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Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on rapid chloride migration and accelerated corrosion

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HIGHLIGHTS

- Coarse CCA generally has a detrimental effect on chloride migration.
- This can be largely 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 increasing use of crushed concrete aggregates (CCA), formerly referred to as recycled concrete aggregates (RCA), has led to research into the effects of coarse CCA in higher value structural applications. Concerns exist regarding the effect on chloride ion ingress which ultimately can cause deterioration of reinforced concrete. This concern is reflected in existing European and British concrete design standards as limitations prevent their use in environments where chlorides may be present. The rapid chloride migration coefficient and rate of accelerated corrosion of structural CEM I and CEM III/A CCA concretes was measured to determine the effect on chloride ion ingress. Three sources of coarse CCA were evaluated; results show that coarse CCA generally had a detrimental effect on the chloride ion ingress of structural concrete. However, these effects can be mitigated by the inclusion of GGBS to produce structural CEM III/A concretes, thus allowing higher proportions of coarse CCA. It is recommended that the GGBS and coarse CCA content be limited to 50% and 60% respectively as this reduces the risk of a significant detrimental effect on chloride ion ingress. The results also suggest that the limitations in existing European and British standards are conservative and sustainable structural CEM III/A concrete with the inclusion of coarse CCA could 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.
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1. Introduction

The utilisation of crushed concrete aggregates (CCA), formerly referred to as recycled concrete aggregates (RCA) is increasing annually, particularly with the increased recent interest into the more sustainable sourcing and procurement of materials [52,23,64]. 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 [7,19].

One particular area of uncertainty is the effect of CCA on the longevity of reinforced concrete structures exposed to aggressive chloride environments during their service life [16,17,13]. The ingress of chloride ions predominantly occurs through exposure to marine environments or when de-icing salts are applied to highway structures during routine winter operational activities. The estimated cost of maintenance and refurbishment to corrosion

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damaged reinforced concrete bridges was estimated at $8.29 billion annually in the USA alone [51], with chloride ion induced corrosion being the most common cause of deterioration.

The results derived from scientific studies are not clear in confirming whether higher replacement levels of natural aggregates produce structural concretes with the desired durability properties. Further research is thus required to determine the effect of coarse CCA on the resistance to chloride ion ingress of structural concrete before it can be accepted and implemented as a possible replacement material in higher value applications.

This study investigates the effects of three sources of coarse CCA from known structural elements on the rapid chloride migration coefficient and accelerated time to corrosion initiation and cracking of structural concrete.

2. Background to corrosion and coarse CCA

2.1. Chloride ion ingress and chloride induced corrosion

The ability of chloride ions to penetrate the concrete cover is a key factor in the service life of a reinforced concrete structure. In reality, chloride ions can ingress concrete through a combination of transport mechanisms, namely absorption by capillary suction, diffusion and permeation [63]. Absorption by capillary suction and diffusion are the dominant mechanisms that occur in aggressive chloride environments, relating to the transport of liquids and ions by surface tension effects in the capillaries of porous materials and concentration gradients respectively. Diffusion is a much slower process as the movement of ions occurs in the pore solution of saturated concrete, whereas absorption occurs in a dry or semi-dry state and is the fastest transport mechanism [41].

Chloride induced corrosion is an electrochemical process and occurs when chloride ions penetrate the concrete cover and react with the passive protective film at the surface of the reinforcing steel, resulting in its depassivation [35,42]. The depassivation process results in the production of complex iron compounds which are soluble in the concrete pore solution [30,37]. A 'critical' or 'threshold' chloride concentration is often discussed when attempting to determine the point at which the passive layer breaks down; there is some debate however, regarding the magnitude of this concentration due to the variability of published values [5]. The most common value published for free chloride content is 0.6% by mass of cement, with 0.4% being reported as the minimum [1,4,21,42]. Once the steel is exposed to the chlorides, the corrosion can then aggressively propagate as pitting occurs, producing further acidity from corrosion products [37,10]. Localised anodic areas exist at the location of the pits and the surrounding reinforcement becomes cathodic (Figs. 1 and 2). The propagation of corrosion generates stresses as the corrosion product produced is voluminous, which ultimately leads to cracking, delamination and subsequent spalling of the protective concrete cover. A crack width greater than 0.3 mm can be detrimental to the durability of reinforced concrete for the majority of environmental exposure classes, and therefore can be indicative of a failure of the protective concrete cover [22,21,57,12].

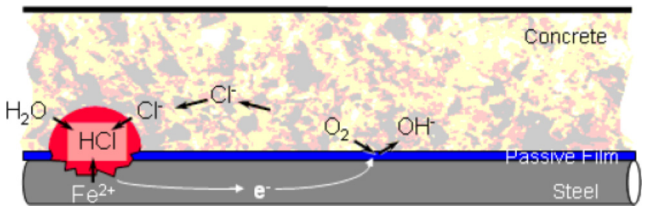


Fig. 1. Electrochemical process of chloride induced corrosion [36]



Fig. 2. Chloride induced 'pitting' corrosion of reinforcing steel.

The composition of concrete can impact its ability to resist the ingress of chloride ions. The transport of liquids predominantly occurs through the cement matrix and depends upon the continuity, tortuosity and radius of the pore structure [41]. Cementitious materials have a chloride binding capacity which reduces the free chlorides in the pore solution of concrete, and in turn changes the concentration gradient that drives diffusion [34]. This binding occurs due to adsorption and chemical reactions with constituents of the cement matrix which predominantly leads to the formation of Friedel's salt (calcium chloroaluminate hydrate) [53,10]. The binding capacity can be increased through the use of supplementary cementitious materials (SCMs) such as pulverised fuel ash (PFA) and/or ground-granulated blast furnace slag (GGBS) due to the generation of additional C–S–H (calcium silicate hydrate) through secondary hydration [49,29,3,8,58,34,25,33,24]. Microstructure analysis of GGBS has shown its ability to form higher quantities of Friedel's salt compared to CEM I concretes [50]. In situations where low oxygen concentrations exist, such as reinforced concrete submerged in water, a 'green rust' is often formed. This precipitate can act as a further chloride-binding mechanism, reducing the free chloride content [30].

Aggregates also play an important role in the transport of liquids as the water absorption properties and quality of the interfacial transition zone (TZ) can accelerate or decrease the ingress of fluids [53,59]. This is a particularly important concept when considering the use of CCA to replace natural aggregates in concrete as it has been suggested that the ability of cement paste to adhere to the surface of aggregates can influence the water absorption effects and reduce the quality of the ITZ [48,11,61,56,43]. It has been proposed that this is due to the release of air from the CCA as water is absorbed during the early curing process which creates additional voids in the ITZ [44]. However, [26] found that no additional voids around the ITZ were evident for the three sources of coarse CCA adopted in this study for CEM I and CEM III/A concretes when using Scanning Electron Microscopy (SEM) analysis.

The process of chloride ion ingress can be accelerated by migration, another transport mechanism which relates to the accelerated diffusion of ions when an electric field is applied, causing negatively charged chloride ions to move towards an anode [20,10]. Although not a true representation of chloride ion ingress in real structures, rapid chloride migration techniques provide a quick indication of a concrete's ability to resist chloride ions when results are compared against a reference concrete [2,55,32].

2.2. Specification of coarse 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 [13]. 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 [16,17]. 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 the importance of further research of coarse CCA to understand the effects 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.

2.3. Effect of coarse CCA on chloride ion ingress and chloride induced corrosion

The majority of published research on the effect of coarse CCA on concrete durability has focused on rapid chloride migration and water absorption test methods to determine acceptable levels of replacement of natural aggregates.

Where researchers have tested a range of coarse CCA replacement levels, the general consensus is that 20–30% coarse CCA can be successfully incorporated without detrimentally affecting the resistance to chloride ion ingress [11,48,56,61,65,47]. The decrease in the resistance to chloride ion ingress is often attributed to the increased water absorption characteristics of the coarse CCA. 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 [65,46] 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. Similar studies on the effects of coarse CCA on structural concrete have shown that CCA contents, as low as 20% and 40% for CEM I and CEM III/A concretes respectively, had a statistically significant detrimental effect on the durability performance [26,27,28].

Research has shown that the latent hydraulic and pozzolanic properties of SCMs can improve the resistance to chloride ion ingress of CCA concrete, allowing higher proportions of coarse CCA to be incorporated [26,27,28,31,60,8,38,40,45,39,62,9,6]. The addition of SCMs can significantly reduce the porosity of the cement matrix, improve quality of the ITZ and increase the chloride binding capacity of concrete, and in the case of rapid chloride migration, replacement levels up to 100% coarse CCA have been shown to perform better than CEM I control concretes [27,31,38,40,45,39,62,9,6]. Berndt [9] found that CEM III/A concrete (with 50% GGBS) was found to perform the best when compared against other replacement levels of SCMs, including 50% fly ash, 70% GGBS and a tertiary blend of 25% fly ash and GGBS.

Accelerated corrosion test methods can also provide a quick indication of a concrete's ability to resist chloride ion ingress when an electric field is applied, and the time to corrosion initiation and crack propagation, when results are compared against a reference concrete [54]. Zhao et al. [66] analysed the effect of coarse CCA on the corrosion rate and time to corrosion induced cracking when subjected to cyclic wetting and drying in a 3.5% NaCl solution. They found that concretes with increasing amounts of coarse CCA had a reduced time to corrosion initiation and a subsequent higher corrosion rate. Propagation of cracking was also more evident in concretes with a higher quantity of coarse CCA. The cracking predominantly occurred through the interfaces between the coarse NA or CCA and the new or old cement matrix, but not between the new and old cement matrices. The steel corrosion rate and the corrosion induced cracking process were not significantly influenced however, when up to 33% coarse CCA was incorporated into CEM I concrete.

3. Methodology

Our aim was to determine the effect of coarse CCA on the rapid chloride migration coefficient and the accelerated time to corrosion initiation and cracking of structural concrete. 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 [18]. The concretes were produced in accordance with BS 1881-125 [14] and all specimens were cured in water at a temperature of (20 ± 2 °C) prior to testing. The constituents for each mix are summarised in Table 1. The free water-binder ratio of 0.5 and the cement content were chosen to comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 [16]. 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 here 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 used in production 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, 36A-60 would refer to a concrete produced with 36% GGBS and CCA source A at 60%.

Six unreinforced and four reinforced concrete cylinders 200 mm × 100 mm diameter) were cast from each mix to undertake rapid chloride migration and accelerated corrosion testing in accordance with NT Build 492 and 356 [55,54]. In the reinforced specimens, steel reinforcing bars (12 mm in diameter) were cast centrally, with a 50 mm cover depth to the base of the cylinder. The reinforced specimens were removed from water curing 14 days prior to testing. A constant voltage of 5 V was applied, and the current was recorded daily. The test was terminated when a visible crack was observed (>0.3 mm), as this can be indicative of

Table 1
Mix design constituents for control batches.

Constituents	Mix Design			
	CEM I	CEM III/A (36%)	CEM III/A (50%)	CEM III/A (65%)
Free water-binder ratio	0.5	0.5	0.5	0.5
Cement (kg/m^3)	390	250	195	136
GGBS (kg/m^3)	–	140	195	254
Water (kg/m^3)	195	195	195	195
Sand (kg/m^3)	653	653	653	653
Coarse 10/20 mm (kg/m^3)	775	775	775	775
Coarse 4/10 mm (kg/m^3)	387	387	387	387

a failure of the protective concrete cover (Fig. 3) [22,21,57,12]. Upon termination of the test, specimens were split axially along the crack plane and the minimum concrete cover measured (Fig. 4).

Statistical analysis using *t*-tests, to determine the effect on sample means, was based on a 10% decrease in performance, which we considered to be significant as this is greater than any expected human or batch reproducibility error. The results of concrete with coarse CCA were compared with 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 against each other for the same purpose. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect. This analysis could not be performed on the results for accelerated corrosion as only two samples for each concrete type and test age were cast.



Fig. 3. Typical cracking of 200 mm × 100 mm diameter reinforced concrete cylinder.

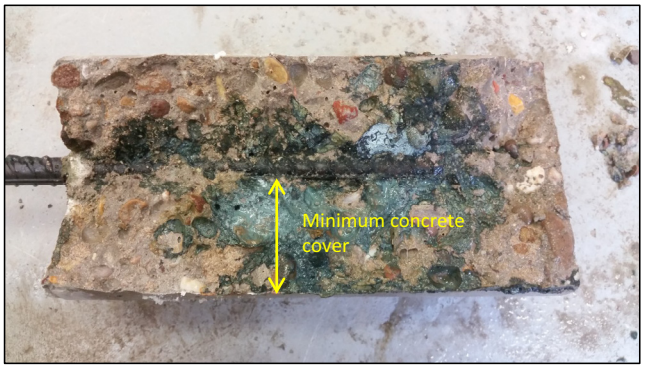


Fig. 4. Measurement of cover depth and development of 'green rust' precipitate.

Table 2
CCA sources obtained.

Source	Site location in UK	Structural Component
A	Office building, Bishop Road, Coventry (circa 1975)	Reinforced concrete beam (internal)
B	Office/Factory building, Derby Road, Loughborough (circa 1976)	Reinforced concrete footing and column base
C		Reinforced concrete slab (ground floor)

4. Aggregate properties

The CCA was obtained from two different demolition sites in the East and West Midlands, UK. The results of water absorption, particle density, chemical analysis, equivalent in-situ strength and petrographic analysis have been previously published [26] for the CCA sources used in this research (Table 2).

Table 3 provides a summary of the characteristics of the coarse CCA sources tested, which conformed to a 'Type A' aggregate suitable for concrete production [13,15]. It can be seen that little correlation exists between the water absorption/particle density, equivalent in-situ strength ($f_{ck,is}$) and the findings of the petrographic analysis. 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 resistance to chloride ion ingress 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 [26].

5. Analysis of results

5.1. Rapid chloride migration

The rapid chloride migration coefficient (D_{nssm}) of cylindrical specimens (50 mm × 100 mm diameter) was measured at 28 and 91 days (Figs. 5 and 6).

Figs. 5 and 6 show that the rapid chloride migration coefficient generally increased with increasing coarse CCA content at 28 and 91 days. At both ages, the CEM I concretes produced with source B CCA generally performed worse for replacement levels >30%, with a higher probability of a detrimental effect ($P > 0.464$), followed by sources A and C.

At both ages, all CEM III/A concretes with up to 100% CCA content had a lower rapid chloride migration coefficient than the control CEM I concretes, irrespective of CCA source, by a factor 2–6. At 28 days, the probability of a detrimental effect of 10%, when compared to the control CEM I concrete, significantly reduces when GGBS is incorporated, even for low levels of replacement (36% – $P < 0.081$). This probability of a detrimental effect further reduces for CEM III/A concretes tested at 91 days ($P < 0.002$).

A detrimental effect was observed for the majority of concretes tested when CCA was incorporated, even for replacement levels as low as 30% when compared to the respective CEM I and CEM III/A control concretes (Table 4). A statistically significant detrimental effect was not observed for 50C-30 and 65A-30 concretes at 28 days, and 0A-30 and 50A-30 concretes at 91 days, and so were omitted from the statistical analysis data.

5.2. Accelerated time to corrosion initiation and cracking

The time to corrosion initiation and cracking of reinforced cylindrical specimens (200 mm × 100 mm diameter) was measured after curing the specimens for 28 and 91 days (Figs. 7–13).

Table 3
Summary of coarse CCA characteristics.

Source	24 h water absorption [%]		SSD particle density [Mg/m^3]		Contaminants	$f_{ck,is}$ [MPa]	Key notes of petrographic analysis
	10/20	4/10	10/20	4/10			
A	4.81	6.80	2.40	2.30	None	17.6	Quartz dominated aggregates, high estimated strength and cement content, lower w/c ratio
B	6.75	8.33	2.35	2.31	None	25.6	Complex lithology, highest estimated w/c ratio and lowest cement content, some microcracking exists
C	5.30	6.41	2.33	2.27	None	33.4	Quartz dominated aggregates, lowest estimated w/c ratio and high cement content, some microcracking exists

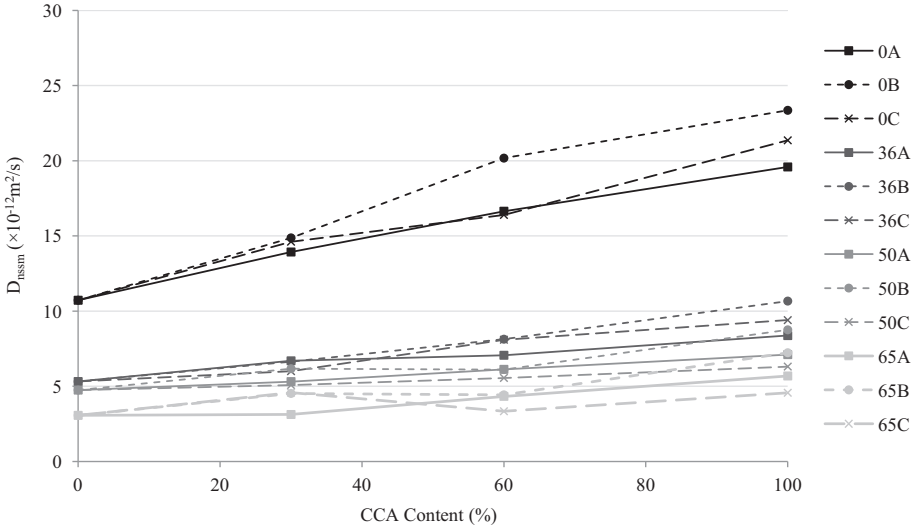


Fig. 5. Rapid chloride migration coefficient (D_{nssm}) at 28 days.

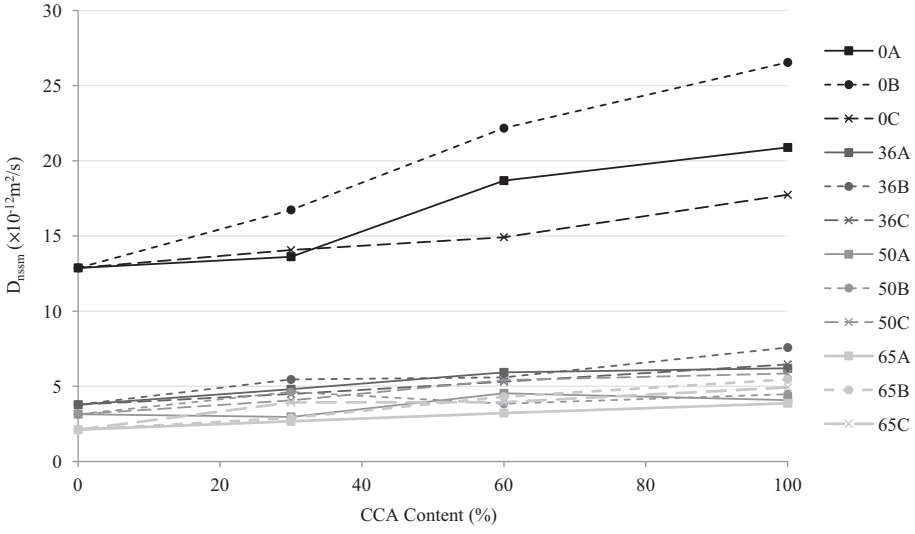


Fig. 6. Rapid chloride migration coefficient (D_{nssm}) at 91 days.

Table 4
Probability of a detrimental effect of 10% due to coarse CCA.

Binder Type	28 days	91 days
CEM I	P > 0.939	P > 0.438
CEM III/A (36% GGBS)	P > 0.643	P > 0.921
CEM III/A (50% GGBS)	P > 0.576	P > 0.825
CEM III/A (65% GGBS)	P > 0.441	P > 0.865

The results for CEM I concretes (Figs. 7 and 8) show that the time to corrosion initiation (1), indicated by the definitive change in gradient of the current measurements, and time to cracking (2), indicated by termination of the test, occurred earlier for concretes with increasing coarse CCA content. CEM I concretes produced with coarse CCA from source B also appeared to perform

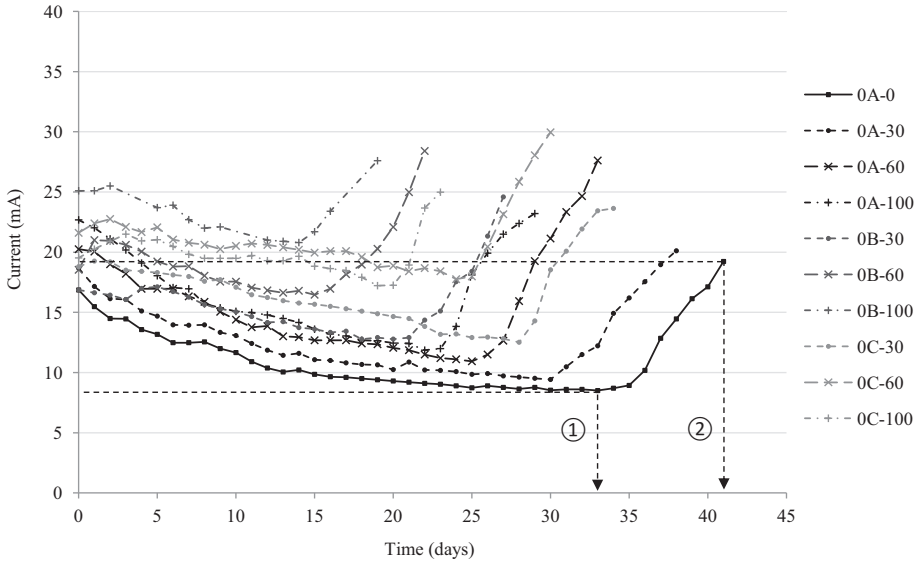


Fig. 7. Time to corrosion initiation and cracking (CEM I, 28 days).

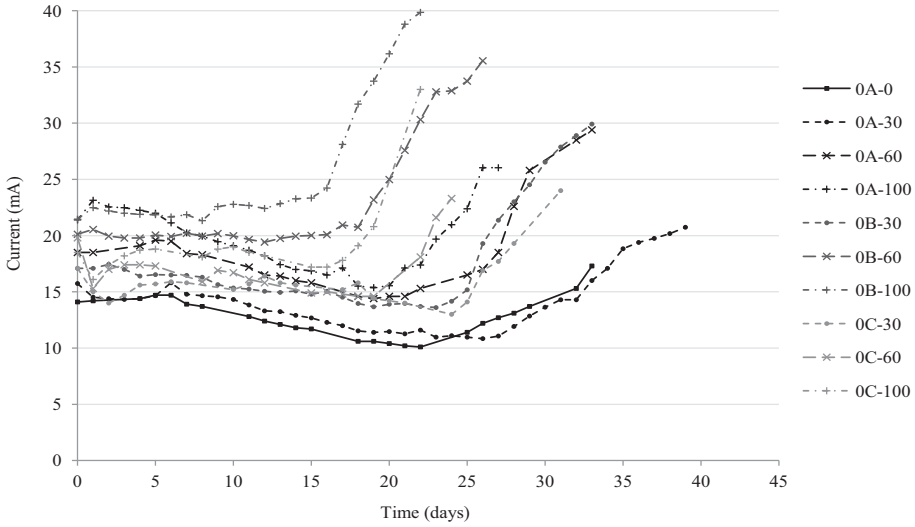


Fig. 8. Time to corrosion initiation and cracking (CEM I, 91 days).

the worst at both testing ages, followed by sources A and C, with both corrosion initiation and cracking occurring at earlier ages.

The measured current (mA) for CEM I concretes at 91 days is generally higher (Fig. 8), particularly after corrosion has initiated. The accelerated time to corrosion initiation and cracking also occurred at a faster rate compared to the same concretes tested at 28 days. An anomaly was observed for the control (0A-0) CEM I concrete at 91 days, which appeared to corrode and crack at an earlier time compared to the 0A-30 concrete.

The 28 day results for CEM III/A concretes (Figs. 9–11) show that the time to corrosion initiation and cracking generally increases with increasing GGBS content, with the maximum time to cracking observed at 134, 140 and 205 days for concrete produced with 36%, 50% and 65% GGBS respectively. Similar to the CEM I concretes the time to corrosion initiation and cracking occurred earlier for concretes with increasing coarse CCA content, and source B coarse CCA performing worst, followed by sources A and C.

The measured current (mA) in concretes with higher quantities of GGBS (>36%) generally was more susceptible to fluctuation during the time period of chloride ion ingress and specimen saturation (Figs. 10 and 11), which made the time to corrosion initiation difficult to determine. The time to cracking for these concretes however was still evident as the visual condition was monitored daily. Fig. 12 highlights the beneficial effects of GGBS at later ages. The time to corrosion initiation and cracking are delayed for all three coarse CCA concrete sources, and the measured current (mA) was generally lower throughout monitoring. These phenomena were observed for all CEM III/A concretes at 91 days, for all GGBS and coarse CCA replacement levels and have therefore been omitted for clarity.

Fig. 13 shows the time to corrosion initiation and cracking of control CEM I concrete (with 100% NA) compared against 100% coarse CCA concretes at 91 days, which is more representative of the longer-term performance of structural concrete.

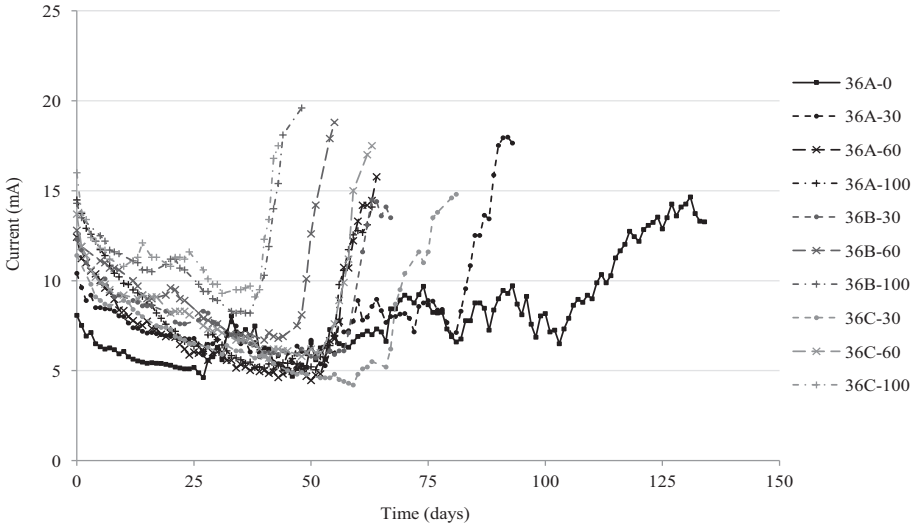


Fig. 9. Time to corrosion initiation and cracking (CEM III/A, 36% GGBS, 28 days).

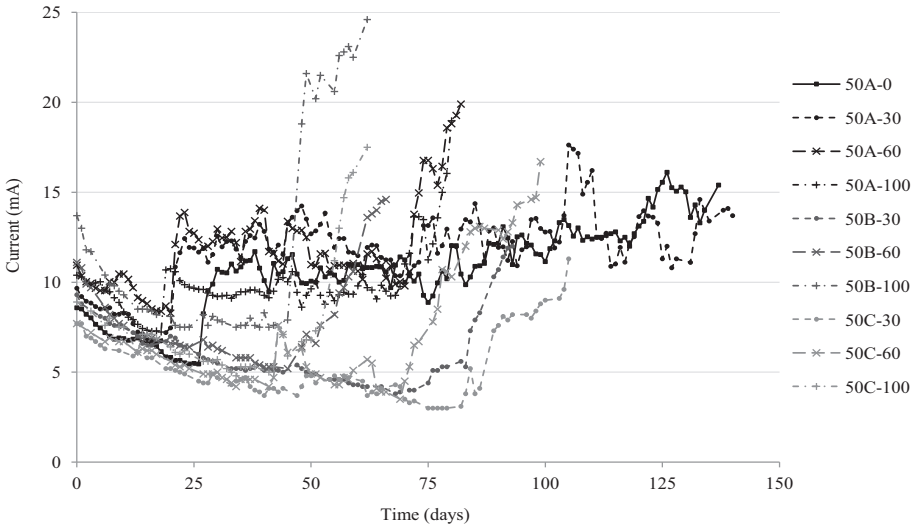


Fig. 10. Time to corrosion initiation and cracking (CEM III/A, 50% GGBS, 28 days).

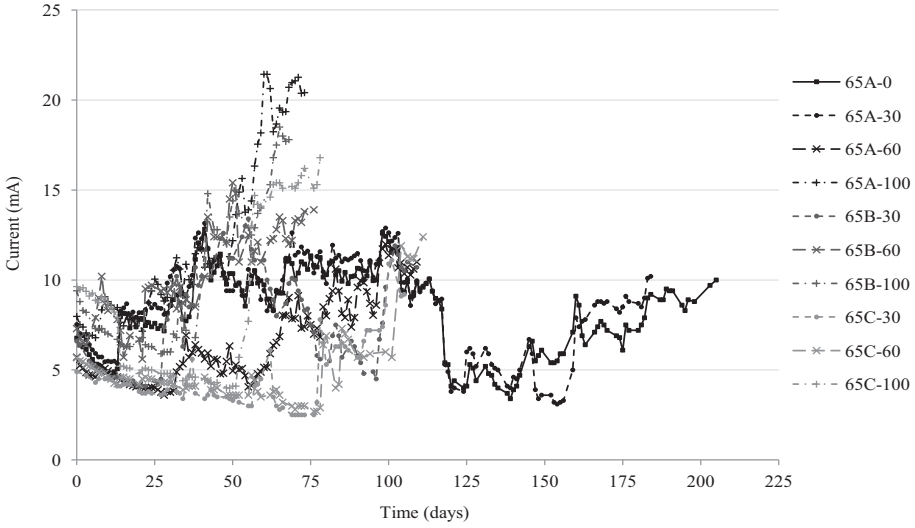


Fig. 11. Time to corrosion initiation and cracking (CEM III/A, 65% GGBS, 28 days).

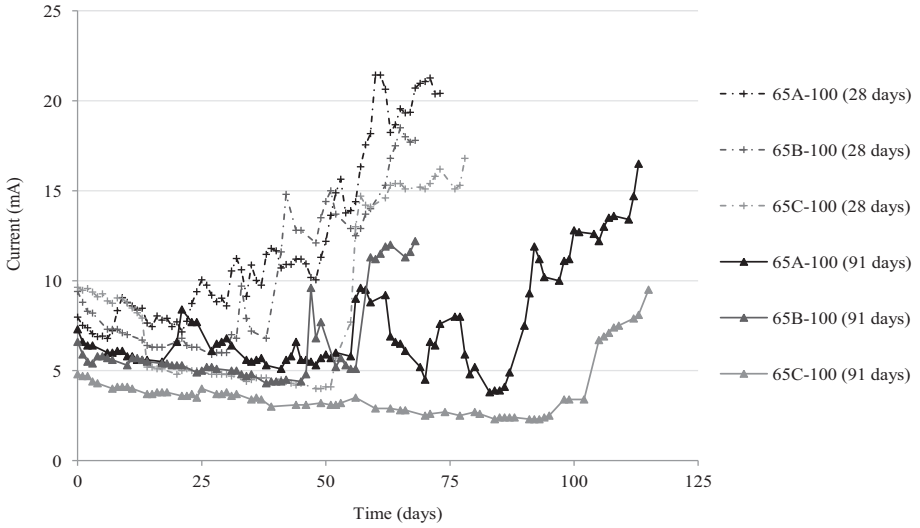


Fig. 12. Time to corrosion initiation and cracking (CEM III/A, 65% GGBS, 28 and 91 days).

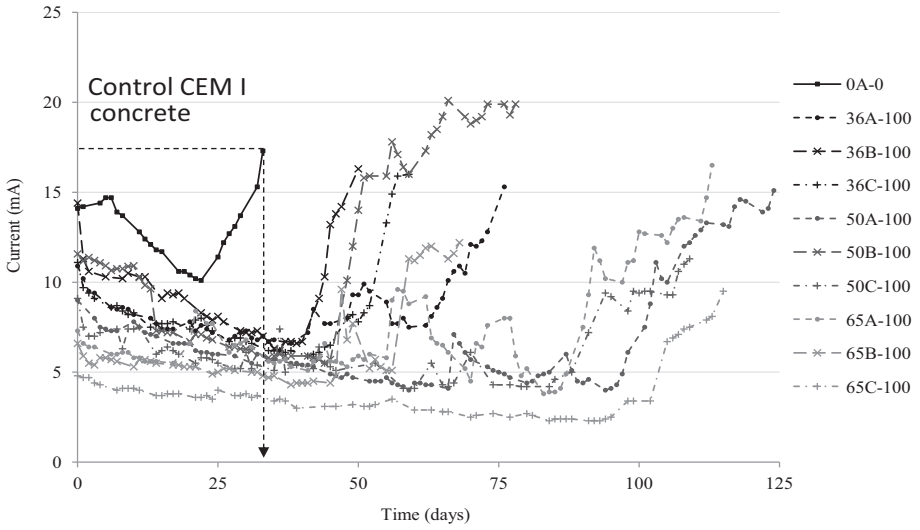


Fig. 13. Time to corrosion initiation and cracking (91 days).

Table 5
Durability factor (Q) for 100% coarse CCA concretes (91 days).

0A0	36A100	36B100	36C100	50A100	50B100	50C100	65A100	65B100	65C100
1.00	2.30	1.52	1.79	3.76	2.36	3.30	3.42	2.06	3.49

The durability factor (Q) (the ratio of the time to cracking for each test specimen against the reference specimen) is shown in Table 5.

6. Discussion

The rapid chloride migration and accelerated corrosion tests have shown that low quantities of coarse CCA (30%) have a slight detrimental effect on the resistance to chloride ion ingress of the concrete (Figs. 5–11), as indicated by an increase in the chloride migration coefficient and a reduced time to corrosion initiation and cracking. These findings are in agreement with other research into the effect of coarse CCA on chloride ion ingress (in the majority of cases rapid chloride migration only) [11,48,56,61,65,66,47]. The statistical analysis indicates relatively high probabilities of a detrimental effect (corresponding to a 10% increase in the rapid chloride migration coefficient) for all binder types tested at both 28 and 91 days (Table 4).

Nevertheless, structural CEM III/A concretes produced with up to 100% coarse CCA outperformed the control CEM I concrete produced with 100% NA, by a factor of 2–6 with more than 36% GGBS (Figs. 5, 6 and 13; Table 5). This highlights the beneficial latent hydraulic effects of GGBS at increasing the resistance to chloride ion ingress, particularly at later ages as shown in Figs. 6 and 12 [49,29,3,8,58,34,25,33,24], and demonstrates that higher quantities of coarse CCA can be incorporated to produce a more sustainable structural concrete, without compromising the

resistance to chloride ion ingress. This is a significant finding for the wider implementation of coarse CCA to produce sustainable structural concrete and complements similar published research by the authors [26,27,28]. The findings in this study demonstrate that the existing limitations in European and British standards of 0% coarse CCA when exposed to chloride environments are quite conservative [16,17,13]. Moreover, the BS8500 guidance on cover depth and concrete mix design proportions, which is based on the binder type and environmental exposure conditions [16,17], suggests that the cover 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.

Dodds et al. [26] concluded that maximum GGBS and coarse CCA replacement levels could be increased to 50% and 60% respectively to prevent an increased risk of detriment to durability, as determined the results of surface and bulk resistivity, absorption by capillary action and SEM analysis. The higher coarse CCA limit is valid if the compressive cube strength of CEM III/A concretes can be tested for conformity at later ages (91 days) compared to the traditional 28 day tests (although further research may be beneficial to determine the effects of superplasticisers on coarse CCA concrete). The findings in this paper suggest that up to 100% coarse CCA in structural CEM III/A concretes could be incorporated without increasing the risk of a detrimental effect on chloride ion ingress when compared to the control CEM I concrete $P < 0.081$ – 28 days; $P < 0.002$ – 91 days). This recommendation however should be reduced to 60% coarse CCA to conform to the findings of previously published work by the authors, conducted on the same structural concrete mixes and produced with the same coarse CCA sources. The recommended inclusion of 50% GGBS was also found to perform best in other research when compared against other replacement levels of SCMs, including 50% fly ash, 70% GGBS and a tertiary blend of 25% fly ash and GGBS [9]. The recommended replacement levels are higher than those imposed by the existing limitations in British and European standards, particularly when coarse CCA structural concrete is to be exposed to chloride ion environments, and highlights the need for new best practice guidance.

The measured current (mA) for CEM I concretes at 91 days is generally higher than at 28 days (Figs. 7 and 8), particularly after corrosion has initiated, and generally the corrosion initiation and cracking occurs at a faster rate. Contrary to this, the measured current (mA) for CEM III/A concretes at 91 days is generally lower throughout monitoring and the corrosion initiation and cracking occurs at a much slower rate compared to the 28 day results (Fig. 12). A similar observation can be made of the rapid chloride migration results where higher coefficients were measured for the CEM I concretes at 91 days compared to 28 days, and the opposite for CEM III/A concretes. The combined findings highlight 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 CEM I and CEM III/A concretes, and demonstrated the beneficial latent hydraulic effects of GGBS concretes.

One anomaly is the accelerated corrosion data for the control (0A-0) CEM I concrete at 91 days, which appeared to corrode and crack at an earlier time compared to the 0A-30 concrete. This may be explained by the difference in measured minimum cover depths for both of the concretes (37.3 mm and 41.8 mm respectively). Fluctuation was also observed in the measured current (mA) in concretes produced with higher quantities of GGBS (>36%) during the time period of chloride ion ingress and specimen saturation (Figs. 10 and 11), which made the time to corrosion initiation difficult to determine. The time to cracking for these concretes however was still evident as the visual condition was monitored daily and visible cracks (>0.3 mm) were detected. It is more likely that the fluctuation in current may be due to the process of chloride binding which in turn changes the concentration gradient in the pore solution [34]. The formation of higher quantities of Friedel's salts in CEM III/A concrete hypothesised in literature therefore may have some influence on the amount of current passing between the anode and the cathode [53,10,50,24].

Source B CCA was found to be the worst performing aggregate, followed by sources A and C. At both ages, the statistical analysis showed that replacement levels of source B coarse CCA greater than 30% had the highest probability of a detrimental effect ($P > 0.464$), indicated by a 10% increase in the rapid chloride migration coefficient. The aggregate and concrete testing of the CCA sources (Table 3) sought to characterise the CCA sources to be able to predict their effect on chloride ion ingress. Little correlation was found between the water absorption/particle density, chemical analysis, equivalent in-situ strength and petrography; however the information as a whole provided some indication that source B might 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 potential risks. In particular, the results of water absorption, chemical analysis and petrographic analysis had a good correlation to potential performance.

Rapid chloride migration and accelerated corrosion test methods are able to provide a quick indication of a concrete's ability to resist chloride ion ingress when an electric field is applied), time to corrosion initiation and crack propagation when results are compared against a reference concrete [54]. Migration, however, is not a true representation of chloride ion ingress through a combination of capillary suction, diffusion and permeation which occur in real-scale reinforced concrete structures [41,63]. The results therefore do not directly correlate to the long-term durability performance of the structural concretes tested, and further research would have to be conducted over much longer time periods to obtain chloride ingress data on similar structural CCA concretes. We acknowledge that this is a limitation of this study and care should be taken when implementing the findings into practice.

7. Conclusions and recommendations

In summary, the results show that the inclusion of coarse CCA generally has a detrimental effect on the chloride ion ingress of structural concrete when an electrical field is applied. The detrimental effects can be overcome through the use of GGBS to produce structural CEM III/A concretes, allowing higher proportions of coarse CCA to be utilised. It can be concluded that CEM III/A concretes with up to 100% coarse CCA, irrespective of the CCA sources adopted in this study, outperform control CEM I concrete with 100% natural aggregates. If the cover depth of CEM III/A concretes can be increased, similar to that of CEM I concrete, then the risk of potential durability performance issues can be further reduced. It is however, recommended that the replacement of GGBS and coarse CCA be limited to 50% and 60% respectively to conform to the findings of previously published work by the authors, conducted on the same structural concrete mixes and produced with the same coarse CCA sources. This is to reduce the risk of a non-compliant structural concrete.

The results of water absorption, chemical analysis and petrographic analysis provided some indication of potential performance, in that source B coarse CCA may be the worst performing aggregate. It is recommended that sources of coarse CCA be tested

in a similar manner before inclusion within structural concrete to be able to foresee potential risks.

The recommended replacement levels clearly demonstrate that the existing limitations in British and European standards are stringent, particularly when coarse CCA structural concrete is to be exposed to chloride ion environments. This reinforces the concept that the common concerns and ambiguities in industry are not being addressed, as the limitations imposed do not reflect the findings of published data. This highlights the need for new best practice guidance that encourages collaboration between academia and the construction industry that will potentially lead to a change in the design approach to specifying coarse CCA in structural concrete.

The findings highlight that sustainable structural CEM III/A concrete can be a viable option for future responsibly sourced projects, provided there is a reliable and consistent source of CCA. This is a positive outcome for the wider implementation of coarse CCA into structural concrete applications. Further research is required to correlate the migration and accelerated corrosion results presented, against the ingress of chloride ions through the transport mechanisms that occur in real-scale reinforced concrete structures, namely capillary suction, diffusion and permeation.

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