminates the need for aggregate screening, and in turn helps to reduce any potential waste being produced. Recycled aggregate producers however are looking to improve the quality and performance of CCA to allow specification in higher grade applications such as sub-base materials and pipe bedding as this has a higher market value [3,6]. The use of CCA in structural concrete is currently limited due to uncertainty regarding performance [6].

With a large quantity of hard demolition arisings becoming available, and an industry shift towards incorporating CCA into a wider variety of higher value applications [6], certain situations may arise where CCA may be a suitable replacement material in structural concrete, 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 natural aggregates (NA) [7,8,9].

The European standard for concrete specification states that *'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%'* [10]. The British standard permits the inclusion of 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 [11,12]. 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 an ambiguous statement as no performance criteria or limits are included to determine suitability. This highlights uncertainty with respect to incorporating coarse CCA into structural concrete [13]. Further research is therefore required to understand the true effects of coarse CCA on the mechanical and durability properties, if a more robust framework for the use of coarse CCA is to become a possibility in the future.

A review of existing research has highlighted that the effect of CCA on the mechanical properties of structural concrete has been investigated [14-18]. The effect of CCA on long-term durability performance however, is less well established, particularly in relation to chloride ingress and corrosion initiation. The durability of reinforced concrete is primarily influenced by the connectivity, continuity and tortuosity of its pores, as this is how gases, liquids and other substances penetrate the concrete cover to reinforcement [19-21]. The majority of published research on the effect of coarse CCA on concrete durability has focused on rapid migration and 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 [22-27]. 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 [24]. Limbachiya *et al* (2000) established that a replacement level of up to 100% may not have a significant effect on the durability performance of high strength Portland cement (CEM I) concretes, provided the CCA source is obtained from high quality precast concrete sources [18].

Supplementary cementitious materials (SCMs) have latent hydraulic and pozzolanic properties which can improve the durability performance of CCA concrete, due to the reduced porosity of the cement matrix, improved quality of the ITZ and improved chloride binding capacity [28-32]. Dodds *et al* (2016) also established that inclusion of SCMs; pulverised fuel ash (PFA 30% - CEM IIB-V) and ground granulated blast furnace slag (GGBS 50% - CEM III/A), can improve the resistance of concrete to water and chloride ingress even when up to 60% coarse CCA replaced NA [33]. Berndt (2009) found that CEM III/A (at 50%) concrete was found to perform best when compared against other replacement levels of SCMs when 100% CCA was used [31].

The aim of this limited study therefore, was to examine one source of coarse CCA, in varying amounts in structural concrete, in order to determine its resistance to water and chloride ion ingress. GGBS was also incorporated to replace CEM I by 50% (to produce a CEM III/A concrete) to quantify the potential beneficial effects on durability performance. The compressive strength was tested to determine compliance with the characteristic and target mean strength.

## 2  METHODOLOGY

Structural concretes were designed to achieve characteristic ($f_{c,cube}$) and target mean strengths of 39MPa and 53MPa respectively by the BRE mix design method [34]. CEM I and CEM III/A (50%) concrete mixes were tested at a free water-binder ratio of 0.5. The concretes were produced in accordance with BS 1881-125 [35] and all specimens were cured in water at a temperature of (20±2°C) until the date of testing. The free water-binder ratio and cement content of 390kg/m³ were chosen to comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 [11]. Coarse CCA (4/20mm) was incorporated at increments of 20%, up to 100%, to replace coarse NA by mass, denoted as 'CCA' followed by the replacement percentage. Additional water was added to account for the higher aggregate absorption characteristics of the coarse CCA in accordance with the BRE mix design method [34]. No admixtures were used in production and no additional cement was added to compensate for the inclusion of CCA. All CCA concretes were compared against a control concrete made with 100% NA (rounded quartzite river gravel and sand). Table 1 details the test method justification.

Table 1: Test method justification

| Test | Standard | Justification |
|---|---|---|
| Compressive cube strength | BS EN 12390-3 [36] | To determine compliance of mixes with characteristic ($f_{c,cube}$) and target mean strengths and to analyse the effect of coarse CCA on compressive strength. |
| Surface resistivity | AASHTO T358-15 [37] | To determine the effect of coarse CCA on electrical resistivity of concrete, which provides an indication of its ability to resist chloride ion penetration. |
| Absorption by capillary action | BS EN 13057 [38] | 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 initially in a dry state. |
| Rapid Chloride Migration [39] | NT BUILD 492 [39] | To determine the effect of coarse CCA on the chloride migration coefficient in concrete. The results cannot be directly compared to natural diffusion tests; however it provides a rapid indication of durability performance, and is comparative. |

Statistical analysis was undertaken using t-tests to determine the effect on sample means when coarse CCA was 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. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect.

## 3  CCA COMPOSITION

BS EN 206-1 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 [10]. The CCA obtained for this study was from the demolition of a 1970's office building structure in Leicester,

UK. Three randomly selected samples were sent for petrographic analysis [40,41] to determine concrete composition and type (Figure 1). Randomly selected samples of coarse CCA were also tested for water absorption properties, and concrete cores from larger sections were obtained to determine compressive strength [42-45].

The 30 minute and 24 hour water absorption values for the coarse CCA are shown in Table 2 and compared against that of the NA used in this study. The 24 hour water absorption of the coarse CCA has been reported elsewhere between 3.60% and 11.57%, dependent on the original source of concrete [22-27,29-32], and is similar to the results obtained in this study. The results of compressive strength testing from cored specimens are shown in Table 3.

Table 2: Water absorption properties of CCA and NA

|  | CCA | | NA | |
|---|---|---|---|---|
|  | 30 minutes [%] | 24 hour [%] | 30 minutes [%] | 24 hour [%] |
| 10/20mm (Coarse) | 5.57 | 5.93 | 0.63 | 0.89 |
| 4/10mm (Coarse) | 9.72 | 9.92 | 1.07 | 1.15 |

Table 3: Determination of equivalent in-situ characteristic strength from cored specimens

| Sample | Compressive strength of cored specimen [MPa] | Correction Factor [$K_{is,cyl}$] | Corrected compressive strength [MPa] | Equivalent in-situ characteristic strength [$f_{ck,is}$] [MPa] |
|---|---|---|---|---|
| A | 52.8 | 0.998 | 52.7 | 40.8 |
| B | 47.5 | 0.991 | 47.1 | |
| C | 43.1 | 1.009 | 43.5 | |



Figure 1: Thin section of demolition concrete for petrographic analysis [46]

The key findings of the petrographic analysis were:
- The concrete was produced with partly-crushed gravel typical of East/South-East England (sandstone, limestone, quartzite and chert), quartz-dominated sand and ordinary Portland cement.
- No evidence of cement replacements or admixtures was detected.
- Estimated water-cement ratio, slump and 28 day strength were 0.58, 30-60mm and 38.5MPa respectively; the latter is similar to that of the determined equivalent in-situ characteristic strength.
- Estimated cement content was 325kg/m³, 13.8% of total weight of concrete.
- There was no obvious segregation, excessive voids, honeycombing or visible microcracking.

- Junctions between aggregates and enclosing binder were tightly sealed, indicative of good quality ITZ.
- Phenolphthalein indicator solution suggests maximum carbonation from the surface was 20-25mm.

# 4   ANALYSIS OF RESULTS

## 4.1  Compressive Cube Strength

Tests were conducted on 100mm cube samples at 28 and 56 days. The results show that the inclusion of coarse CCA does have an increasingly detrimental effect on compressive strength at both 28 and 56 days for both CEM I and CEM III/A concretes (Figures 2 and 3 respectively). In the majority of cases the characteristic strength ($f_{c,cube}$ - 39MPa, indicated by the horizontal line) at 28 days was achieved, except for the CEM III/A concretes made with 80% and 100% coarse CCA. At 56 days the characteristic strength was met for all concrete mixes.
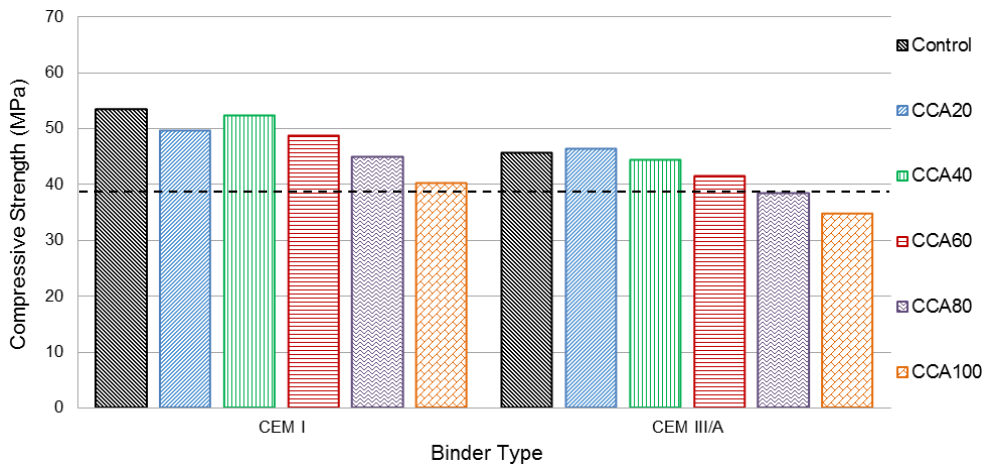


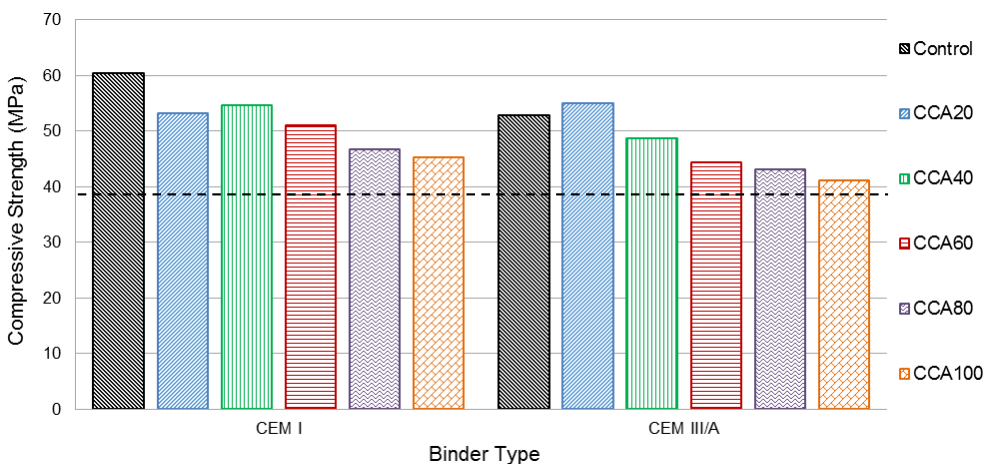Figure 2: 28 day compressive cube strengths



Figure 3: 56 day compressive cube strengths

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A left-tailed t-test was used to determine if the addition of CCA had a detrimental effect (10% decrease) on sample means, compared to the control concretes for each binder type. The results are shown in Table 4. Higher probabilities (highlighted in bold) of a detrimental effect were observed for coarse CCA contents above 60%, for both CEM I and CEM III/A concretes at 28 days. At 56 days a higher probability was observed for lower coarse CCA contents, which suggests that coarse CCA had a greater detrimental effect on compressive strength at later ages.

Table 4: Probability of a detrimental effect on compressive cube strength

|  | Coarse CCA content (%) | | | | |
|---|---|---|---|---|---|
|  | 20 | 40 | 60 | 80 | 100 |
| CEM I – 28 days | 0.249 | 0.107 | 0.389 | **0.876** | **0.939** |
| CEM III/A – 28 days | 0.002 | 0.010 | 0.304 | **0.980** | **0.997** |
| CEM I – 56 days | 0.216 | **0.455** | **0.951** | **0.989** | **0.993** |
| CEM III/A – 56 days | 0.017 | 0.284 | **0.862** | **0.944** | **0.979** |

## 4.2 Surface Resistivity

The surface resistivity of cylindrical specimens (200mm × 100mm diameter) was measured at 28 days (Figure 4). This is a relatively quick method of assessing the microstructure and subsequent transport properties of different concretes [47]. The results are commonly interpreted following the recommendations in Table 5. Lower resistivities indicate a more porous concrete microstructure as it allows a higher current to pass between the probes at the surface.

Table 5: Interpretation of four-point Wenner probe readings [37,48]

| Concrete Society Technical Report 60 | | AASHTO T358 | |
|---|---|---|---|
| Resistivity [kΩcm] | Interpretation | Resistivity [kΩcm] | 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 |
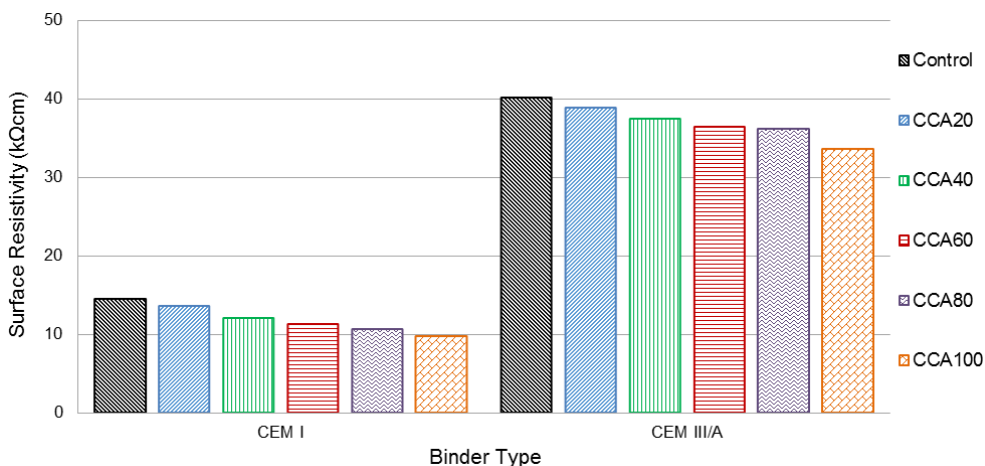


Figure 4: Concrete surface resistivity at 28 days

The results show that the CEM I concretes had a lower surface resistivity than CEM III/A concretes, by a factor of 3 to 4. A structural CEM III/A concrete incorporating up to 100% CCA performed better than the control CEM I concrete. The addition of coarse CCA had an increasingly detrimental effect on the surface resistivity of both concrete types. The results for the CEM I concretes indicate a 'moderate' corrosion rate/chloride ion penetration. In contrast, the results for CEM III/A concretes indicate a 'low' corrosion rate/chloride ion penetration.

The results of statistical analysis are shown in Table 6. Higher probabilities (highlighted in bold) of a detrimental effect against the control concretes for each binder type were observed for coarse CCA contents above 20% and 60%, for both CEM I and CEM III/A concretes respectively. This suggests that GGBS has reduced the detrimental effect of coarse CCA on surface resistivity.

Table 6: Probability of a detrimental effect on surface resistivity

|  | Coarse CCA content (%) | | | | |
| --- | --- | --- | --- | --- | --- |
|  | 20 | 40 | 60 | 80 | 100 |
| CEM I – 28 days | 0.099 | **0.961** | **0.997** | **0.998** | **0.999** |
| CEM III/A – 28 days | 0.066 | 0.209 | 0.377 | **0.462** | **0.899** |

## 4.3 Absorption by Capillary Action

Kropp *et al* describe sorptivity as the *'transport of liquids into porous solids due to surface tension acting in capillaries'* [19]. 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 (60mm × 100mm diameter slices) were sealed on the side to ensure uni-directional ingress of water. Cumulative absorption was measured at 28 days for CEM I and CEM III/A concrete mixes (Figure 5a and 5b respectively) and the sorption coefficients were determined from the gradients at 12 minutes and 24 hours (Table 7).

Table 7: 28 day sorption coefficients for all concretes tested

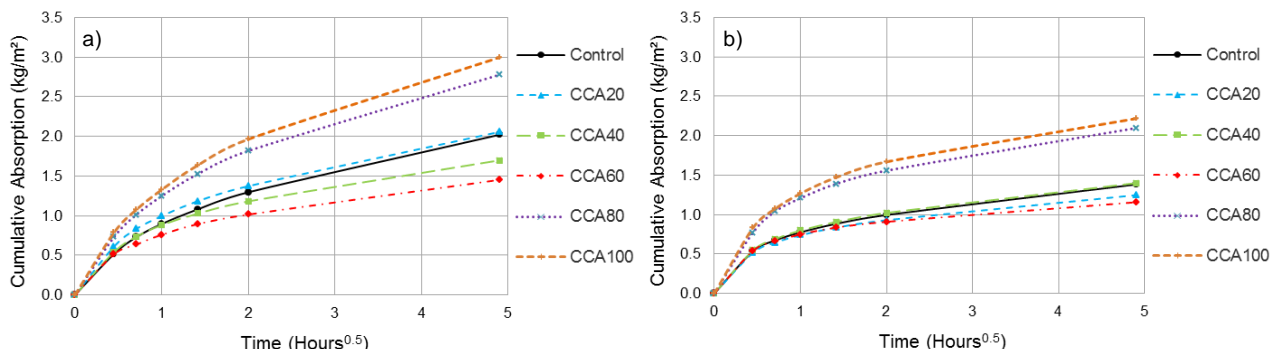|  | CEM I | | | | | | CEM III/A | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| CCA Content (%) | 0 | 20 | 40 | 60 | 80 | 100 | 0 | 20 | 40 | 60 | 80 | 100 |
| 12 mins Sorption Coefficient [$kg/m^2.h^{0.5}$] | 1.15 | 1.36 | 1.14 | 1.14 | 1.63 | 1.75 | 1.19 | 1.15 | 1.21 | 1.21 | 1.72 | 1.86 |
| % change | - | 18 | -1 | -1 | 42 | 52 | - | -3 | 2 | 2 | 45 | 56 |
| 24 hour Sorption Coefficient [$kg/m^2.h^{0.5}$] | 0.41 | 0.42 | 0.34 | 0.30 | 0.57 | 0.61 | 0.28 | 0.25 | 0.29 | 0.24 | 0.43 | 0.45 |
| % change | - | 2 | -17 | -27 | 39 | 49 | - | -11 | 4 | -14 | 54 | 61 |



Figure 5: Cumulative absorption at 28 days for a) CEM I, and b) CEM III/A concrete

Some anomalies were observed in this test method. In the instances of 40% and 60% coarse CCA content in CEM I concrete, and 20% and 60% coarse CCA content in CEM III/A concrete, the cumulative absorption at 24 hours was lower than the respective control concretes. As this apparent improvement in durability has not been observed in other test methods it is difficult to determine the exact cause for the reduced absorption. One possibility is that the combination of rounded NA and angular coarse CCA for these mixes reduced the continuity of the capillaries in the cement matrix. In any case there was a significant increase in the cumulative absorption for CCA contents above 60% for both CEM I and CEM III/A concretes, and the inclusion of GGBS reduced the sorption coefficients at 24 hours. This can be further clarified from the results of statistical analysis comparing CCA concretes against the control concretes for each binder type, with the higher probabilities highlighted in bold (Table 8). A structural CEM III/A concrete incorporating up to 60% CCA performed better than the control CEM I concrete.

Table 8: Probability of a detrimental effect on 24 hour sorption coefficients

| | Coarse CCA content (%) | | | | |
| --- | --- | --- | --- | --- | --- |
| | 20 | 40 | 60 | 80 | 100 |
| CEM I – 28 days | 0.073 | 0.009 | 0.003 | **0.983** | **0.996** |
| CEM III/A – 28 days | 0.014 | 0.051 | 0.010 | **0.994** | **0.995** |

## 4.4 Rapid Chloride Migration

Migration of chloride ions occurs when an electric field is applied across a concrete specimen (50mm × 100mm diameter slice), causing the negatively charged chloride ions to move towards an anode [49]. The non-steady state chloride migration coefficients in Figure 6 have been calculated from average penetration depths.
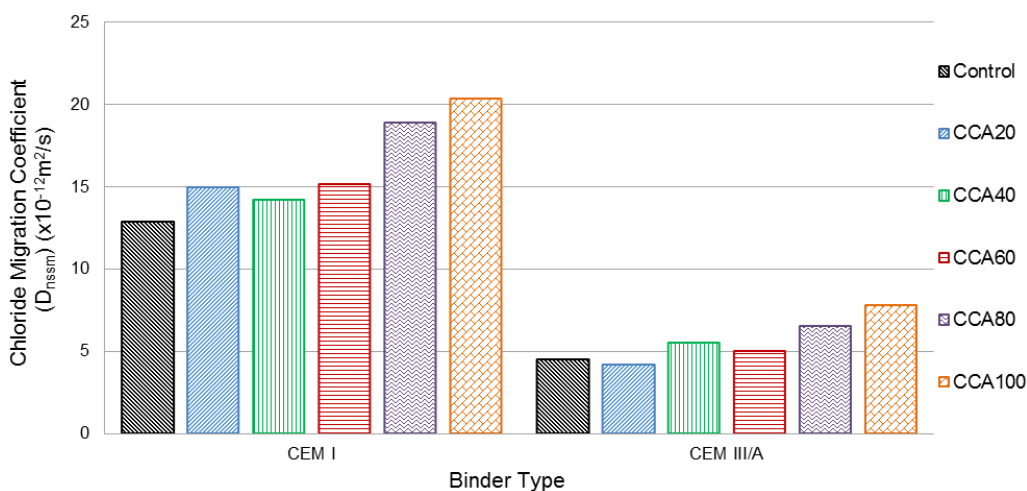


Figure 6: Chloride migration coefficients at 28 days

The results show that the inclusion of coarse CCA content had an increasingly detrimental effect on the chloride migration coefficient of concrete. CEM III/A concretes were found to provide enhanced resistance to chloride ion penetration compared to CEM I concrete, by a factor of 2 to 3. A structural CEM III/A concrete incorporating up to 100% CCA performed better than the control CEM I concrete. Statistical analysis shows a relatively high probability (highlighted in bold) that the chloride migration coefficient will increase by more than

10% for all CCA contents compared to the control concretes for each binder type; except for the 20% content in CEM III/A concrete (Table 9).

Table 9: Probability of a detrimental effect on chloride migration coefficients

| | Coarse CCA content (%) | | | | |
|---|---|---|---|---|---|
| | 20 | 40 | 60 | 80 | 100 |
| CEM I – 28 days | **0.831** | **0.520** | **0.835** | **0.976** | **0.993** |
| CEM III/A – 28 days | 0.135 | **0.756** | **0.508** | **0.914** | **0.981** |

## 5   DISCUSSION

### 5.1  Compressive Cube Strength

In the majority of cases, the characteristic strength ($f_{c,cube}$ - 39MPa) at 28 days was achieved, except for the CEM III/A concretes made with 80% and 100% coarse CCA (Figure 2). The characteristic strength however, was met for all concrete mixes at 56 days due to the latent hydraulic effects of GGBS (Figure 3) [28-32]. This suggests that the BRE method of mix design [34] is suitable for designing structural concrete produced with up to 100% coarse CCA. It should be noted that a large margin of 14MPa was used in this study to determine the target mean strength. This ultimately allowed some variability to occur in the compressive strength results when higher quantities of CCA replacement was used [24].

The results confirm previous research that the inclusion of coarse CCA has a detrimental effect on the compressive strength of concrete. The statistical analysis shows that a higher probability of a detrimental effect was observed for coarse CCA contents above 60% when compared against the control concretes for each binder type, for both CEM I and CEM III/A concretes at 28 days (Table 4). This suggests that 60% coarse CCA inclusion is acceptable for CEM I and CEM III/A concretes without increasing the risk of a non-compliant concrete (i.e. not achieving the specified characteristic strength).

### 5.2  Surface Resistivity

Figure 4 shows that an increase in the coarse CCA content generally reduced the surface resistivity of concrete. This is possibly due to the increased porosity of the CCA [22-27]. In all cases, the GGBS had a beneficial effect on surface resistivity, by a factor of 3 to 4, reducing the potential chloride ion penetration from a 'moderate' to 'low' level (Table 5). A structural CEM III/A concrete incorporating up to 100% CCA performed better than the control CEM I concrete.

The results of the statistical analysis indicate that a detrimental effect against the control concrete occurs for coarse CCA contents above 20% and 60% for CEM I and CEM III/A concretes respectively (Table 6). This highlights the beneficial effect of incorporating GGBS to reduce the porosity of the cement matrix as a higher quantity of coarse CCA can be utilised. This finding is in agreement with other research on SCMs and CCA concrete [28-33].

### 5.3  Absorption by Capillary Action

The cumulative absorption, sorption coefficients and statistical analysis indicate that higher quantities of coarse CCA (>60%) have a large detrimental effect when compared against the control concretes for each binder type (Figures 5a and 5b, Tables 7 and 8). Some anomalies exist for the lower quantities of CCA

replacement for both CEM I and CEM III/A concretes as the cumulative absorption at 24 hours was lower than the respective control concretes. One possibility for the reduced cumulative absorption is that the combination of rounded NA and angular coarse CCA for these mixes reduced the continuity of the capillaries in the cement matrix. In any case, there was a significant increase in the cumulative absorption for CCA contents above 60% for both CEM I and CEM III/A concretes, and the inclusion of GGBS reduced the sorption coefficients at 24 hours due to a reduced porosity of the cement matrix and improved ITZ [28-33]. A structural CEM III/A concrete incorporating up to 60% CCA performed better than the control CEM I concrete, which suggests that up to 60% coarse CCA inclusion is acceptable which is higher than previously reported values [22-27].

## 5.4 Rapid Chloride Migration

Figure 6 shows that an increase in the coarse CCA content generally increased the chloride migration coefficient of concrete, primarily due to its own increased porosity [22-27]. Although the statistical analysis (Table 9) shows that CCA contents as low as 20% can increase the probability of a detrimental effect (by 10% increase) when compared with the control concrete for each binder type, the results clearly show that the inclusion of GGBS reduced the chloride migration coefficient by a factor of 2 to 3, most likely due to a reduced porosity of the cement matrix, improved ITZ and an increased chloride binding effect [28-33]. The chloride migration coefficient for 100% CCA content in CEM III/A concrete was 39% lower than that of the control CEM I concrete with 100% NA. This suggests that higher proportions of coarse CCA can be adopted when CEM III/A concrete is to be exposed to chloride environments.

# 6   CONCLUSIONS

From this limited study of CCA, which is part of a wider research project, the results show that the inclusion of coarse CCA generally has a detrimental effect on the transport mechanisms in the resultant concrete, as well as the compressive strength.

The compressive strength testing showed that the characteristic strength ($f_{c,cube}$) of the majority of concretes tested was met at 28 days, with the remaining mixes achieving it by 56 days. This suggests that the BRE method of mix design can be suitably applied for designing structural concrete produced with up to 100% coarse CCA. From the results of the statistical analysis it is recommended that the coarse CCA inclusion is limited to 60% to reduce the risk of a non-compliant concrete (i.e. not achieving the specified characteristic strength).

The tests conducted into the durability have highlighted that the inclusion of coarse CCA can have an increasingly detrimental effect on water and chloride ion ingress. A detrimental effect (of 10% decrease in performance) can be observed, even for coarse CCA quantities as low as 20% for CEM I concrete, and as low as 40% for CEM III/A concretes, when compared against the control concretes for each binder type. Moreover, the inclusion of GGBS significantly increased the concretes resistance to water and chloride ion ingress compared to CEM I concretes due to the reduced porosity of the cement matrix, improved ITZ and the increased chloride binding capacity of the material. A structural CEM III/A concrete incorporating up to 60% CCA performed better than the control CEM I concrete for all durability test methods adopted. From these results it is recommended that up to 60% coarse CCA can be adopted in structural concrete, provided that GGBS (50%) is also incorporated; as it has been demonstrated that the resulting concrete is suitable when exposed to chloride environments. This is a positive finding for the increased incorporation of CCA into a wider variety of higher-value structural applications.

# ACKNOWLEDGMENTS

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