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Corrosion risk assessment of structural concrete with coarse crushed concrete aggregate

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Crushed concrete aggregates (CCA) are an increasingly popular replacement for natural aggregates (NA) in structural concrete due to industry demands for more recycled, low carbon footprint and responsibly sourced materials. There is uncertainty regarding chloride-ion ingress, which can ultimately cause deterioration of reinforced concrete. This is reflected in European and British concrete design standards, which currently exclude CCA in chloride environments. Structural concretes with up to 60% coarse CCA (and CEM I, CEM II/B-V and CEM III/A binders) were exposed to aggressive chloride environments and monitored with electrochemical techniques and subsequent destructive testing to determine their risk of corrosion initiation. The results showed that CEM II/B-V and CEM III/A concretes with up to 60% coarse CCA outperformed the control CEM I concrete with 100% NA, and had a lower risk of corrosion initiation. It is recommended that further monitoring is required over longer periods to determine the corrosion-initiation risk. Supplementary cementitious materials had a beneficial effect on the chloride-ion ingress resistance, significantly increased the predicted time to corrosion initiation beyond the 50-year design life and largely outweighed any observed detrimental effects from an increased coarse CCA content, suggesting that limitations imposed by existing design standards are conservative.

1.   Introduction

The recycling of demolition concrete is increasingly important in the construction industry, particularly with the move towards a more sustainable way of sourcing materials (Defra, 2015; NFDC, personal communication, 2016; Wrap, 2015).

In the UK, a high proportion of demolition concrete, known as crushed concrete aggregate (CCA) and formerly referred to as recycled concrete aggregate, is utilised as general fill, sub-base material or within low-grade concrete (Barritt, 2015). Certain situations, however, may arise where CCA may be a suitable replacement material for structural concrete, such as for a specific project/client requirement, for improved project sustainability credentials, where a good quality, consistent source of CCA is available on site and/or where there is a short supply of natural aggregates (NA) (Filho *et al.*, 2013; Hassan *et al.*, 2016; Yehualaw and Woldesenbet, 2016). Chloride-ion ingress is the most common cause of early deterioration of reinforced concrete (RC) when de-icing salts are applied to highway structures during routine winter operational activities (NACE International, 2012). There is limited research on the effect of coarse CCA on the longevity of RC structures exposed to aggressive chloride environments, particularly the risk of corrosion initiation during its service life; hence, the use of coarse CCA is limited for structural applications (BSI, 2013; BSI, 2015a, 2015b). Furthermore, it is not evident whether higher replacement levels of NA produce structural concretes with the necessary durability. Thus, further research is required to determine the effect of coarse CCA on the risk of corrosion initiation before it can be accepted as a replacement material in higher-value applications.

This study therefore investigated the effects of coarse CCA on the risk of corrosion initiation, the predicted time to corrosion initiation and the depth of chloride-ion ingress when exposed to aggressive chloride environments, to encourage the appropriate use of coarse CCA in structural concrete.

2.   Background information

2.1   Corrosion risk assessment of structural concrete
Chloride-induced corrosion is an electrochemical process that occurs when chloride ions penetrate the concrete cover and react with the passive protective film at the surface of the

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reinforcing steel, resulting in its depassivation (Glass *et al.*, 2000; Kropp, 1995). A 'critical' or 'threshold' chloride-ion 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. The most common value published for free chloride-ion content is 0·6% by mass of cement, with 0·4% being reported as the minimum (Alonso and Sanchez, 2009; Angst *et al.*, 2009; CS, 2004a; Kropp, 1995). Once steel is exposed to chloride ions, corrosion can aggressively propagate as 'pitting' occurs, producing further acidity from corrosion products (Bertolini *et al.*, 2004; Glass *et al.*, 2007). Localised anodic areas exist at the location of the pits and the surrounding reinforcement becomes cathodic (Figure 1). The process is further accelerated as chloride ions migrate towards the positively charged anodic region (Bertolini *et al.*, 2004; Claisse, 2014).

Non-destructive testing, such as half-cell potential surveys and surface resistivity tests, are well-established methods of
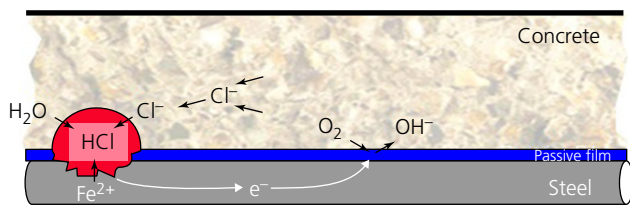

Figure 1. Electrochemical process of chloride-induced corrosion (Glass *et al.*, 2006)

assessing the corrosion risk of structural concrete (Assouli *et al.*, 2008). These methods can be used in combination to provide an overall assessment of the risk of corrosion initiation (CS, 2004a).

Half-cell potentials are interpreted following the American Society for Testing and Materials (ASTM) recommendations in Table 1 for saturated copper/copper sulfate (Cu/CuSO$_4$) and silver/silver chloride (Ag/AgCl/0·5 M KCl (potassium chloride)) reference electrodes (ASTM, 2009).

Surface-resistivity tests can provide an indication of the microstructure of concrete as a measure of the flow of ions between the anodic and cathodic regions (Broomfield and Millard, 2002; Goodier *et al.*, 2015). The results are commonly interpreted according to the recommendations in Table 2. Both sources indicate that a surface resistivity above 20 kΩ cm is associated with a low corrosion rate and chloride-ion penetration.

There are limitations to both methods as the results can be affected by the ambient relative humidity (RH), temperature, pH value of the concrete pore solution and oxygen availability (Angst and Elsener, 2014; Assouli *et al.*, 2008; CS, 2004a; Holmes *et al.*, 2011).

When there is probable risk of corrosion initiation, intrusive testing can be undertaken to establish the depth of chloride-ion penetration and subsequent corrosion risk. A common approach involves the measurement of chloride-ion concentration by silver nitrate potentiometric titration (BSI, 2015c) of drilled concrete dust samples (Castellote and Andrade, 2001; CS, 2004a). The results are often interpreted by the Concrete

Table 1. Interpretation of half-cell potential surveys (ASTM, 2009)

Voltage against copper/ copper sulfate: mV	Voltage against silver/silver chloride / 0·5 M potassium chloride: mV	Interpretation
>−200	>−134	Greater than 90% probability that no corrosion activity is occurring
<−200 and >−350	<−134 and >−284	Uncertain corrosion activity
<−350	<−284	Greater than 90% probability that corrosion activity is occurring

Table 2. Interpretation of four-point Wenner probe readings

Concrete Society Technical Report 60 (CS, 2004a)		Aashto T358 (Aashto, 2015)	
Resistivity: kΩ cm	Interpretation	Resistivity: kΩ 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

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Table 3. Interpretation of chloride-ion concentration (CS, 2004a)

Threshold level by mass of cement: %	Interpretation
>1·0	High corrosion risk
<1·0 and >0·4	Medium corrosion risk
<0·4	Low corrosion risk

Society limits in Table 3; however, they can also provide a chloride-ion concentration profile to determine an apparent chloride diffusion coefficient by linear curve fitting (Poulsen, 1995).

Additionally, a quick observation of the chloride-ion ingress depth can be obtained by spraying 0·1 M silver nitrate solution directly onto freshly split concrete, indicated by the formation of a white precipitate (Meck and Sirivivatnanon, 2003). This method only indicates the chloride-ion ingress depth, rather than the change in ion concentration with depth.

2.2 Concrete resistance to chloride-ion ingress

The ability of chloride ions to penetrate the concrete cover is a key factor in the service life of structural concrete. In reality, chloride ions can ingress concrete through a combination of transport mechanisms, namely absorption by capillary suction, diffusion and permeation (Tuutti, 1982). Absorption by capillary suction and diffusion are the more dominant mechanisms in aggressive chloride environments and can occur simultaneously when concrete is subject to cyclic wetting/drying, which is considered the most detrimental process (denoted as XD3 and XS3 exposure conditions) (BSI, 2013). Diffusion is a much slower process as the movement of ions occurs in the pore solution of saturated concrete (Kropp et al., 1995).

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 on the continuity, tortuosity and radius of the pore structure (Kropp et al., 1995). Cementitious materials also have a chloride-binding capacity, which reduces the free chloride ions in the pore solution of concrete and in turn changes the concentration gradient that drives diffusion (Glass and Buenfeld, 2000). This binding occurs due to adsorption and chemical reactions with constituents of the cement matrix that predominantly leads to the formation of Friedel's salt (calcium chloroaluminate hydrate) (Bertolini et al., 2004; Neville, 2011). 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 (Andrade and Bujak, 2013; Bapat, 2013; Dhir et al., 1996, 1997; Dunne et al., 2015; Glass and Buenfeld, 2000; Glass et al., 1997; Lollini et al., 2016; Reddy et al., 2002).

Aggregates also play an important role in the transport of liquids as the water-absorption properties and quality of interfacial transition zones (ITZ) can accelerate or decrease the ingress of fluids (Neville, 2011; Ryu and Monteiro, 2002). This is a particularly important concept when considering the use of CCA to replace NA in concrete as it has been shown that the cement paste adhered to the surface of aggregates can influence the water-absorption effects and reduce the quality of the ITZ (Bravo et al., 2015; Kwan et al., 2012; Lofty and Al-Fayez, 2015; Pedro et al., 2014; Soares et al., 2014). It is hypothesised that this is due to the release of air from CCA as water is absorbed during the early curing process, which creates additional voids in the ITZ (Leite and Monteiro, 2016).

2.3 Effect of coarse CCA on chloride-ion ingress

The majority of published research on the effect of coarse CCA on concrete durability (water and chloride-ion ingress) has focused on rapid migration and absorption test methods to determine suitable levels of replacement of NA. The general consensus is that replacement levels above 30% coarse CCA have a detrimental effect on the transport properties of CEM I concrete, which is commonly attributed to the increased water absorption of the aggregates (Limbachiya et al., 2012; Lofty and Al-Fayez, 2015; Soares et al., 2014; Zega et al., 2014). In contrast, 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 CEM I concretes, provided the CCA was obtained from high-quality precast concrete sources. Higher replacement levels, up to 100%, have been shown to be suitable when SCMs are also incorporated, particularly in relation to chloride-ion ingress resistance (Berndt, 2009; Kou and Poon, 2013; Lima et al., 2013; Somna et al., 2012). Additionally, Dodds et al. (2017a, 2017b) demonstrated that up to 60% coarse CCA was a suitable replacement level in CEM III/A structural concrete (50% replacement of Portland cement) to achieve a similar, or better, durability performance compared with CEM I control concretes produced with NA, while still achieving the specified characteristic strength.

The quantity of coarse CCA is limited to 30 and 20% in Eurocodes and UK standards, respectively, for structural concrete (BSI, 2013; BSI, 2015a, 2015b). These limits reduce to 0% if the structure is likely to be exposed to chloride ions during its service life. These limitations do not therefore reflect the published findings, which suggest the need for revised practice guidance.

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However, there is limited research on the effect of coarse CCA on the risk of corrosion initiation of structural concretes using common, well-established corrosion-monitoring techniques. This study investigated the risk of corrosion initiation, the predicted time to corrosion initiation and the depth of chloride-ion ingress of coarse CCA structural concretes when exposed to aggressive chloride environments. Their compressive strength, surface resistivity, water absorption by capillary action and rapid migration testing have been reported previously (Dodds *et al.*, 2016).

3. CCA composition

The CCA was obtained from an aggregate recycling facility in Plymouth, UK. The origin and purpose of the demolished structure(s) were unknown (as is virtually all CCA sold from aggregate recycling plants), so it was difficult to characterise the material. The concrete was crushed to a 40 mm down product, which was later processed to remove the fines content ($d < 4$ mm) and larger aggregates ($d > 20$ mm) to obtain a

coarse CCA conforming to 'type A' aggregates suitable for concrete (BSI, 2013).

CCA samples were analysed for cement, alkali and chloride-ion contents to BS 1881:124 (BSI, 2015c) and were within acceptable limits unlikely to cause contamination problems in the new concrete (Table 4).

The water absorption and particle density of the CCA were analysed and compared with those of NA (rounded quartzite river gravel) (Table 5). The particle density of the coarse CCA was lower than that of NA for both coarse size gradings tested. The water absorption of coarse CCA at 24 h was found to be 3–4 times greater than that of the NA, but towards the lower end of the reported range in the literature (between 3·6% and 11·6%), which is indicative of a good-quality source.

4. Methodology

The corrosion risk of coarse CCA was assessed for CEM I, CEM II/B-V and CEM III/A concretes when exposed to aggressive chloride environments. Concrete beams (reinforced) and cubes were subject to chloride-ion ingress by cyclic wetting/drying and natural diffusion, respectively. Table 6 details the test methods adopted. Well-established assessment methods were adopted to determine the subsequent corrosion risk of the RC beams, with a sample size to provide a large surface for chloride-ion ponding. The natural diffusion coefficient provides a comparison with the apparent chloride diffusion coefficient. Concrete cubes were exposed as per the European standard (BSI, 2015d).

The concrete was designed using the Building Research Establishment (BRE) mix design method to achieve

Table 4. Laboratory analysis of CCA

	Sample number	Percent by mass of dried sample
Cement content	1	11·1
	2	12·8
Alkali content	1	Potassium oxide – 0·12
		Sodium oxide – 0·02
	2	Potassium oxide – 0·19
		Sodium oxide – 0·03
Chloride-ion content	1	0·03
	2	0·02
	3	0·01

Table 5. Water absorption and particle density of aggregates

Aggregate type/grading	Saturated and surface-dried particle density: mg/m³	Water absorption (30 min): %	Water absorption (24 h): %
NA 10–20 mm	2·59	0·63	0·89
NA 4–10 mm	2·57	1·07	1·15
NA 0–4 mm (sand)	2·61	0·42	0·54
CCA 10–20 mm	2·47	3·13	3·67
CCA 4–10 mm	2·44	4·15	4·35

Table 6. Justification of test methods

Exposure	Test method	Standard/reference	Sample size
Combined absorption and diffusion	Half-cell potential	CS (2004a); ASTM, (2009)	RC beams 500 × 100 × 100 mm
	Surface resistivity	CS (2004a); Aashto (2015)	
	Apparent chloride diffusion coefficient	Poulsen (1995); BSI (2015c)	
	Chloride-ion penetration depth	Meck and Sirivivatnanon (2003)	
Diffusion	Natural diffusion coefficient	BSI (2015c); BSI (2015d)	Concrete cubes 100 mm³

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characteristic and target mean strengths of 35 MPa and
49 MPa, respectively (BRE, 1997). The constituents of each mix
are summarised in Table 7. Additional binder content was
added to compensate for the inclusion of the coarse CCA
(10 kg/m^3 per 20% coarse CCA inclusion) and the water content
for the CEM II/B-V mixes was reduced following recommen-
dations in the BRE mix design method for crushed aggregates.

The coarse CCA replaced the coarse NA at 20, 40 and 60% by
mass. The mixes were labelled PC (CEM I), FA (CEM II/B-V)
and BS (CEM III/A), followed by the numeric CCA content.
For example, concrete mix PC60 refers to a CEM I concrete
made with 60% coarse CCA (and 40% NA).

Two concrete beams (500 mm × 100 mm × 100 mm) were cast
for each mix with a 16 mm dia. steel reinforcing bar with a top
concrete cover of 65 mm to comply with the durability recom-
mendations for a 50-year design life in XS3 exposure conditions
(BSI, 2015a, 2015b). A 4 mm cross-linked polyethylene coated
titanium wire was riveted to the steel reinforcement prior to
casting and extended above the cast concrete surface. The beams
were stripped the next day and moist-cured under a damp
hessian cloth for 28 d before being subjected to 2 d of ponding
(wetting) with 3% chloride-ion solution, followed by 12 d of
drying in the internal laboratory environment on a cyclic basis.
The exposure conditions were chosen to allow sufficient drying
of the concrete surface in order to maximise the absorption
effects. A ponding area of approximately 38 400 mm^2 was
created using 15 mm high PVC profiles and a silicone-based
sealant (Figure 2). The four vertical sides of the beam were
sealed using a bitumen-based waterproofing paint to help
promote unidirectional movement of the chloride-ion solution.

Close interval half-cell potential (50 mm spacing) readings
were recorded on the top face of each beam before exposure to
the chloride-ion solution (dry reading) and immediately after
removing the chloride-ion solution (wet reading), and an value
average was calculated (ASTM, 2009; CS, 2004a). All ponded
chlorinated water was removed with a cloth prior to recording
the half-cell potential measurements. Surface-resistivity readings

were also recorded at six locations along the top of the beams,
and an average calculated, prior to ponding at approximately
28, 56, 90, 180 and 360 d (Aashto, 2015; CS, 2004a).

After approximately 12 months of cyclic exposure, one beam
for each concrete mix that was demonstrating the most
likely probability of corrosion initiation (using the criteria in
Tables 1 and 2 and identifying areas of anodic activity) was
drilled at 10 mm depth intervals until the steel reinforcement
was reached at 65 mm (20 mm dia. drill bit). The dust samples
were subsequently tested for chloride-ion content (BSI, 2015c).
A chloride profile was determined and a non-steady-state
apparent chloride diffusion coefficient calculated following the
linear curve fitting method (Poulsen, 1995). The same beams
were then split vertically and analysed visually for signs of cor-
rosion (Figure 3). Chloride-ion penetration depths were
measured using the colourimetric technique (Meck
and Sirivivatnanon, 2003). The calculated apparent chloride
diffusion coefficients were used to predict the time taken to
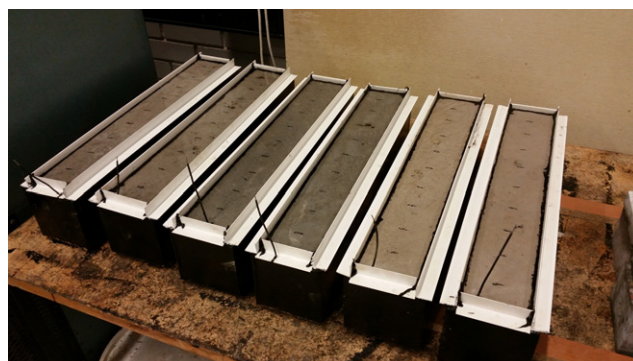corrosion initiation using the error function solution to Fick's

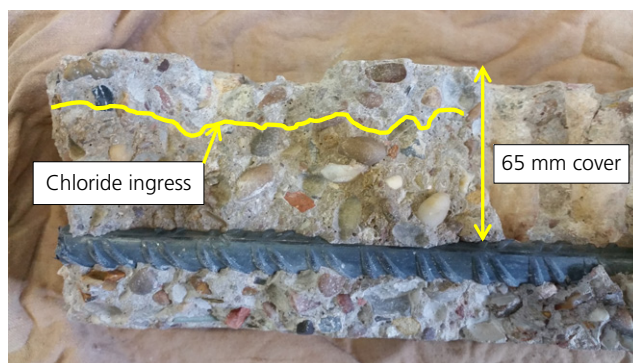**Figure 2.** RC beams prepared for cyclic wetting/drying

Table 7. Mix design constituents

	PC (CEM I)	FA (CEM II/ B-V – 30%)	BS (CEM III/ A – 50%)
Water–binder ratio	0·5	0·4	0·5
Cement: kg/m^3	390	307	195
PFA: kg/m^3	—	131	—
GGBS: kg/m^3	—	—	195
Water: kg/m^3	195	175	195
Sand: kg/m^3	653	650	653
Coarse 10–20 mm: kg/m^3	775	759	775
Coarse 4–10 mm: kg/m^3	387	378	387

Figure 3. Visual analysis and measurement of chloride-ion
ingress, CEM I concrete

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Figure 4. Cubes exposed to chloride-ion solution by the inversion method

Figure 5. Monitoring of temperature and RH over time

second law of diffusion, identified as a chloride-ion concentration of 0·4% reaching the surface of the steel reinforcement (CS, 2004b). The remaining beams were continually ponded and assessed for corrosion-initiation risk, when exposed to the same cyclic wetting/drying process.

Two concrete cubes (100 mm^3) were cast for each mix, and tested for chloride-ion ingress by natural unidirectional diffusion (BSI, 2015d). The cubes were sealed on five faces and exposed to a 3% sodium chloride (NaCl) solution by the inversion method (Figure 4). Dust samples for chloride-ion analysis were ground from the cube specimens after 3 months exposure in thin layers as detailed in the standard and used to calculate a non-steady-state chloride diffusion coefficient (BSI, 2015c; Poulsen, 1995).

5.   Analysis of results
As previously stated, the assessment of corrosion risk can be influenced by the ambient RH and temperature (Angst and Elsener, 2014; Assouli et al., 2008; CS, 2004a; Holmes et al., 2011). All testing was undertaken in a laboratory environment subject to seasonal fluctuations between 18 and 26°C and 31–64% RH, which should be considered as part of the interpretation (Figure 5).

5.1   Close interval half-cell potentials
The half-cell potential of the reinforcing steel was recorded bi-weekly, before and immediately following 2 d of ponding; these are referred to as 'dry' and 'wet' readings, respectively. Surface-saturated concrete is recommended for taking half-cell potentials as it improves the electrical connection between the reference electrode and the steel (CS, 2004a). Therefore, only the 'wet' half-cell potential readings are presented and discussed.

Figures 6–8 show the development of wet half-cell potentials of the reinforcing steel in CEM I, CEM II/B-V and CEM III/A concretes, respectively. Two beams were monitored for each coarse CCA content, denoted as 'a' and 'b', respectively. The interpretation limits for a low and high probability of corrosion initiation are indicated (ASTM, 2009).

The majority of half-cell potentials remained above the recommended threshold for a low probability of corrosion initiation (less than −134 mV), particularly for the CEM I and CEM II/B-V concretes, even with a coarse CCA content up to 60%. At early ages, the half-cell potentials were more negative and had large variations within the same batch and also across the batch, with no particular trend regarding the coarse CCA content. As time progressed, the half-cell potentials gradually increased in magnitude and became stable. This effect was more exaggerated in the concrete produced with SCMs, most likely due to the delayed hydration process of pozzolanic and latent hydraulic materials (Dhir et al., 1996, 1997; Glass and Buenfeld, 2000; Glass et al., 1997).

Only one beam (PC20a) for the CEM I concrete and two beams (BS20a, BS40b) for the CEM III/A concrete decreased below the threshold for a high probability of corrosion initiation; these, however, quickly returned to the zone of uncertain corrosion activity. These beams, among others, were selected for destructive testing to further investigate probable corrosion initiation after 12 months. The half-cell potentials for all the CEM II/B-V concretes suggested a low risk of corrosion initiation. Overall, no concrete beams showed signs of obvious corrosion initiation in the first 18 months of cyclic ponding and, interestingly, the beams produced with up to 60% coarse CCA had similar half-cell potentials to those of the control concretes.
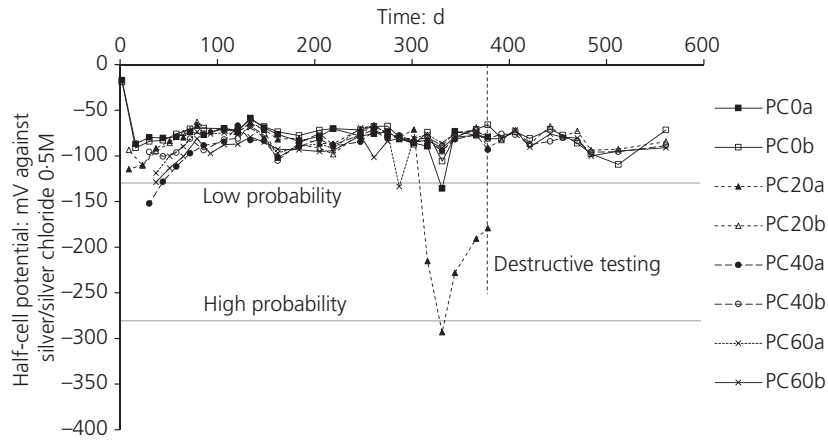
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Figure 6. Development of wet half-cell potential over time, CEM I concrete
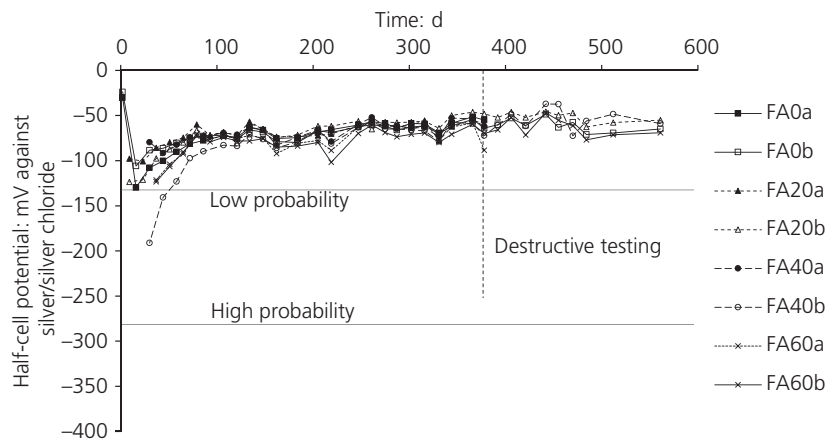

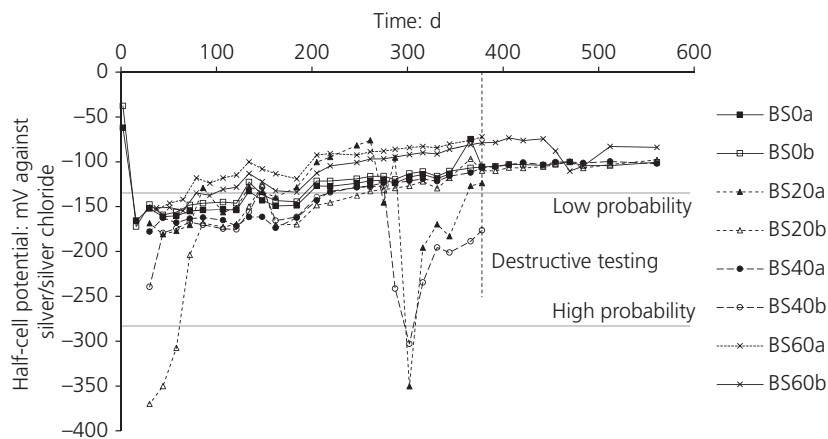**Figure 7.** Development of wet half-cell potential over time, CEM II/B-V concrete

Figure 8. Development of wet half-cell potential over time, CEM III/A concrete

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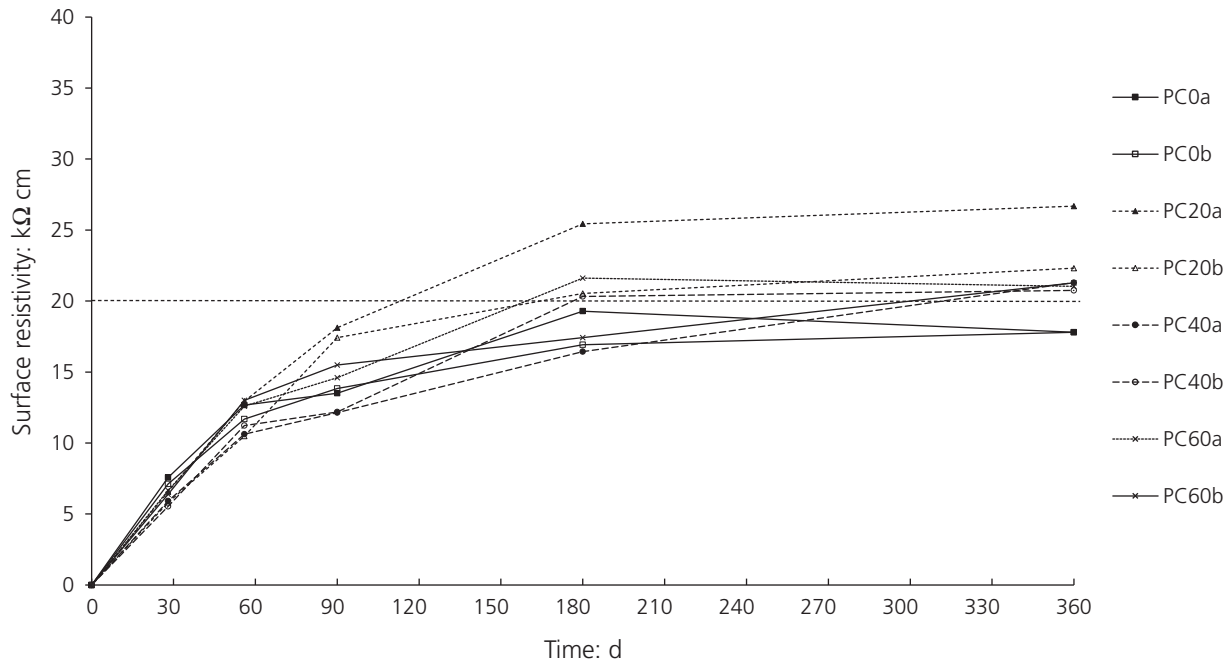aggregate
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Figure 9. Development of surface resistivity over time, CEM I concrete

5.2 Surface resistivity

High levels of moisture can significantly influence surface resistivity readings; therefore, the results were obtained before ponding at approximately 28, 56, 90, 180 and 360 d (CS, 2004a).

Figures 9–11 show the development of 'dry' surface resistivity of the CEM I, CEM II/B-V and CEM III/A concretes, respectively. The 20 kΩ cm limit, which both interpretations (Aashto, 2015; CS, 2004a) acknowledge as a low chloride-ion penetration and corrosion rate, is indicated.

The results clearly show the beneficial effects of SCMs, indicated by the large increase in surface resistivity over time. The surface resistivity of the CEM II/B-V and CEM III/A concretes (even with up to 60% coarse CCA content) continued to increase over time, with values approximately 3–5 times higher in magnitude than those of the reference CEM I concretes. The majority of CEM II/B-V and CEM III/A concretes achieved the 20 kΩ cm threshold for low corrosion rate/ chloride-ion penetration by 56 d. In comparison, the surface resistivity of the CEM I concrete remained much lower, with the majority of results being just above the 20 kΩ cm threshold for low corrosion rate/chloride-ion penetration (Aashto, 2015; CS, 2004a). There does not appear to be any evident trend for a higher coarse CCA content having a significant effect on the development of surface resistivity with time.

5.3 Chloride-ion ingress

The apparent chloride diffusion coefficient and chloride-ion penetration depth for all concrete types are shown in Figures 12 and 13, respectively. Table 8 shows the predicted time to corrosion using the error function solution to Fick's second law of diffusion, identified by a chloride-ion content of 0·4% reaching the surface of the steel reinforcement.

Analysis of the chloride-ion ingress resistance and the prediction of time to corrosion initiation shows a strong correlation with the observations already presented. The CEM II/B-V and CEM III/A concretes with up to 60% coarse CCA content outperformed the control CEM I concrete at resisting the ingress of chloride ions when a combination of absorption and diffusion was occurring simultaneously. In both cases, the inclusion of SCMs increased the chloride-ion ingress resistance and increased the predicted time to corrosion initiation to greater than 120+ years, which is higher than the original 50-year design life of the structural concrete. Additionally, the inclusion of SCMs had a larger influence on the chloride-ion ingress resistance compared with the quantity of coarse CCA, which does not appear to have an evident trend in relation to the chloride-ion ingress.

The natural diffusion coefficients for all concrete types are shown in Figure 14. As with the results of cyclic ponding, the CEM II/B-V and CEM III/A concretes with up to 60% coarse
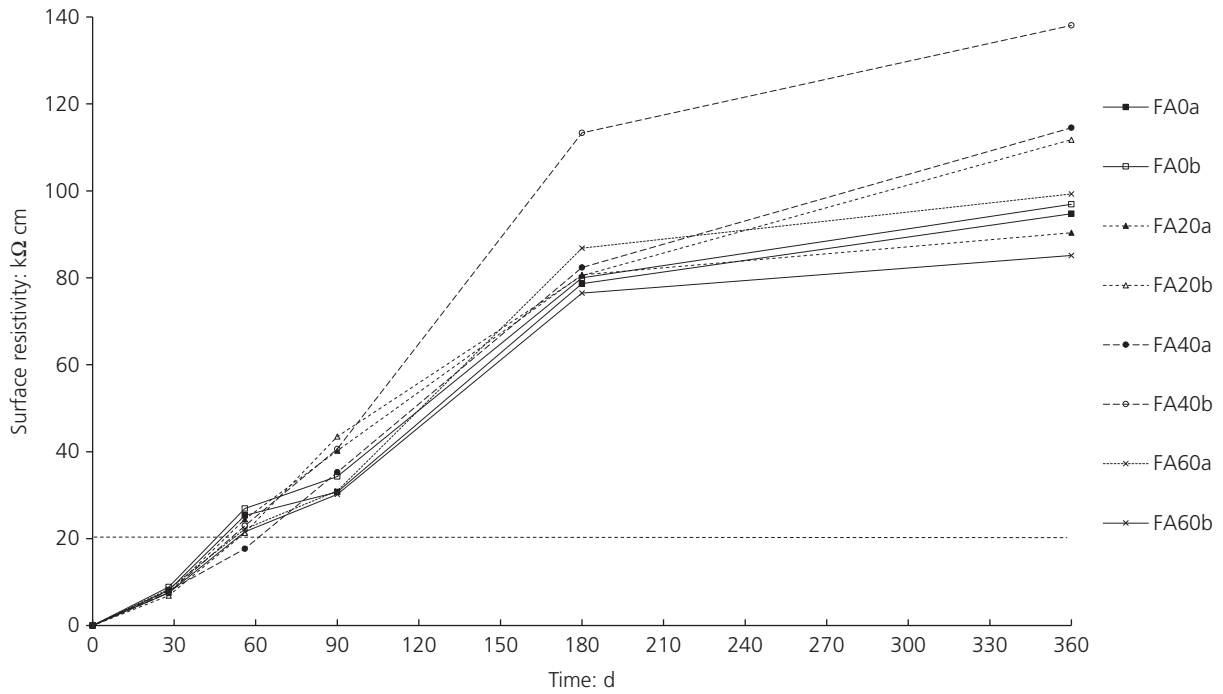
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Figure 10. Development of surface resistivity over time, CEM ll/B-V concrete
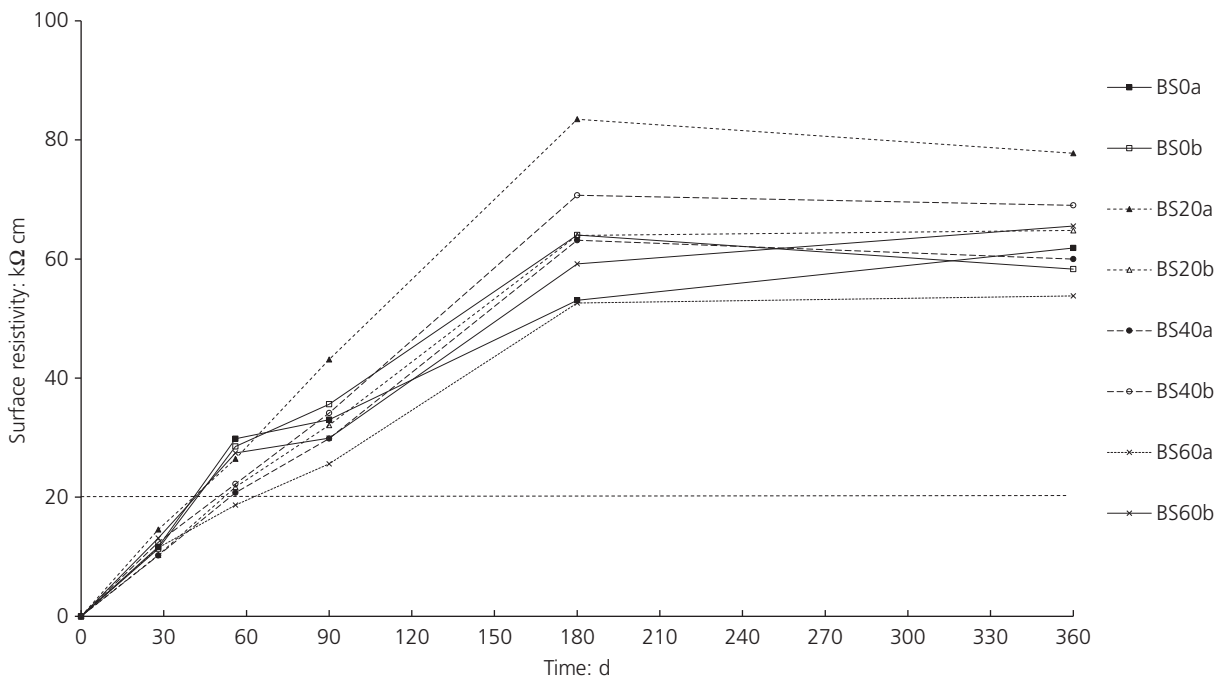
Figure 11. Development of surface resistivity over time, CEM lll/A concrete

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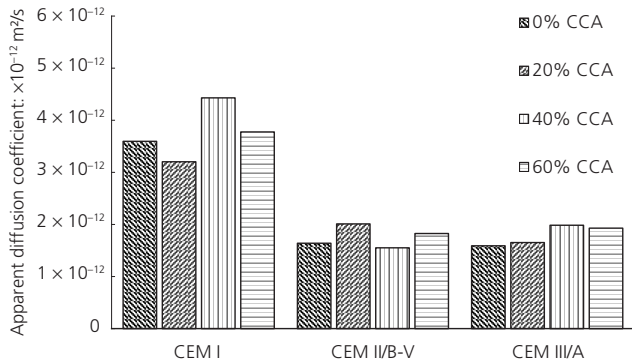Dodds, Goodier, Christodoulou, Austin and Dunne

Figure 12. Apparent diffusion coefficient following 12 month exposure to cyclic wetting/drying
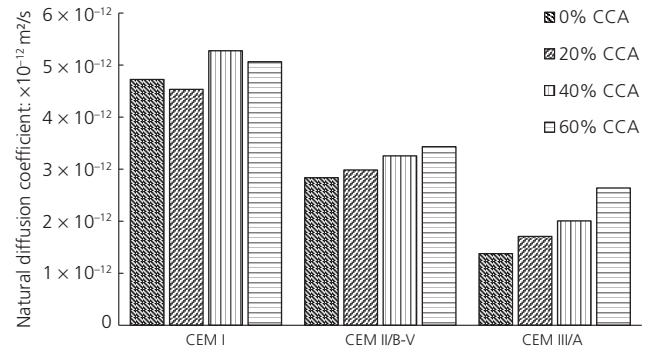

Figure 14. Natural diffusion coefficients following a 90 d exposure to chloride-ion solution
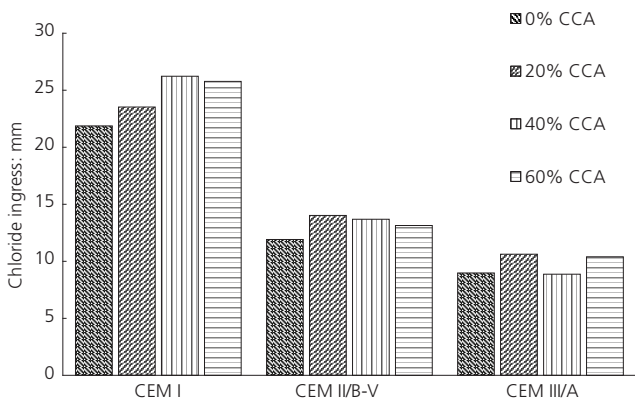

Figure 13. Chloride-ion ingress following 12 month exposure to cyclic wetting/drying

Table 8. Prediction of time to corrosion initiation (years)

CCA content: %	0	20	40	60
CEM I	39	66	42	47
CEM II/B-V	120+	120+	120+	120+
CEM III/A	120+	120+	120+	120+

CCA content outperformed the control CEM I concrete at resisting the ingress of chloride ions when diffusion was the only transport mechanism. In this case, there appears to be a more evident trend of decreasing chloride-ion ingress resistance with a higher coarse CCA content.

6. Discussion

The effects of coarse CCA on the risk of corrosion initiation, the predicted time to corrosion initiation and the depth of chloride-ion ingress when exposed to aggressive chloride environments were investigated, to encourage the appropriate use of coarse CCA in structural concrete. The majority of close interval half-cell potentials and surface resistivity results indicated a low risk of corrosion initiation for all the concrete types tested. Only three cases of probable corrosion activity were identified throughout the testing period (Figures 6–8), as indicated by a decrease in the half-cell potential below −284 mV (Figures 6 and 8). The results of destructive testing and measurement of chloride-ion ingress resistance, however, indicated that none had taken place (Figures 12 and 13, Table 8).

For all the test methods, the CEM II/B-V and CEM III/A concretes with up to 60% coarse CCA outperformed the control CEM I concretes with 100% NA. These concretes had lower risks of corrosion initiation compared with control CEM I concretes, as indicated by stable half-cell potential readings above the −134 mV threshold for low corrosion initiation risk, surface-resistivity readings significantly higher than the 20 kΩ cm threshold for low chloride-ion penetration/corrosion rate, a higher chloride-ion ingress resistance for all transport mechanisms tested and a higher predicted time to corrosion initiation beyond the design life of the structural concrete adopted for this study. Additionally, the delayed hydration of CEM II/B-V and CEM III/A concretes continued to reduce the risk of corrosion initiation, as indicated by the magnitude of half-cell potentials and surface resistivity readings continuing to increase with time. The inclusion of SCMs also had a larger influence on the chloride-ion ingress resistance compared with the quantity of coarse CCA, which largely outweighed any observed detrimental effects. In the majority of the test methods adopted in this study, there did not appear to be an evident trend of resistance to chloride-ion ingress with increasing coarse CCA content. These findings are in agreement with other published studies on the beneficial effects of SCMs and highlight the advantages of their use in combination with coarse CCAs (Dhir *et al.*, 1996, 1997; Glass and Buenfeld, 2000; Glass *et al.*, 1997).

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Dodds *et al.* (2017a, 2017b) demonstrated that up to 60% coarse CCA was a suitable replacement level in CEM III/A structural concrete (at 50% replacement of Portland cement) in terms of the effect on microstructure, water and chloride-ion ingress and compliance with characteristic cube strength at later ages. The current research used well-established assessment techniques to determine the corrosion risk of CEM I, CEM II/B-V and CEM III/A concretes with coarse CCAs. The results complement the existing research as it has been shown that CEM II/B-V and CEM III/A concretes produced with up to 60% coarse CCA have a lower risk of corrosion initiation than control CEM I concrete produced with 100% NA when exposed to aggressive chloride environments. The replacement level of 60% coarse CCA is double the recommended limit in other published literature and the existing European and British standards – a significant outcome for the wider implementation of coarse CCA in structural concrete (Limbachiya *et al.*, 2012; Lofty and Al-Fayez, 2015; Soares *et al.*, 2014; Zega *et al.*, 2014). The findings presented highlight that the limitations imposed by existing design standards are conservative at best and do not properly reflect the findings of published data.

7. Conclusions

Currently, there is limited research on the effect of coarse CCA on the longevity of RC structures exposed to aggressive chloride environments, particularly in relation to corrosion initiation, and hence in this regard the research presented here is unique. Structural concretes with varying quantities of coarse CCA were exposed to aggressive chloride environments. The risk of corrosion initiation was assessed using commonly adopted techniques for RC structures. On the basis of analysis of the results and determining the risk of corrosion initiation from a range of test methods, the following conclusions can be made.

(*a*) For all test methods adopted, the CEM II/B-V and CEM III/A concretes produced with up to 60% coarse CCA outperformed the control CEM I concrete produced with 100% NA, and had a lower risk of corrosion initiation.

(*b*) Similar published work by the authors has shown that low quantities of coarse CCA (30%) can have a detrimental effect on the microstructure, water and chloride-ion ingress and compressive cube strength (Dodds *et al.*, 2017a, 2017b). From the results presented in this paper there did not appear to be an evident trend of resistance to chloride-ion ingress with increasing coarse CCA content. Therefore, further research is required to determine if the same detrimental effect is observed when assessing the corrosion initiation risk over longer periods of monitoring.

(*c*) Throughout testing, only three cases of probable corrosion activity were identified. The results of destructive testing and the measurement of chloride-ion

ingress resistance, however, confirmed that no corrosion had occurred and that the corrosion risk remained low. This highlights the benefit of assessing the corrosion risk using a range of test methods and not solely relying on the results of a half-cell potential survey.

(*d*) The beneficial pozzolanic and latent hydraulic effects of CEM II/B-V and CEM III/A concretes were apparent from the continual increase in half-cell potential and surface-resistivity readings. This conclusion is further strengthened by the observation of improved resistance to chloride-ion ingress for all transport mechanisms tested and the predicted time to corrosion initiation, which remained well above the 50-year design life of structural concrete adopted for this study. Additionally, the inclusion of SCMs had a larger influence on the chloride-ion ingress resistance compared with the inclusion of coarse CCA, and largely outweighed any observed detrimental effects.

The findings of this study complement the existing research by Dodds *et al.* (2017a, 2017b) and further highlight that CEM II/B-V and CEM III/A structural coarse CCA concretes can be a viable option for future responsibly sourced projects provided that a reliable and consistent source of coarse CCA can be obtained. This is a significant outcome for the wider implementation of coarse CCA into structural concrete applications and highlights the need for new best practice guidance that allows the specification of coarse CCA in structural concrete.

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