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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 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/CuSO4) 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 micro-structure 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 Society Technical Report 60 (CS, 2004a).

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 Society Technical Report 60 (CS, 2004a).

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

<table>
<thead>
<tr>
<th>Voltage against copper/copper sulfate: mV</th>
<th>Voltage against silver/silver chloride / 0·5 M potassium chloride: mV</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;−200</td>
<td>&gt;−134</td>
<td>Greater than 90% probability that no corrosion activity is occurring</td>
</tr>
<tr>
<td>&lt;−200 and &gt;−350</td>
<td>&lt;−134 and &gt;−284</td>
<td>Uncertain corrosion activity</td>
</tr>
<tr>
<td>&lt;−350</td>
<td>&lt;−284</td>
<td>Greater than 90% probability that corrosion activity is occurring</td>
</tr>
</tbody>
</table>

### Table 2. Interpretation of four-point Wenner probe readings

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity: kΩ cm</td>
<td>Resistivity: kΩ cm</td>
</tr>
<tr>
<td>Interpretation</td>
<td>Interpretation</td>
</tr>
<tr>
<td>Very high corrosion rate</td>
<td>High chloride-ion penetration</td>
</tr>
<tr>
<td>High corrosion rate</td>
<td>Moderate chloride-ion penetration</td>
</tr>
<tr>
<td>Low to moderate corrosion rate</td>
<td>Low chloride-ion penetration</td>
</tr>
<tr>
<td>Low corrosion rate</td>
<td>Very low chloride-ion penetration</td>
</tr>
<tr>
<td>—</td>
<td>Negligible chloride-ion penetration</td>
</tr>
</tbody>
</table>
drying, which is considered the most detrimental process simultaneously when concrete is subject to cyclic wetting/mechanisms in aggressive chloride environments and can occur by capillary suction and diffusion are the more dominant suction, diffusion and permeation (Tuutti, 1982). Absorption of transport mechanisms, namely absorption by capillary chloride ions can ingress concrete through a combination 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.
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

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**Table 4. Laboratory analysis of CCA**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Percent by mass of dried sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement content</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11·1</td>
</tr>
<tr>
<td>2</td>
<td>12·8</td>
</tr>
<tr>
<td>Alkali content</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Potassium oxide – 0·12</td>
</tr>
<tr>
<td>2</td>
<td>Sodium oxide – 0·02</td>
</tr>
<tr>
<td>2</td>
<td>Potassium oxide – 0·19</td>
</tr>
<tr>
<td>2</td>
<td>Sodium oxide – 0·03</td>
</tr>
<tr>
<td>Chloride-ion content</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0·03</td>
</tr>
<tr>
<td>2</td>
<td>0·02</td>
</tr>
<tr>
<td>3</td>
<td>0·01</td>
</tr>
</tbody>
</table>

**Table 5. Water absorption and particle density of aggregates**

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

**Table 6. Justification of test methods**

<table>
<thead>
<tr>
<th>Exposure and diffusion</th>
<th>Test method</th>
<th>Standard/reference</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined absorption</td>
<td>Half-cell potential</td>
<td>CS (2004a); ASTM, (2009)</td>
<td>RC beams 500 × 100 × 100 mm</td>
</tr>
<tr>
<td>and diffusion</td>
<td>Surface resistivity</td>
<td>CS (2004a); Aashto (2015)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apparent chloride diffusion coefficient</td>
<td>Poulsen (1995); BSI (2015c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chloride-ion penetration depth</td>
<td>Meck and Sinivivattanom (2003)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Natural diffusion coefficient</td>
<td>BSI (2015c); BSI (2015d)</td>
<td>Concrete cubes 100 mm³</td>
</tr>
</tbody>
</table>
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/m³ per 20% coarse CCA inclusion) and the water content for the CEM II/B-V mixes was reduced following recommendations 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 recommendations 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 mm² 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 corrosion (Figure 3). Chloride-ion penetration depths were measured using the colourimetric technique (Meck and Sirivivatanon, 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

Table 7. Mix design constituents

<table>
<thead>
<tr>
<th>Component</th>
<th>PC (CEM I)</th>
<th>FA (CEM II/B-V – 30%)</th>
<th>BS (CEM III/A – 50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/binder ratio</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Cement: kg/m³</td>
<td>390</td>
<td>307</td>
<td>195</td>
</tr>
<tr>
<td>PFA: kg/m³</td>
<td>—</td>
<td>131</td>
<td>—</td>
</tr>
<tr>
<td>GGBS: kg/m³</td>
<td>—</td>
<td>—</td>
<td>195</td>
</tr>
<tr>
<td>Water: kg/m³</td>
<td>195</td>
<td>175</td>
<td>195</td>
</tr>
<tr>
<td>Sand: kg/m³</td>
<td>653</td>
<td>650</td>
<td>653</td>
</tr>
<tr>
<td>Coarse 10–20 mm: kg/m³</td>
<td>775</td>
<td>759</td>
<td>775</td>
</tr>
<tr>
<td>Coarse 4–10 mm: kg/m³</td>
<td>387</td>
<td>378</td>
<td>387</td>
</tr>
</tbody>
</table>
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 mm³) 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).

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. 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.
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.
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
Figure 10. Development of surface resistivity over time, CEM II/B-V concrete

Figure 11. Development of surface resistivity over time, CEM III/A concrete
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).
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; Lofly 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 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; Lofly 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.

(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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