CHLORIDE ION INGRESS AND CHLORIDE-INDUCED CORROSION INITIATION OF COARSE CCA STRUCTURAL CONCRETE

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Abstract:

The specification of crushed concrete aggregates (CCA) is increasing, with the construction industry still seeking new ways to improve the quality and performance. In higher value applications, such as structural concrete, further research is required to understand the effect of coarse CCAs, particularly on durability. This 4 year research programme investigated the effect of coarse CCA on transport mechanisms within CEM I and CEM III/A structural concretes, with particular emphasis on chloride ion ingress and corrosion initiation.

CEM III/A concretes with up to 100% coarse CCA outperformed control CEM I concrete with 100% natural aggregates in durability performance tests, irrespective of the source of CCA. The results indicate that coarse CCA can be incorporated up to 60% replacement of natural aggregates if the criterion for compressive strength compliance at 28 days is relaxed for CEM III/A concretes.

Water absorption, chemical and petrographic analysis, of the sources of coarse CCA with known compositions, had a good correlation with durability performance. This type of testing is recommended on future construction projects to mitigate potential risks.

Keywords: Coarse aggregate, CCA, Chloride ion ingress, Durability, Recycling.

i. Introduction

In the UK, the majority of recycled aggregate (RA) is utilised as general fill material, unbound aggregates (road base/sub-base, pipe bedding and capping layers), and in lower grade concrete. RA producers, however, are seeking to improve the quality and performance of their aggregates to sell into higher value applications to increase profits (Barritt, 2015).

There is a wide-spread, poor perception of crushed concrete aggregates (CCA) in industry because the effects on mechanical and durability performance are not well understood. Most research has focused on the effect on mechanical properties including compressive and tensile strength, modulus of elasticity and creep, with some consensus of an increasing detriment with higher replacement levels of natural aggregates (Limbachiya *et al*, 2000; Ajdukiewicz and Kliszczewicz, 2002; Etxeberria *et al*, 2007; Collery *et al*, 2015; Silva *et al*, 2016). The effect of CCA on long-term durability, however, is less well understood, particularly in relation to water and chloride ion ingress and the risk of corrosion initiation, which are the causes of the vast majority of infrastructure deterioration and subsequent repair or demolition. This gap in knowledge needs to be addressed if we are to significantly increase the quantity of CCA in structural applications and help protect our limited natural resources.

Chloride ion ingress of reinforced concrete usually occurs through exposure to marine environments or de-icing salts applied to highway structures during winter maintenance. This contributes to the initiation of reinforcement corrosion and can cause significant deterioration (Concrete Society, 2004a,b). The estimated cost of corrosion to reinforced concrete bridges is estimated at $8 billion annually in the USA alone (NACE International, 2012), with chloride-induced corrosion being the most common cause of deterioration. The UK's National Audit Office (NAO) also highlighted the increased expenditure on the maintenance of highways infrastructure which usually occurs throughout the winter months, November to March (NAO, 2014).

This research programme examined the effect of recycled CCA on the durability of structural concrete containing supplementary cementitious materials (SCMs). The research was undertaken over a 4 year period with a large quantity of data collected and analysed. The detailed results are presented in published journal papers as part of the overall thesis (Dodds *et al*, 2017a,b,c). This paper provides an overview of the key findings and recommendations of the study.

ii. Background Information

RA has become a popular alternative to natural aggregates since the early 1980's. RA can consist of concrete, concrete and clay masonry units, mortar, natural stone, bituminous materials, glass and deleterious materials such as paper, wood, metals and plastics, and is also referred to as construction and demolition waste (CDW). Across Europe, a large quantity of CDW is available which contributes to increased waste to landfill (Monier *et al*, 2011).

Data from an annual survey by the UK National Federation of Demolition Contractors (NFDC) has shown that the concrete, masonry and stone hardcore quantities have increased since 2011 (Figure 1). The majority of such arisings are either crushed on-site for use on the site, or are left unprocessed and removed off-site and most likely taken to recycling plants for further processing and treatment before being sold on.

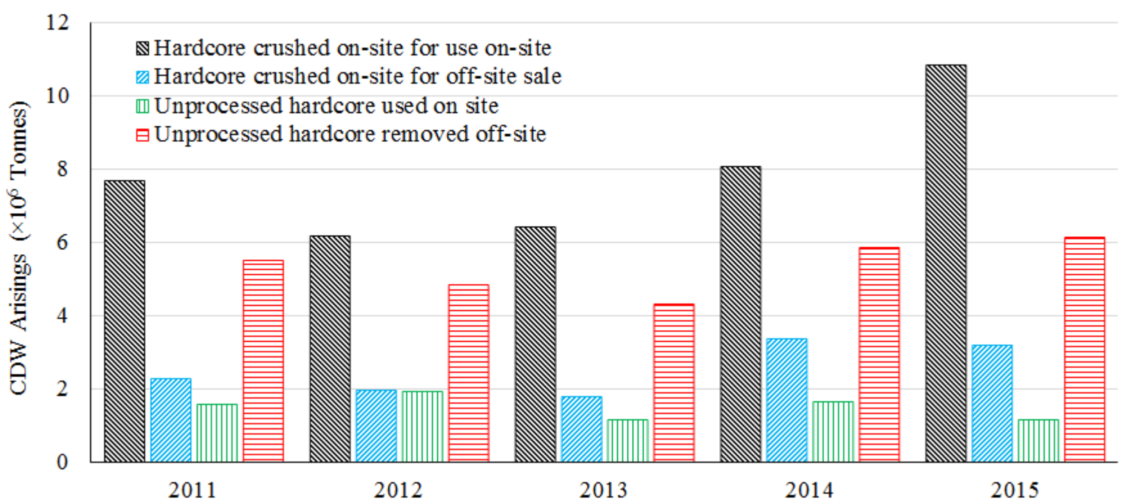

Fig. 1 CDW arisings in the UK 2011-2015 (NFDC, 2016)

With larger quantities of concrete CDW becoming available, and a desire to incorporate RA into higher value applications, we chose to focus this research on the effects of CCA in structural concrete, rather than the different types of RA. It is therefore of interest in situations where CCA may be a suitable replacement material in structural concrete, such as: a specific project/client requirement; improved project sustainability; a good quality, consistent source of CCA is available on-site; and/or where there is a short supply of natural aggregates (Filho *et al*, 2013; Hassan *et al*, 2016; Yehualaw and Woldesenbet, 2016; McGinnis *et al*, 2017).

The European standard for concrete specification, BS EN 206, provides recommendations for coarse CCA (diameter ≥ 4mm) in Annex E: *'Type A aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%'* (BSI, 2013a). This limit can be increased to 50% if no reinforcing steel or embedded metal is present. If the source of the CCA is unknown or does not conform to the criteria of Type A aggregates (>90% concrete products, mortar, and concrete masonry units) (BSI, 2013b) then the replacement allowance for the majority of exposure classes, including chlorides, reduces to 0%.

The UK's Bridge Advice note (BA 92/07) for the design of highway structures states that compliance with BS EN 12620 and BS 8500-2 for all aggregates is essential; however it also says that the use of coarse CCA is not advised, particularly in sensitive or critical structural components until further research is conducted (DMRB, 2007). The prevailing UK standards are thus constraining the uptake of CCA in concrete structures; a situation this research sought to challenge.

iii. Experimental programme

The constituents of each mix are summarised in Table 1. The water-binder ratio of 0.5 and the cement content comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 (BSI, 2015). Five sources of coarse CCA (4/20mm) were incorporated at 30%, 60% and 100% to replace the coarse NA by mass. GGBS was incorporated at 36%, 50% and 65% replacement of CEM I by mass, to produce a range of CEM III/A concretes. No admixtures were included and no additional cement was added to compensate for the inclusion of CCA.

Table 1. Concrete mix constituents

Constituents	CEM I	CEM III/A (36%)	CEM III/A (50%)	CEM III/A (65%)
Cement (kg/m³)	390	250	195	136
GGBS (kg/m³)	-	140	195	254
Water (kg/m³)	195	195	195	195
Sand (kg/m³)	653	653	653	653
Coarse 10/20mm (kg/m³)	775	775	775	775
Coarse 4/10mm (kg/m³)	387	387	387	387

The five site sources of coarse CCA are shown in Table 2. Sources 1 and 2 were 40mm to dust products. Sources 3 to 5 were extracted from selected components of the reinforced concrete structures, broken down and crushed with a primary jaw crusher to produce a 40mm down product in the laboratory. All sources were further sieved to obtain a coarse aggregate grading suitable for concrete (4 to 10mm and 10 to 20mm).

Table 2. CCA sources

Source Ref.	Location/Site	Source
1	Dorton Group Recycling Facility, Plymouth	Mixed source of CCA
2	1970's office building, Leicester	Mixed CCA from unknown structural elements
3	1970's office building, Coventry	Reinforced concrete beams
4	1970's factory, Loughborough	Reinforced concrete footing and column base
5	1970's factory, Loughborough	Reinforced concrete slab

Explanations of the properties investigated and associated test methods are detailed in Table 3. The majority of tests were undertaken at 28, 56 and 91 days.

Table 3. Properties and test methods

Test method	Standard	Justification
Compressive cube strength	BS EN 12390-3	To determine compliance of mixes with the characteristic ($f_{c,cube}$) and target mean strengths.
Surface & bulk resistivity	AASHTO T358	To determine the quality of the microstructure of concrete, indicated by the electrical surface and bulk resistivity.
Absorption by capillary action	BS EN 13057	To determine the sorptivity of concrete with no external pressures applied.
SEM analysis	N/A	To provide microscopic imagery of the new cement matrix, the cement matrix of the adhered mortar of the coarse CCA and the quality of the interfacial transition zones between coarse aggregates and cement paste.
Rapid chloride migration	NT-BUILD 492	To determine the migration of chloride ions in concrete when an electric field is applied.
Accelerated corrosion	NT-BUILD 356	To determine the time to corrosion and cracking when an electric field is applied.
Unidirectional natural diffusion	BS EN 12390-11	To determine the rate of unidirectional diffusion of chloride ions in concrete. This is the key transport mechanism when concrete is in a saturated state.
Half-cell potential mapping	ASTM C876	The results can provide an indication of the risk of corrosion initiation using close interval half-cell measurements.
Chloride ion concentration	Concrete Society TR 60	The results can provide an indication of the risk of corrosion initiation, and also be used to form a chloride ion concentration profile to determine an apparent chloride diffusion coefficient.
Chloride ion ingress	N/A	This test provides a quick indication of the chloride ion ingress depth, indicated by the formation of white precipitate on the surface.

It was established at an early stage that it would be difficult to characterise source 1 and 2 as the location of the source materials was unknown (i.e. from mixed sources or structural elements). Irrespective of the origin, tests were conducted to determine the cement content, water absorption and particle density of random samples of the coarse CCA, along with potential contamination testing in the form of alkali and chloride ion content. For sources 3 to 5, additional characterisation could be undertaken in the form of petrographic analysis, to determine the aggregate type, cement type, possible presence of admixtures, segregation, microcracking and voids. An estimate of the mix constituents, cement content, water/cement ratio, slump and 28 day strength could also be obtained.

Figure 2 shows that the inclusion of coarse CCA generally increased the 24 hour sorption coefficient of concrete for all binder types tested. This is most likely due to the increased water absorption of the coarse CCA itself. The magnitude of difference in the results of CEM I and CEM III/A concretes has shown that up to 100% coarse CCA, irrespective of the sources in this study, can be incorporated into structural CEM III/A concrete and have a better durability performance than that of control CEM I concrete. Further results in relation to water ingress and concrete microstructure are presented and discussed in Dodds *et al*, 2017a.

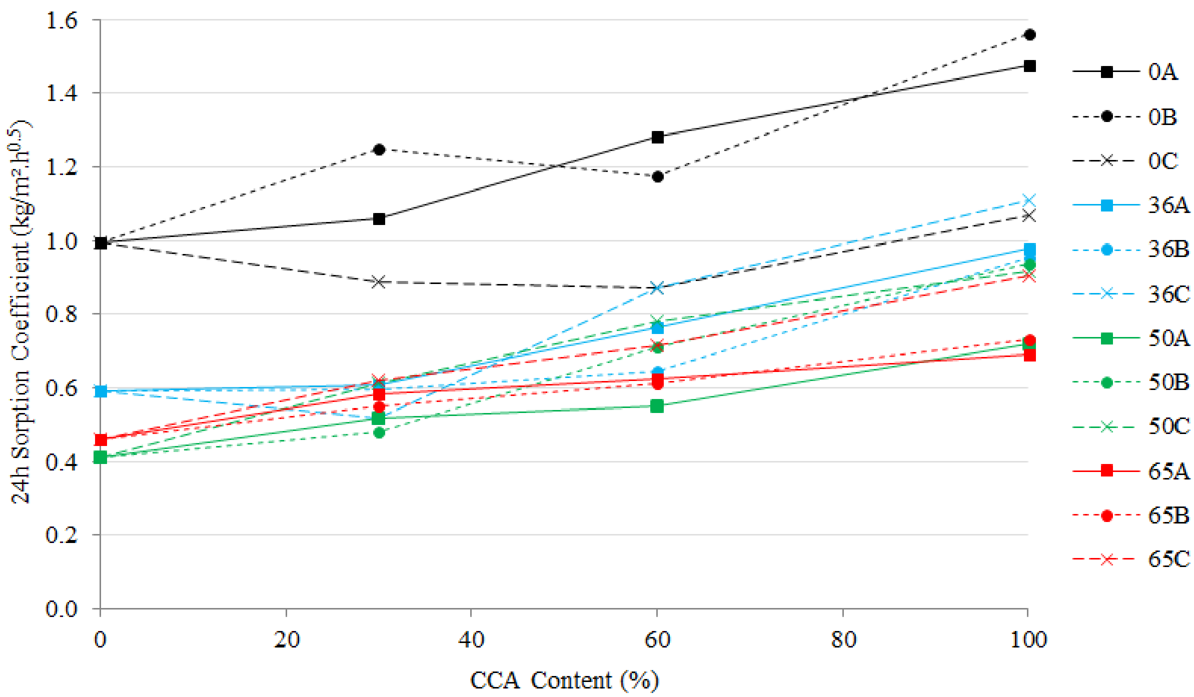

Fig. 2 24 Water sorption coefficient at 91 days

The rapid chloride migration and accelerated corrosion tests showed that low quantities of coarse CCA (30%) have a detrimental effect on the resistance to chloride ion ingress of the concrete, as shown in Figure 3 and 4. The time to corrosion initiation and cracking in Figure 4 is identified by an increase in the current and termination of the test, represented by points 1 and 2 respectively.

Similar to the results of sorptivity testing, structural CEM III/A concretes produced with up to 100% coarse CCA outperformed the control CEM I concrete produced with 100% natural aggregates, by a factor of 2 to 6 with more than 36% GGBS. This highlights the beneficial latent hydraulic effects of GGBS at increasing the resistance to chloride ion ingress 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. Further results in relation to chloride ion ingress and corrosion initiation are presented and discussed in Dodds *et al*, 2017b.

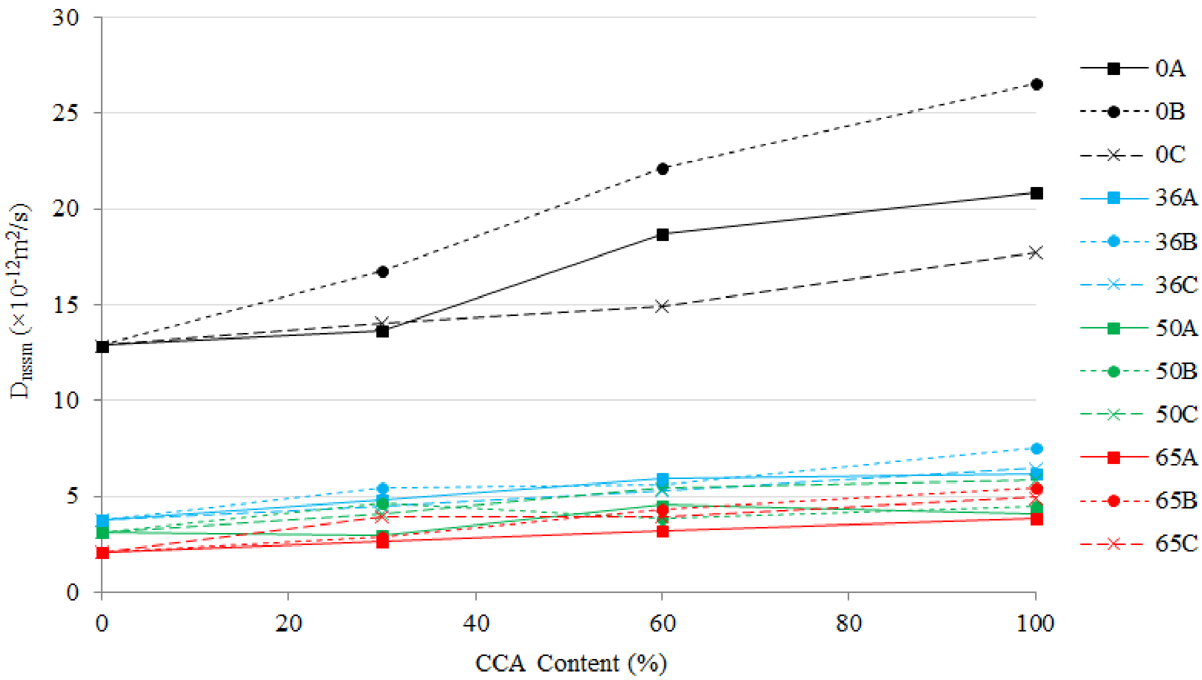

Fig. 3 Rapid chloride migration coefficient at 91 days

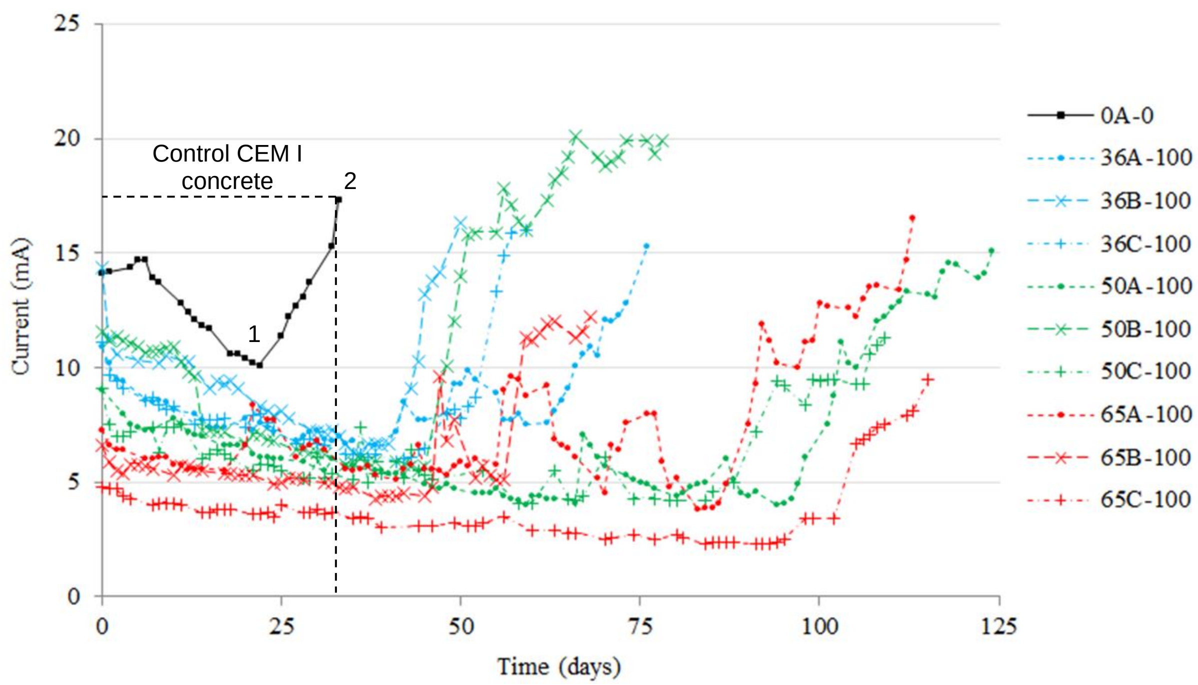

Fig. 4 Time to corrosion initiation and cracking

iv. Conclusions

Following an extensive research programme, the following conclusions can be drawn:

1. The inclusion of coarse CCA, even in low quantities such as 20%, generally had a detrimental effect on the compressive strength and durability (microstructure and water and chloride ion ingress) of structural concrete. This trend was observed in the data from each test method adopted, and for different sources of coarse CCA of known and unknown compositions; this finding was confirmed through statistical analysis of sample means.
2. The detrimental effects caused by coarse CCA can be largely overcome through the use of GGBS (at 50% replacement of Portland cement) to produce CEM III/A concretes, allowing higher proportions of coarse CCA to be incorporated.
3. CEM III/A concretes produced with up to 100% coarse CCA, irrespective of the CCA sources adopted in this study, have been shown to outperform control CEM I concrete with 100% natural aggregates in durability performance tests. If the cover depth of CEM III/A CCA concretes can be increased, similar to that of CEM I concrete, then the risk of potential durability performance issues can be further reduced.
4. The results of water absorption, and chemical and petrographic analysis for sources of coarse CCA with known compositions had a good correlation with durability results. It is therefore recommended that when sources of coarse CCA are to be used, they are tested using these methods to determine the potential water ingress, possible contamination and the original concrete composition.
5. The findings of this study have highlighted that sustainable structural CEM III/A concrete can be a viable option for future responsibly sourced projects, provided that a reliable and consistent source of coarse CCA can be obtained. This is a significant outcome for the wider implementation of coarse CCA into structural concrete applications.
6. The replacement of natural aggregate with coarse CCA should be limited to 30% in CEM III/A concretes (at 50% replacement of Portland cement) in cases where compliance with the 28 day characteristic strength ($f_{c,cube}$) is of particular importance. If the criterion for compliance at 28 days can be relaxed and the compressive cube strength of CEM III/A concretes tested at later ages for conformity (56 or 90 days), then higher quantities of coarse CCA may be incorporated up to 60% to produce a more sustainable structural concrete. Further details of the effect of coarse CCA on the compressive cube strength is presented in Dodds *et al*, 2017a.

v. Impact on the Wider Industry

1. The recommendation of coarse CCA characterisation, in the form of water absorption testing and chemical and petrographic analysis, highlights the potential benefits of segregating good quality reinforced concrete sources on demolition sites to better predict potential impacts on durability performance. The additional testing of segregated demolition arisings may result in a higher initial cost to the project; this however would be low compared with demolition and construction costs and provides huge potential benefits in terms of improving sustainability.
2. The UK and other well developed nations already have positive recycling rates; however there is strong evidence to suggest that higher quantities of coarse CCA will be available in future years. It is therefore in the best interest for all parties involved to utilise these materials in a wider variety of applications nearer to the demolition site if they are found to be suitable.

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