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Durability Performance of Coarse Crushed Concrete Aggregate Structural Concrete

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DURABILITY PERFORMANCE OF COARSE CRUSHED CONCRETE AGGREGATE STRUCTURAL CONCRETE

By
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A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

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I would like to express my gratefulness to my academic and industrial supervisors; Dr Chris Goodier, Professor Simon Austin, Dr Christian Christodoulou and Dr David Dunne for their expertise, knowledge, guidance, support and understanding. Without their valued input, this research would not have been possible. I would also like to thank the laboratory staff; Mark Harrod, Neil Parkes, Lewis Darwin, Jonathan Hales and Paul Reeves for their assistance in the laboratory.

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ABSTRACT

Crushed or recycled concrete aggregates (CCA/RCA) is an increasingly popular material as a replacement for natural aggregates in concrete due to industry demands for more recycled, lower carbon and responsibly sourced materials. In the UK, the majority of CCA is utilised in non-structural applications such as: a general fill material, road base/subbase or in low-grade concrete. Recycled aggregate producers however, are seeking new ways to incorporate CCA into higher value applications such as structural concrete to increase profits. Opportunities to incorporate CCA into structural concrete may also arise because of project demands for sustainability or in situations where natural aggregates are in short supply.

Limited research has been published regarding the effect of coarse CCA on the durability of structural concrete, particularly in respect to water and chloride ion ingress and possibility of corrosion initiation. The aim of this EngD research programme was to investigate the effect of coarse CCA and supplementary cementitious materials (SCMs) on the durability performance of structural concrete, with particular emphasis on the key liquid transport mechanisms within concrete, namely absorption by capillary action, diffusion and migration. This addressed an industry concern regarding the detrimental effect of coarse CCA which has resulted in a limit on replacement levels of coarse natural aggregates in structural concrete, as defined in Eurocodes and local national standards for concrete.

In this study, structural concrete was produced with varying levels of coarse CCA replacement (up to 100%), from five different sources and/or structural elements across the UK, with various combinations of SCMs to replace in part the Portland cement. Petrographic analysis was used as an innovative technique to characterise the coarse CCA sources to determine suitability which yielded positive results. The durability performance of the resultant concrete was analysed by exposing the concrete to aggressive chloride environments.

The results indicate that the inclusion of coarse CCA, even as low as 20%, had a detrimental effect on the durability performance of structural concrete, in relation to absorption by capillary action, diffusion and migration. This effect however, can be offset through the use of SCMs, which have been shown to outperform control Portland cement concrete with 100% natural aggregates in durability performance tests. The results also suggest that cementitious materials had a greater influence on durability performance than the type and source of coarse aggregates used.

It is recommended that the replacement of natural aggregate with coarse CCA be limited to 30% in cases where compliance with the 28 day characteristic strength is of particular importance. If the criterion for compliance at 28 days can be relaxed and the compressive cube strength of concretes with SCMs 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. It is recommended that Portland cement is partially replaced with 50% ground granulated blast-furnace slag (GGBS) to produce a CEM III/A concrete.

This is a significant step towards the potential wider implementation of coarse CCA in structural concrete, provided a suitable quantity of SCM is adopted along with a reliable and consistent source of coarse CCA.

KEY WORDS

Crushed concrete aggregates, recycled concrete aggregates, durability, chloride ion ingress, corrosion initiation

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PREFACE

This thesis presents the research undertaken between October 2013 and August 2017 for the award of the degree Doctor of Engineering (EngD) at Loughborough University.

The research was funded by the Engineering and Physical Sciences Research Council (EPSRC) through the Centre for Innovative and Collaborative Construction Engineering (CICE) at Loughborough University and AECOM Ltd.

This thesis discusses the results of laboratory experimental research undertaken regarding the incorporation of coarse crushed concrete aggregate (CCA – formerly referred to as recycled concrete aggregate (RCA)) to replace natural coarse aggregate in structural concretes with various supplementary cementitious materials (SCMs), and their consequent effect on durability performance. The published peer-reviewed papers, produced in partial fulfilment of the award requirements of the Engineering Doctorate, are included in Appendices B to F.

The thesis has the following five main sections, as required by Loughborough University regulations:

1. Background to the research – Introduces the general subject domain of coarse CCA, its suitability for structural concrete applications, and the potential effects on durability. It also provides details of the industrial sponsor, AECOM, and their general interest and motives regarding the research programme.
2. Aim and objectives – Sets out the individual objectives for the research programme and how they contribute to the aim.
3. Methodology – Describes the consideration of various approaches to effectively complete the research and details the chosen methodology to complete each of the individual objectives.

4. The research undertaken – Provides a detailed discussion of the research undertaken and the publications which have resulted from the research programme.
5. Findings and implications – Details the key findings from the research, and discusses the contribution to the existing international knowledge base and the potential impact on the industrial sponsor and the wider industry. This section also discusses the recommendations for further research and highlights possible limitations of the research.

ACRONYMS/ABBREVIATIONS

AECOM	Architecture, Engineering, Construction, Operations and Maintenance
BA	Bridge Advice (Note)
BRMCA	British Ready-Mixed Concrete Association
BS	British Standard
BS EN	British Standard European Norm (European Standard)
BRE	Building Research Establishment
BSI	British Standards Institution
CCA	Crushed Concrete Aggregate
CDW	Construction and Demolition Waste
CICE	Centre for Innovative and Collaborative Construction Engineering
CIRIA	Construction Industry Research and Information Association
CPD	Continuing Professional Development
DEFRA	Department for Environment, Food and Rural Affairs
DMRB	Design Manual for Roads and Bridges
EC	European Commission
EngD	Doctor of Engineering
ENR	Engineering News-Record
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
$f_{c,cube}$	Characteristic Cube Strength
FHA	Federal Highway Administration
GB	Great Britain
GGBS	Ground Granulated Blast-Furnace Slag
ICE	Institution of Civil Engineers
ITZ	Interfacial Transition Zone
JIF	Journal Impact Factor
HMRC	HM Revenue and Customs
MCHW	Manual of Contract Documents for Highway Works
MPA	Mineral Products Association
MPa	Megapascal

NACE	National Association of Corrosion Engineers
NAO	National Audit Office
NFDC	National Federation of Demolition Contractors
NRMCA	National Ready-Mixed Concrete Association
PED	Parliamentary Estates Directorate
PhD	Doctor of Philosophy
PFA	Pulverised Fuel Ash
RA	Recycled Aggregate
RCA	Recycled Concrete Aggregate
RE	Research Engineer
SABCE	School of Architecture, Building and Civil Engineering
SCMs	Supplementary Cementitious Materials
SEM	Scanning Electron Microscopy
SHW	Specification for Highway Works
SJR	SCImago Journal Rank
TfL	Transport for London
UK	United Kingdom
URS	United Research Services
USA	United States of America
WRAP	Waste & Resources Action Programme

CONTENTS

FIGURES

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PAPERS

The following papers, included in appendices B to F, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research. The papers are listed in order of discussion throughout the EngD thesis.

PAPER 1 (SEE APPENDIX B)

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D. Fitt, M. Snowden, P, 2016. *Durability performance of structural concrete made with coarse recycled concrete aggregates*. IN: Beushausen, H. (ed.). Performance-based approaches for concrete structures: Proceedings (fib Symposium 2016), Cape Town, South Africa, 21-23rd November 2016. ISBN: 978-2-88394-120-5. https://dspace.lboro.ac.uk/2134/23683.

PAPER 2 (SEE APPENDIX C)

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D, 2017. *Corrosion risk assessment of structural concrete with coarse crushed concrete aggregate*. Proceedings of the Institution of Civil Engineers - Construction Materials. Ahead of print, DOI: https://doi.org/10.1680/jcoma.17.00056.

PAPER 3 (SEE APPENDIX D)

Dodds, W. Goodier, C. Austin, S. Christodoulou, C. Dunne, D. Wingrove, E, 2017. *The effect of coarse crushed concrete aggregate on the durability of structural concrete*. IN: Pecur, I.B. Baricevic, A. Stirmer, N. Bjegovic, D. (ed.). 1st International conference on construction materials for sustainable future: Book of abstracts (CoMS 2017), Zadar, Croatia, 19-21st April 2017. ISBN: 978-953-8168-04-8. https://dspace.lboro.ac.uk/2134/24326.

PAPER 4 (SEE APPENDIX E)

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D, 2017. *Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on microstructure and water ingress*. Construction and Building Materials, Volume 145, pp183-195. DOI: 10.1016/j.conbuildmat.2017.03.232. ISSN: 0950-0618. https://dspace.lboro.ac.uk/2134/24801.

PAPER 5 (SEE APPENDIX F)

Dodds, W. Christodoulou, C. Goodier, C. Austin, S. Dunne, D, 2017. *Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on rapid chloride migration and accelerated corrosion*. Construction and Building Materials, Volume 155, pp511-521. DOI: 10.1016/j.conbuildmat.2017.08.073. ISSN: 0950-0618. https://dspace.lboro.ac.uk/2134/26920.

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1 BACKGROUND TO THE RESEARCH

This section introduces the general subject domain of coarse CCA, its suitability for structural concrete applications, and its effect on durability. It also provides details of the industrial sponsor, AECOM, and their general interest and motives regarding the research programme.

1.1 THE GENERAL SUBJECT DOMAIN

Recycled aggregate (RA) has become a popular alternative to replace natural or virgin aggregates in the construction industry since the 1980's. RA now accounts for 25% of the total aggregates market in the UK and its market share has doubled in the last 15 years (WRAP, 2015a). RAs include concrete, concrete and clay masonry units, mortar, natural stone, bituminous materials, glass and deleterious materials such as; paper, wood, metals and plastics. It is also referred to as construction and demolition waste (CDW). The large increase in popularity can be attributed to an increased interest towards a more sustainable way of resourcing materials, and government strategies such as increased aggregate levy and landfill tax (HMRC, 2015; WRAP, 2015b; DEFRA, 2016; HMRC, 2016).

In the UK, the majority of 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 enable utilisation in higher value applications to increase profits (Barritt, 2015). The Waste and Resources Action Programme (WRAP) report '*Quality Protocol for Aggregates from Inert Waste'* highlights the quality controls required to comply with the standard and specification of RA in new concrete; in accordance with BS EN 12620, BS 8500 and the Specification for Highway Works (SHW) for concrete road pavements (BSI, 2013a; Environment Agency and WRAP, 2013; BSI, 2015a,b; MCHW, 2016).

The European standard for structural concrete, BS EN 206-1, states that crushed concrete aggregate (CCA – formerly referred to as recycled concrete aggregate (RCA)) may only be utilised, up to a maximum of 30% replacement of natural aggregates (BSI, 2013b). CCA is a higher classification of RA and must consist of >90% concrete product and have much smaller quantities of other constituents and possible contaminants for quality control purposes (BSI, 2015b).

Reinforced concrete is the most common construction material worldwide due to its favourable composite structural properties, as well as its performance benefits in strength, durability, fire resistance and thermal mass (MPA, 2015). The specification of ready-mixed and precast concrete is also increasing, with approximately 16 and 38 million tonnes produced annually in the UK respectively (British Precast, 2016; BRMCA, 2016). With the increasing specification of concrete worldwide there is an obvious growing pressure on quarrying to meet the demand for natural aggregates. The increasing quantity of CDW produced each year provides an opportunity for CCA to be incorporated into a wider variety of applications including structural concrete (NFDC, 2016). Further research into the effects of CCA is particularly beneficial for countries to help improve sustainability, reduce import costs and maintain aggregate demand for large construction projects (Filho *et al*, 2013; Hassan *et al*, 2016; Yehualaw and Woldesenbet, 2016; McGinnis *et al*, 2017).

There is a wide-spread poor perception of CCA in industry because the effects on mechanical and durability performance are not well understood. Most research has focused on the effect of CCA on its mechanical properties such as: compressive and tensile strength, modulus of elasticity and creep, with a general consensus that there is an increasingly detrimental effect with a higher replacement level 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 related properties however, is less well established, particularly in relation to water and chloride ion ingress and the risk of corrosion initiation, which are the causes of the vast majority of 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 hence protect our limited natural resources.

Chloride ion ingress of reinforced concrete usually occurs through exposure to marine environments or when de-icing salts are applied to highway structures during routine winter maintenance. This can ultimately contribute 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 $8.29 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 for the maintenance of highways infrastructure which usually occurs throughout the winter months, November to March (NAO, 2014).

The aim of this doctoral research was to investigate the effect of coarse CCA and supplementary cementitious materials (SCMs) on the durability performance of structural concrete, with particular emphasis on the key liquid transport mechanisms of concrete, namely resistance to water and chloride ion ingress and the risk of corrosion initiation. The aim was achieved through a review of the existing literature in relation to the general subject domain, an identification of current practices in industry related to the use of CCA, an extensive experimental programme to obtain empirical data and providing scientific evidence of its effect on the durability performance and suitability in new structural concrete. The subsequent benefits sought for the industrial sponsor and wider industry was a more robust framework for the specification of CCA in new structural concrete, a deeper understanding of the effects on durability, and an identification of the common concerns and barriers to the wider implementation of CCA in higher value structural applications. This study built upon the existing international knowledge base in this field and employed a variety of laboratory test methods to verify the expected outcomes and hypotheses.

1.2 THE INDUSTRIAL SPONSOR

AECOM Ltd was the industrial sponsor for this research. The company was established in 1990 from an engineering and technology firm, Ashland Technology, who primarily were involved with oil & refinery works in Kentucky, USA. Over the past 27 years AECOM has grown considerably and during this time has acquired a number of engineering, design and planning firms to become the multinational engineering firm it is known as today. In 2014 AECOM combined with the URS Corporation, a move which doubled its revenue and workforce to strengthen its position as the world's #1 engineering design firm (ENR, 2017). As a Fortune 500 company, it now operates in over 150 countries with around 95,000 employees worldwide. The company acts as a multi-disciplinary consultant and operates in a number of market sectors to provide professional and technical services to both public and private clients.

The Bridges and Structures team in Birmingham, UK is part of AECOM's Transportation sector and has been involved in the design, repair, refurbishment and rehabilitation of a large number of structures. The company has a reputation for providing innovative solutions and developing new technologies for the industry, and also has an established relationship with Loughborough University's School of Architecture, Building and Civil Engineering (SABCE). With a keen interest in development, and an overall increased pressure on the construction industry from Government, AECOM is always seeking to improve sustainability on new construction projects by responsibly sourcing materials. This has led to the investment in the research of recycled materials, and their use in higher value structural applications. The intended benefits of this research to AECOM and the wider industry are:

- An improved approach to the specification of coarse CCA from demolition arisings in new structural concrete.
- A deeper understanding of the effect of coarse CCA on the durability performance of structural concrete, with particular emphasis on water and chloride ion ingress and the risk of corrosion initiation.
- An understanding of the common concerns and barriers of the wider implementation of coarse CCA in higher value applications in both the demolition and construction industry.
- Commercial competitiveness in relation to the responsible sourcing of materials.
- Maintaining strong relations with Loughborough University and the academic community, providing network opportunities with academics, research groups, societies, professional bodies and institutions.

AECOM, as a key delivery partner for a number of large asset management frameworks in the UK, also provided work placements for the author (a Research Engineer (RE)) throughout the EngD programme. These experiences broadened the understanding of the durability of reinforced concrete structures, and the principles and practices adopted on site and during the design phase when assessing the risk of corrosion and deterioration. The placements focused on principal inspections, intrusive investigations, non-destructive testing works and the subsequent repair and corrosion management strategies of reinforced concrete structures for major asset owners such as: Transport for London (TfL), Network Rail, Glasgow City Council, the Parliamentary Estates Directorate (PED), Federal Highway Administration

(FHA) and Birmingham Airport Ltd. In addition to the published papers of this research, the work experience has led to a journal paper in the Institution of Civil Engineers (ICE) - Construction Materials, a subsequent journal discussion paper, and a conference paper on the performance of galvanic and hybrid electrochemical treatments in reinforced concrete (Dodds *et al*, 2014, Dodds *et al*, 2016a; Dodds *et al*, 2017a), as detailed in Appendix A.

1.3 THE CONTEXT OF THE RESEARCH

This literature review provides an insight to the context of the proposed research, confirms the requirement for further research, and helped to refine the aim and objectives. It focuses on the existing approaches to utilising CCA in the construction industry, the specification guidelines within European and national standards, the effects on mechanical and durability properties, the influence of SCMs and key liquid transport mechanisms within concrete; it does this with specific emphasis on water and chloride ion ingress and corrosion initiation.

1.3.1 AVAILABILITY AND USE OF CCA

As discussed in section 1.1, RA has become a popular alternative to replace natural aggregates since the early 1980's (Figure 1.1). This increase is mainly attributed to an industry-wide push towards a more sustainable way of resourcing materials and government incentive strategies such as increased landfill tax and aggregate levy (HMRC, 2015; WRAP, 2015a,b; DEFRA, 2016; HMRC, 2016). 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 can also be referred to as CDW.

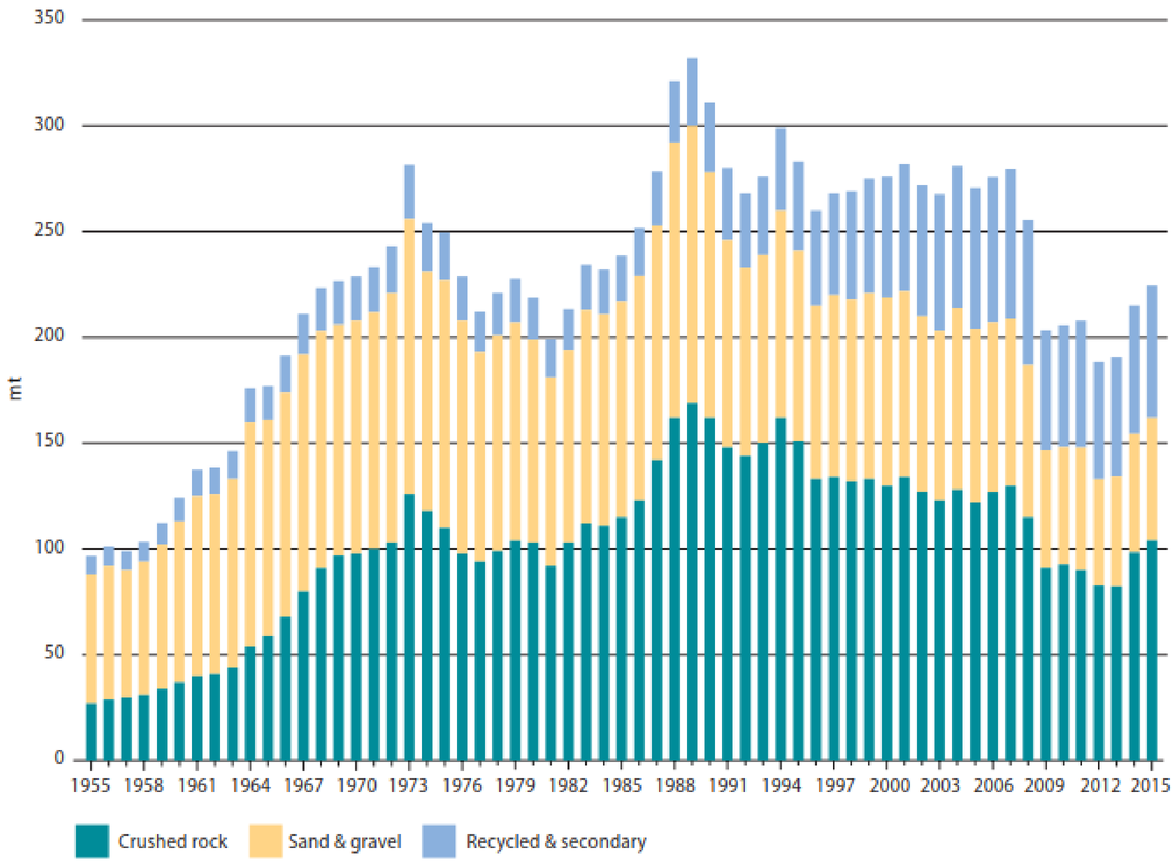

Figure 1.1 Great British (GB) aggregates market by sources of supply (MPA, 2016)

Figures 1.2 and 1.3 show the quantities of CDW produced and the percentage of reported recycling rates respectively for the 27 European Union (EU) member states (Monier *et al*, 2011).

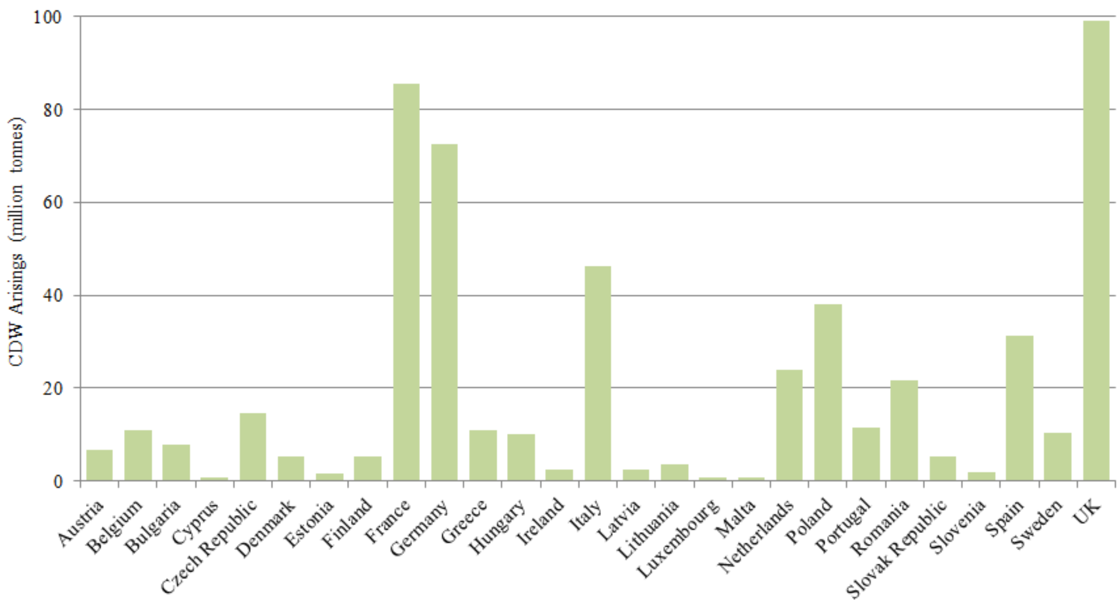

Figure 1.2 CDW Arisings (million tonnes) of 27 EU member states (Monier *et al*, 2011)

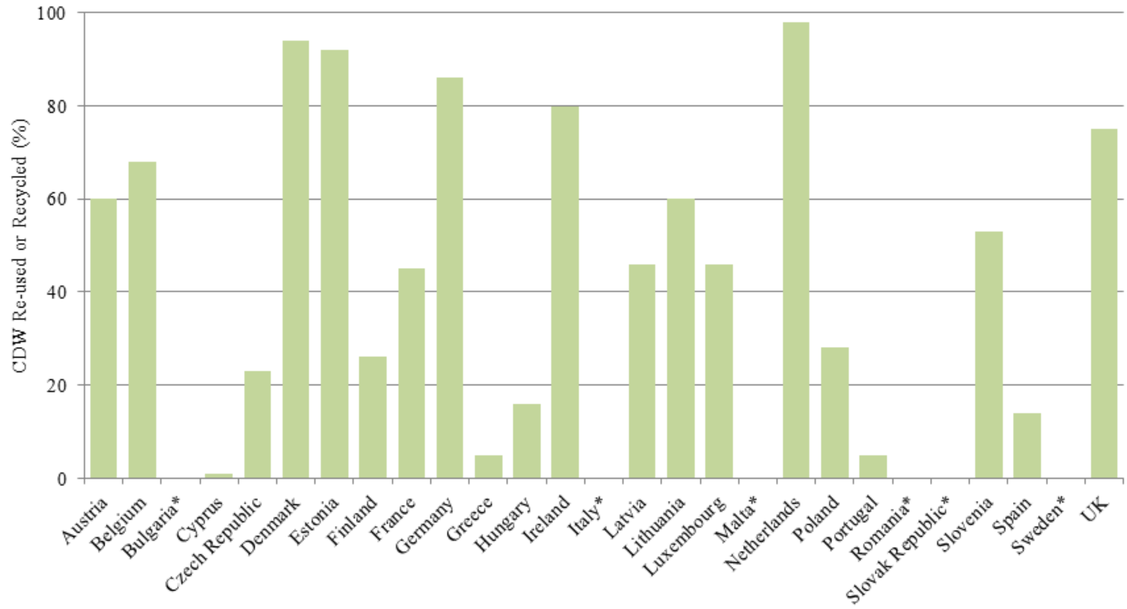

Figure 1.3 CDW Re-used or recycled (%) of 27 EU member states (Monier *et al*, 2011)
***Data unavailable – worst case assumed (0%)**

The UK reported that it has already achieved the EU's target for a CDW recycling rate of 70% by the year 2020, alongside Denmark, Estonia, Germany, Ireland and the Netherlands (EC, 2008; Monier *et al*, 2011). Although this is a positive indicator of an improved approach to sustainable construction and the responsible sourcing of materials across Europe, there still exists a large quantity of CDW to be utilised in a variety of applications, with concrete and masonry in particular being the main constituent (Table 1.1).

Table 1.1 Composition of CDW of 27 EU member states (Monier *et al*, 2011)

Constituents	% (min)	% (max)	Million tonnes (min)	Million tonnes (max)
Concrete and Masonry – total	40	84	184	387
Concrete	12	40	55	184
Masonry	8	54	37	249
Asphalt	4	26	18	120
Other mineral waste	2	9	9	41
Wood	2	4	9	18
Metal	0.2	4	1	18
Gypsum	0.2	0.4	1	2
Plastics	0.1	2	0	9
Miscellaneous	2	36	9	166

Data obtained from a survey, undertaken annually by the UK National Federation of Demolition Contractors (NFDC) has shown that the quantities produced are increasing year on year (Figure 1.4). The consequence of CDW is increased waste to landfill, which is not desirable, especially for the UK. These figures represent concrete, masonry and stone arisings only (defined as hardcore materials) and do not include asphalt, timber, metals, plastics, glass and hazardous materials. This data highlights that the majority of CDW 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. Georgopoulos and Minson (2014) demonstrated that the sustainability benefits of using CCA is soon diminished when the material has to be transported long distances, therefore utilisation in applications closer to the source are preferred.

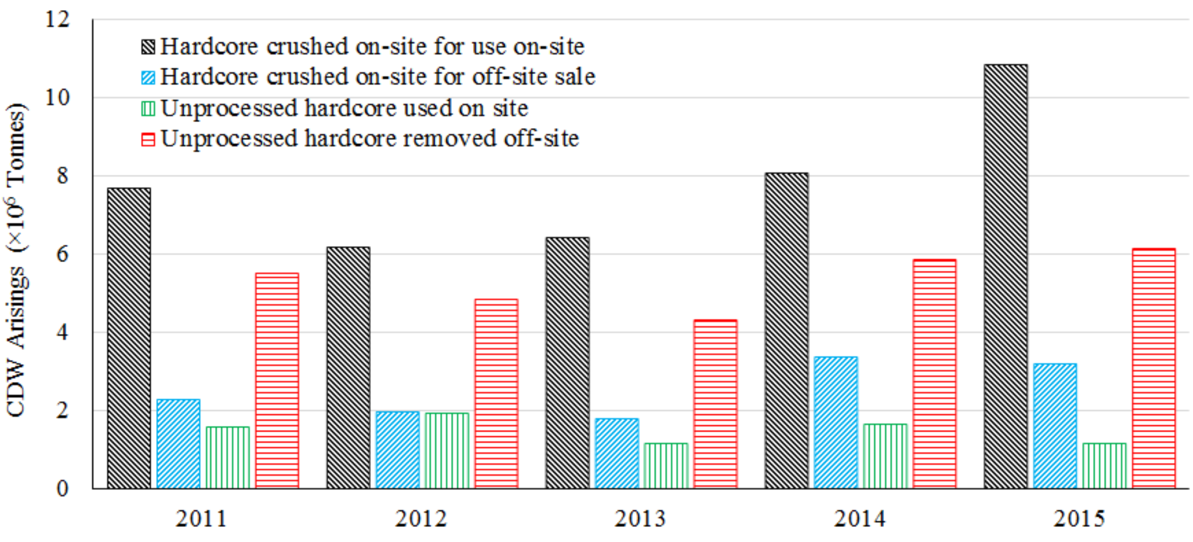

Figure 1.4 CDW arisings in the UK 2011-2015 (NFDC, 2016)

Situations may also arise where CCA may be a suitable replacement material in structural concrete, such as: a specific project/client requirement; improved project sustainability credentials; a good quality, consistent source of CCA is available on-site; and/or where there is a short supply of natural aggregates (Filho *et al*, 2013; Hassan *et al*, 2016; Yehualaw and Woldesenbet, 2016; McGinnis *et al*, 2017).

With a large quantity of concrete CDW becoming available, and an industry shift towards incorporating CCA into a wider variety of higher value applications, this study will focus on research into the effects of CCA on structural concrete, rather than different types of RA.

The WRAP report '*Quality Protocol for Aggregates from Inert Waste*' highlights the quality controls required to comply with the European standard for aggregates and specification of CCA in new concrete (BSI, 2013a; Environment Agency and WRAP, 2013). The British standards for concrete specification define CCA as consisting of >90% concrete product for quality control purposes, and therefore this is usually segregated from other CDW materials (BSI, 2015a,b).

Both coarse and fine CCA can be incorporated into structural concrete applications; however there is debate over the acceptable replacement quantity without affecting performance. The National Ready-Mixed Concrete Association (NRMCA) in the USA accepts that 10% inclusion is suitable for most concrete applications, whereas some countries in Europe allow up to 20%, such as the UK and the Netherlands (Monier *et al*, 2011). European standards for concrete specification allow up to 30% replacement in certain environmental situations (BSI, 2013b). The lack of research and uncertainty of acceptable replacement levels highlights that further research is required in this subject domain to broaden the understanding of the effects of CCA on the performance of structural concrete.

It is acknowledged by the RE that research into the effects of both fine and coarse CCA would be beneficial to the industry. Coarse aggregates, however, account for approximately 65% of total aggregate content and 50% of all structural concrete (Neville, 2011); therefore only coarse CCA was prioritised and investigated in this research programme and is the chosen topic of this thesis.

1.3.2 SPECIFICATION IN EUROPEAN AND NATIONAL STANDARDS

The specification of ready-mixed and precast concrete is increasing, with approximately 16 and 38 million tonnes produced annually in the UK respectively (British Precast, 2016; BRMCA, 2016). With the increasing specification of concrete worldwide there is a growing pressure on quarrying and extraction (gravels) to meet the demand for natural aggregates. This presents an opportunity to incorporate a higher quantity of coarse CCA as a replacement material if a good quality, consistent source can be obtained locally.

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, 2013b). 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, 2013a) then the replacement allowance for the majority of exposure classes, including chlorides, reduces to 0% (Table 1.2). The exposure classes in Table 1.2 relate to the expected ambient environmental conditions during the service life of a structure detailed in Table 1.3.

Table 1.2 Maximum percentage of replacement of natural coarse aggregates (% by mass) (BSI, 2013b)

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (R_{c90}, R_{cu95}, R_{b10-}, R_{a1-}, FL_{2-}, XR_{g1-})	50%	30%	30%	0%
Type B[b]: (R_{c50}, R_{cu70}, R_{b30-}, R_{a5-}, FL_{2-}, XR_{g2-})	50%	20%	0%	0%

[a] Type A recycled 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%.
[b] Type B recycled aggregates should not be used in concrete with compressive strength classes >C30/37.
R_c - Concrete, concrete products and masonry; R_u - Unbound aggregate and natural stone; R_b - Clay masonry units (i.e. bricks and tiles) and aerated concrete; R_a - Bituminous material; FL - Floating material; X - Other: Cohesive, metals, wood, plastic, gypsum; R_g - Glass.

Within Europe, some ambiguities still exist in the classification of coarse RA where values and ranges for type A and B aggregate properties are yet to be determined due to lack of research and knowledge (Table 1.4). Therefore some assumptions have to be made regarding the acceptable limits for the fines content, water absorption and acid-soluble chloride ion content.

Table 1.3 Exposure classes and relevant transport mechanisms (BSI, 2013b)

Class designation	Description of the environment
No risk of corrosion or attack	
X0	For concrete with no reinforcement or embedded metal present; For reinforced concrete that is very dry
Corrosion induced by carbonation	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity
XC4	Cyclic wet and dry
Corrosion induced by chlorides other than from sea water	
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
Corrosion induced by chloride from sea water	
XS1	Airborne salts
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
Freeze/thaw attack with or without de-icing agents	
XF1	Moderate water saturation, without de-icing agent
XF2	Moderate water saturation, with de-icing agent
XF3	Higher water saturation, without de-icing agent
XF4	Higher water saturation, with de-icing agent or seawater
Chemical attack	
XA1	Slightly aggressive chemical environment
XA2	Moderately aggressive chemical environment
XA3	Highly aggressive chemical environment

Table 1.4 Recommendations for coarse RA in European standards (BSI, 2013b)

Property [a]	Clause in EN 12620 (BSI, 2013a)	Type	Category according to EN 12620 (BSI, 2013a)
Fines content	4.6	A + B	Category or value to be declared
Flakiness index	4.4	A + B	$\leq FI_{50}$ or $\leq SI_{55}$
Resistance to fragmentation	5.2	A + B	$\leq LA_{50}$ or $\leq SZ_{32}$
Oven dried particle density ρ_{rd}	5.5	A	≥ 2100kg/m³
		B	≥ 1700kg/m³
Water absorption	5.5	A + B	Value to be declared
Constituents [b]	5.8	A	R_{c90}, R_{cu95}, R_{b10-}, R_{a1-}, FL_{2-}, XR_{g1-}
		B	R_{c50}, R_{cu70}, R_{b30-}, R_{a5-}, FL_{2-}, XR_{g2-}
Water soluble sulfate content	6.3.3	A + B	$SS_{0.2}$
Acid-soluble chloride ion content	6.2	A + B	Value to be declared
Influence on the initial setting time	6.4.1	A + B	$\leq A_{40}$

[a] Category NR (no requirements) applies for all other properties not stated in this table for which a category NR can be declared according to EN12620.
[b] For special applications requiring high quality surface finish the constituent *FL* should be limited to category $FL_{0.2-}$.

Standards also exist at the national level which is more specific to the expected environmental and exposure conditions for that particular region. The UK standard for the specification of concrete allows up to 20% coarse CCA by mass, in concrete up to strength class C40/50, except when the structure is likely to be exposed to chlorides (BSI, 2015a,b). The 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.

The requirements for coarse CCA in the UK standard for concrete specification are described in Table 1.5. There are small differences in the criteria for type A aggregates between the European and UK standards, including: a reduced acceptable level of unbound aggregate, natural stone, hydraulically bound aggregate (5% maximum); an increased acceptable content of bituminous materials (1% to 5%); and a specified maximum fines content of 4% by mass.

Table 1.5 Requirements for coarse CCA in UK standards (BSI, 2015b)

Properties	BS EN 12620 size or category (BSI, 2013a)	Description of category
Aggregate size	$d \geq 4$mm, $D \geq 10$mm	-
Maximum fines	f_4	≤ 4% by mass of particles passing the 0.063mm sieve
Maximum acid-soluble sulfate (SO_3)	$AS_{0.8}$	≤ 0.8% by mass acid-soluble sulfate
Content of: concrete, concrete products, mortar, concrete masonry units	Rc_{90}	≥ 90% mass
Content of: concrete, concrete products, mortar, concrete masonry units, unbound aggregate, natural stone, hydraulically bound aggregate	Rcu_{90}	≥ 90% mass
Content of: clay masonry units (i.e. bricks and tiles), calcium silicate masonry units, aerated non-floating concrete	Rb_{10-}	≤ 10% by mass
Content of bituminous materials	Ra_{5-}	≤ 5% by mass
Content of other materials: Cohesive (i.e. clay and soil) Miscellaneous metals, ferrous and non-ferrous Non floating wood, plastic and rubber Gypsum plaster and glass	XRg_{1-}	≤ 1% by mass
Floating materials by volume	FL_{2-}	≤ 2cm³/kg

The UK specification for highway works (SHW), covering both concrete road pavements and structural concrete for highways structures, states that all aggregates must conform to BS EN 12620 and BS 8500-2 (BSI, 2013a; MCHW, 2014; BSI, 2015b; MCHW, 2016). Additionally, for reinforced concrete highway structures CCA can only be incorporated if it is accepted by the overseeing organisation through a departure from the standard process. This suggests that the current default practice is usually 0% replacement of natural aggregates (MCHW, 2014). Alternatively, for concrete pavements a limiting quantity is not prescribed, but a maximum allowable quantity should be determined from trial mixes. This is caveated with a requirement that only CCA from appropriate identified structures of known history should be adopted (MCHW, 2016). The UK's Bridge Advice (BA) note 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. This standard may require some updating to reflect the new findings and developments in research similar to the SHW (DMRB, 2007).

In addition to the UK and European standards, Construction Industry Research and Information Association (CIRIA) and WRAP have provided advice to the government, businesses and communities in the re-use and recycling of materials and products, and over the past 10 years have published best practice guidance to support the construction industry in reducing waste and improving resource efficiency (WRAP, 2006; WRAP, 2007; WRAP, 2008; WRAP, 2009; WRAP, 2015a,b). Their research has mainly focused on overcoming barriers and common concerns within industry for the wider implementation of CCA, and has attempted to establish some form of classification for the types of RA. This work has ultimately led to the publication of the WRAP report '*Quality Protocol for Aggregates from Inert Waste'* which highlights the quality controls required to comply with the European standard for aggregates and specification of CCA in new concrete (BSI, 2013a; Environment Agency and WRAP, 2013). This guidance can provide clients and designers with some confidence in the recycled materials they choose to adopt on a construction project. More recently, WRAP has encouraged greater collaboration between demolition contractors, consultants, contractors and clients at an early stage in the design process of new construction (WRAP, 2015a,b). It is highlighted within this report that clients and designers should make use of the demolition industry expertise and where possible state within tender documents their positive position on the use of CCA and clearly define project recycling targets.

1.3.3 Effect of coarse CCA on the mechanical properties of structural CEM I concretes

It is common practice within industry to design a concrete mix based on a characteristic strength recommended by design standards and include it within the project specification as a quality control measure (BSI, 2013b; BSI, 2015a,b). This approach to design often leads to a strong focus on concrete achieving the designed characteristic strength at 28 days, as non-compliance will cause complications, cost increases or disputes. This may be the root cause of the generally poor perception of CCA in industry regarding its inclusion in structural concrete, as there is considerable concern regarding its effect on compressive strength. In some cases it is even recommended to reduce the water/cement ratio and increase the cement content to ensure the 28 day characteristic strength is achieved (Padmini *et al*, 2009).

Nevertheless, the majority of design codes (inlcuding Eurocode 2) allow coarse CCA under certain conditions. Their properties can be accounted for in the existing concrete mix proportioning charts, which enables a prediction of the effects on compressive strength and other performance aspects (Collery *et al*, 2015). Additionally, the current codes can be used to design CCA structural elements. This, however, generally leads to an increase in the nominal cover and depth of reinforced concrete sections, to have a service-life, load bearing capacity and maximum deflection comparable to natural aggregate concrete (Silva *et al*, 2016), which somewhat negates the sustainability benefits of CCA.

A review of the literature on the effect of CCA on the mechanical performance of structural concrete has shown that the subject domain has generally been well investigated (Table 1.6). Suitable replacement levels are often not proposed in the research, although there is a general agreement that even low quantities (30%) can cause a detrimental effect on the mechanical properties of structural CEM I concretes (100% Portland cement), including: compressive and tensile strength; modulus of elasticity; and creep. This effect is also dependent on the original source, quality and consistency of recycled concrete. In contrast to this, two studies have shown that up to 100% coarse CCA may be incorporated without compromising the mechanical performance of structural concrete, if the original source is of good quality and high strength (>50MPa) (Tabsh and Abdelfatah, 2009; Kou and Poon, 2015).

Table 1.6 Summary of the effect of coarse CCA on mechanical properties of CEM I structural concrete

Author(s)	Test methods	Coarse CCA replacement levels	Conclusion(s)
Limbachiya *et al*, 2000	Compressive and flexural strength, modulus of elasticity, drying shrinkage, creep	30%, 50%, 100%	Up to 30% coarse CCA had no effect on the compressive cube strength. The mechanical properties of high strength CCA concrete were found to be satisfactory.
Limbachiya, 2004	Compressive and flexural strength, modulus of elasticity, drying shrinkage	20%, 30%, 50%, 100%	Up to 20% coarse CCA had no effect on the compressive cube strength. The CCA concrete had similar mechanical properties provided it is designed based on equal strength.
Etxeberria *et al*, 2007	Compressive and tensile strength, modulus of elasticity	25%, 50%, 100%	100% coarse CCA concrete has 20-25% lower compressive strength and therefore needs higher cement contents. The tensile strength can be higher. The modulus of elasticity is lower than that of conventional concrete.
Kwan *et al*, 2012	Compressive strength, drying shrinkage	15%, 30%, 60%, 80%	The replacement of up to 80% coarse CCA is still acceptable to achieve the target strength.
Butler *et al*, 2013	Compressive and tensile strength, modulus of elasticity, fracture energy	100%	The CCA concrete should be thoroughly tested rather than simply achieving the compressive strength. Tensile strength increases with aggregate strength.
Dilbas *et al*, 2014	Compressive and tensile strength, modulus of elasticity	30%, 40%, 70%	Coarse CCA in concrete generally caused a reduction in mechanical performance.
Bravo *et al*, 2015a	Compressive and tensile strength, modulus of elasticity, abrasion	10%, 25%, 50%, 100%	In most cases the CCA in concrete caused a reduction in mechanical performance. The abrasion resistance seemed to improve.
Adams *et al*, 2016	Compressive and tensile strength, modulus of elasticity, drying shrinkage	25%, 100%	Adequate mechanical properties can be obtained in mixtures including coarse CCA (up to 100%). CCA does not significantly increase the drying shrinkage of concrete.
Bendimerad *et al*, 2016	Plastic shrinkage, modulus of elasticity, tensile strength	30%, 100%	Coarse CCA had a relatively low influence on plastic shrinkage and was an influencing factor on early age cracking, but not proportional to the coarse CCA content.
Omary *et al*, 2016	Compressive and tensile strength, modulus of elasticity	30%, 100%	The compressive and tensile strength of coarse CCA concrete decreases. The modulus increases with increasing porosity.
Puthussery *et al*, 2017	Compressive and tensile strength	25%, 50%, 100%	The tensile strength decreased with increasing coarse CCA content. The compressive strength was comparable to that of control mixes.

1.3.4 EFFECT OF COARSE CCA ON THE DURABILITY PERFORMANCE OF STRUCTURAL CEM I CONCRETES

The durability of reinforced concrete is primarily influenced by its microstructure - the connectivity, continuity, tortuosity and radius of its pores - as this determines how gases, liquids and other substances penetrate the concrete cover to reinforcement (Kropp *et al*, 1995; Ollivier *et al*, 1995). Water and chloride ions can ingress concrete through a combination of liquid transport mechanisms, namely absorption by capillary action, diffusion and permeation (Tuutti, 1982). These mechanisms are discussed in greater detail in section 1.3.6. Aggregates play an important role in the transport of liquids and ions as the water absorption properties and quality of the interfacial transition zones (ITZ) can accelerate or decrease the ingress of fluids. The specific gravity of aggregates can be a good indicator of this (Ryu and Monteiro, 2002; Neville, 2011). This is a particularly important concept when considering the use of CCA to replace NA in concrete as it has been shown 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 (Kwan *et al*, 2012; Pedro *et al*, 2014; Soares *et al*, 2014; Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015). It is thought that this may be 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).

The effect of coarse CCA on durability is undeniably less well understood compared to mechanical properties, and requires further investigation. The majority of published research, regarding the effect of coarse CCA on concrete durability, has focused primarily on rapid migration and absorption test methods to determine acceptable levels of replacement of natural aggregates.

The general consensus from literature that has tested a range of coarse CCA replacement levels is that 25-30% of coarse CCA can be successfully incorporated into CEM I concrete without significantly affecting the transport properties of concrete (Limbachiya *et al*, 2000; Topçu and Şengel, 2004; Kwan *et al*, 2012; Limbachiya *et al*, 2012; Soares *et al*, 2014; Zega *et al*, 2014; Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015). Larger quantities, up to 75%, have been shown to be successful in structural concrete; however this is dependent on the quality of the original concrete source (Zega *et al*, 2014). It was also noted that higher amounts of coarse CCA also increased the variability of durability performance compared to the control concretes. Limbachiya *et al* (2000) established that a replacement level of up to 100% may not have a significant effect on the durability performance of high strength Portland cement concretes, provided the CCA source was obtained from high quality precast concrete. In contrast to this, other researchers have tested coarse CCA in CEM I concrete at 100% replacement levels of natural aggregates only. In these cases the durability properties were found to be significantly affected, which suggests that lower replacement levels require testing in future research to determine suitable inclusion levels (Ann *et al*, 2008; Debieb *et al*, 2010; Beltran *et al*, 2014; Matias *et al*, 2014; Pedro *et al*, 2014). The cause of the detrimental effect on structural concretes has primarily been attributed to the increased water absorption properties of the coarse CCA. The 24 hour water absorption of coarse CCA has been reported to be between 3.6% and 11.6%, dependent on the original source of concrete, which highlights the potential variability of CCA concretes (Ann *et al*, 2008; Berndt, 2009; Limbachiya *et al*, 2012; Somna *et al*, 2012; Hwang *et al*, 2013; Pedro *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015).

1.3.5 SCMs in Structural CCA Concrete

It is well established that the latent hydraulic and pozzolanic properties of SCMs, such as pulverised fuel ash (PFA) and ground granulated blast-furnace slag (GGBS), can improve the mechanical and durability performance of structural concrete. The addition of SCMs have been shown to reduce the porosity of the cement matrix, improve quality of the ITZ and/or increase the chloride binding capacity of concrete (Dhir *et al*, 1996; Dhir *et al*, 1997; Bertolini *et al*, 2004; Neville, 2011; Bjegovic *et al*, 2012; Andrade and Bujak, 2013; Bapat, 2013; Dyer, 2014; Lollini *et al*, 2016; Scott and Alexander, 2016). This is evident in European and British standards for concrete specification as concretes with SCMs are permitted to have a lower design cover compared to CEM I concrete of the same strength (BSI, 2013b; BSI, 2015a,b). The chloride binding capacity of concrete will be discussed in greater detail in Section 1.3.7.

Research has shown that the use of SCMs can allow higher proportions of coarse CCA to be incorporated in structural concrete before a detrimental effect is observed. Table 1.7 details the reported values of coarse CCA replacements that have been shown to produce concrete of equivalent, or better, durability performance compared to CEM I concrete produced with 100% natural aggregates. The findings of water permeability, water absorption, carbonation resistance, chloride ion resistance, freeze/thaw resistance and sulphate attack are presented, with the binder type, replacement quantities and free water/binder ratio stated for each study.

Table 1.7 drawn from the literature, highlights that the use of SCMs generally allows higher quantities of coarse CCA replacements to be utilised in structural concrete than the limitations imposed by existing European and British standards (BSI, 2013b; BSI, 2015a,b).

Table 1.7 Suitable proportions of coarse CCA in structural concrete produced with SCMs

Deterioration mechanism	SCM (binder type)	Free w/b ratio	Suitable coarse CCA replacement (%)	Author(s)
Water permeability	Fly ash (24%) Fly ash (47, 56%)	0.53 0.53, 0.64	30 100	Lima *et al*, 2013 & Faella *et al*, 2016
	Fly ash (20, 35, 50%) GGBS (20, 35, 50%)	0.65	100	Somna *et al*, 2012
	GGBS (50, 70%)	0.40	0	Berndt, 2009
Water absorption (sorptivity and immersion)	Fly ash (40, 50, 60%)	0.30	0	Saravanakumar and Dhinakaran, 2014
	Fly ash (25, 35%)	0.42-0.55	50	Kou and Poon, 2012
Carbonation (accelerated)	Fly ash (24, 47, 56%)	0.53, 0.64	0	Faella *et al*, 2016
	Fly ash (30%) Fly ash/Metakaolin (20/10%)	0.45	0 25	Singh and Singh, 2016
	Fly ash (25, 35, 55%)	0.55	0	Kou and Poon, 2013
	Fly ash (25, 35%)	0.42-0.55	0	Kou and Poon, 2012
	Fly ash (10%) GGBS (10%) Silica fume (10%)	0.5	0	Xiao *et al*, 2012
Chloride ion ingress (Rapid chloride migration and diffusion)	Fly ash (24, 47%) Fly ash (56%)	0.53 0.64	60 100	Lima *et al*, 2013 & Faella *et al*, 2016
	Fly ash (40%) Fly ash (50, 60%)	0.30	25 50	Saravanakumar and Dhinakaran, 2014
	Fly ash (30%) GGBS (65%)	0.40	0 (28 days) & 100 (56 days)	Hwang *et al*, 2013
	Fly ash (25, 35, 55%)	0.55	100	Kou and Poon, 2013
	Fly ash (25, 35%)	0.42-0.55	100	Kou and Poon, 2012
	Fly ash (20, 35, 50%) GGBS (20, 35, 50%)	0.65	100	Somna *et al*, 2012
	GGBS (50, 70%)	0.40	100	Berndt, 2009
	Fly ash (30%) GGBS (65%)	0.45	100	Ann *et al*, 2008
Freeze/Thaw	Fly ash (30%) GGBS (65%)	0.40	100 0	Hwang *et al*, 2013
Sulphate attack	Fly ash (40%) Fly ash (50, 60%)	0.30	25 50	Saravanakumar and Dhinakaran, 2014
	Fly ash (30%) GGBS (65%)	0.40	100	Hwang *et al*, 2013
	Fly ash (20, 35, 50%) GGBS (20, 35, 50%)	0.65	100	Somna *et al*, 2012
	GGBS (50, 70%)	0.40	0	Berndt, 2009

The literature suggests that coarse CCA structural concretes produced with varying quantities of SCMs perform well in aggressive chloride environments, which contradicts the existing 0% limitation (BSI, 2013b). The resistance to carbonation appears to be reduced when SCMs are incorporated. Generally, concretes with lower hydration rates, such as CEM II/B-V (PFA) and CEM III/A (GGBS) concretes, will carbonate at a faster rate compared to CEM I concretes due to the latent hydraulic and pozzolanic effects and lower quantities of calcium hydroxide ($Ca(OH)_2$) (Bapat, 2013). This effect however, has been found to be less common in real-scale structures, on reinforced concrete ranging from 3 to 63 years old (Bijen *et al*, 1989; Bijen, 1996). The results of the remaining deterioration mechanisms are more varied, with conflicting suitable coarse CCA replacement levels suggested. A wider variety of coarse CCA sources and binder combinations therefore require investigation to determine suitable replacement levels before a more robust framework for the implementation of coarse CCA in structural concrete can be produced.

1.3.6 KEY TRANSPORT MECHANISMS IN CONCRETE

The ability of liquids and gases to penetrate the concrete cover is a key factor in determining the expected service life of a reinforced concrete structure. Liquids and aggressive chemical ions, such as chlorides and sulphates, can ingress concrete through a combination of transport mechanisms, mainly: absorption by capillary suction, diffusion and permeation (Tuutti, 1982). Permeation relates to the flow of liquids or gases caused by an external pressure head, whereas absorption by capillary suction and diffusion relate to the transport of liquids and ions by surface tension effects in the capillaries of porous materials and concentration gradients respectively (Kropp *et al*, 1995). 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. Absorption and diffusion are the more commonly observed mechanisms in real-scale reinforced concrete structures.

The process of 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 ions (chlorides) to move towards an anode (Bertolini *et al*, 2004; Claisse, 2014). Although not a true representation of chloride ion ingress in real structures, rapid migration techniques can provide a quick indication of a concrete's ability to resist chloride ions when results are compared against a reference concrete (Geiker *et al*, 1995; NordTest, 1999; ASTM, 2012).

1.3.7 CHLORIDE ION INGRESS AND CHLORIDE-INDUCED CORROSION

Chloride ion ingress of reinforced concrete usually occurs through exposure to marine environments or when de-icing salts are applied to highway structures during routine winter maintenance. This can ultimately lead 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 \$8.29 billion annually in the USA alone (NACE International, 2012), with chloride-induced corrosion being the most common cause of deterioration. Similar trends have been observed across the UK and Europe, with increasing costs on infrastructure maintenance (NAO, 2014).

Absorption and diffusion are the most common transport mechanisms in real-scale reinforced concrete structures (Figure 1.5), and can often occur simultaneously when concrete is subject to cyclic wetting and drying, which is considered to be the most detrimental process to reinforced concrete durability (BSI, 2013b). For reinforced concrete bridges, a combination of absorption by capillary action and/or diffusion can also occur when de-icing salt solution ponds on the surface of reinforced concrete decks. Further ingress can occur to lower structural components of the bridge through deteriorated bridge expansion joints, or when trafficked standing water on the road surface creates a splash zone to the lower half of abutments.

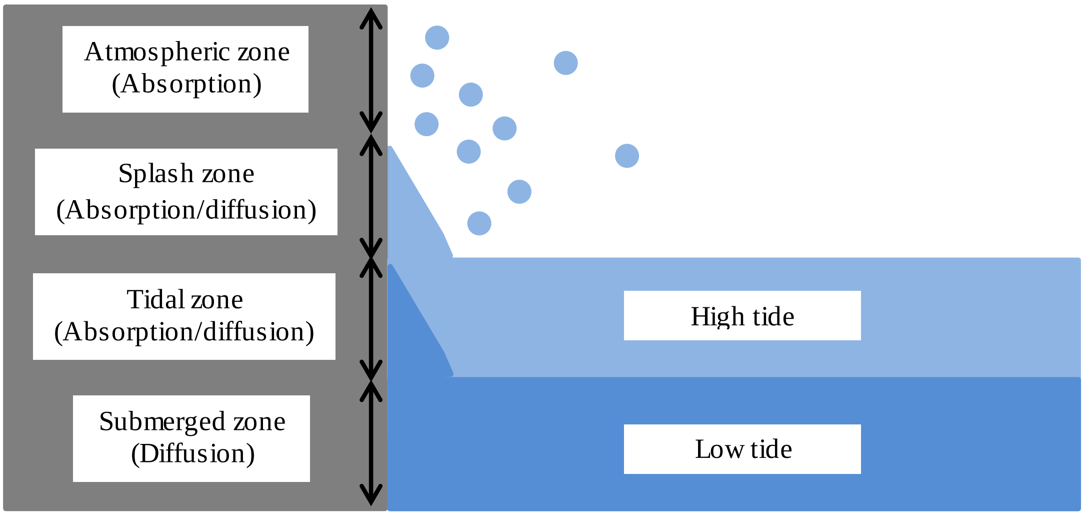

Figure 1.5 Different zones of exposure for marine structures (Dyer, 2014)

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 (Kropp, 1995; Glass *et al*, 2000). The depassivation process results in the production of complex iron compounds which are soluble in the concrete pore solution (Glass *et al*, 2007; Dyer, 2014). 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 due to the variability of published values (Angst *et al*, 2011). The most commonly published value for the critical chloride ion content is 0.4% by mass of cement, however this can change depending on the concrete binder type (Kropp, 1995; Concrete Society, 2004a,b; Alonso and Sanchez, 2009; Angst *et al*, 2009). Once the steel is exposed to the chloride ions, the corrosion can then aggressively propagate as 'pitting' occurs, producing further acidity from corrosion products (Glass *et al*, 2007; Bertlolini *et al*, 2004). Localised anodic areas exist at the location of the pits and the surrounding reinforcement becomes cathodic (Figures 1.6 and 1.7).

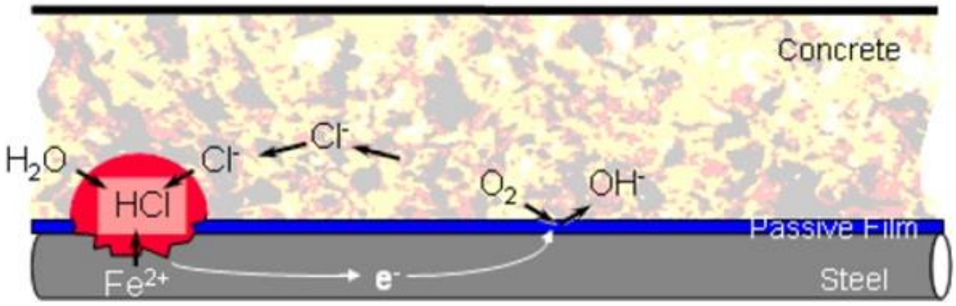

Figure 1.6 Electrochemical process of chloride-induced corrosion (Glass *et al*, 2006)

Figure 1.7 Chloride-induced 'pitting' corrosion of reinforcing steel

The propagation of corrosion generates stresses as the corrosion product is voluminous, which ultimately leads to cracking, delamination and subsequent spalling of the protective concrete cover. Crack widths greater than 0.3mm can be detrimental to the durability of reinforced concrete for the majority of environmental exposure classes, and therefore indicates a failure of the protective cover (BSI, 1992; Raupach, 1996; Concrete Society, 2004a,b; Concrete Society, 2010a).

Cementitious materials have a chloride binding capacity which can increase or reduce the free chloride ion content in the pore solution of concrete, and in turn change the concentration gradient that drives diffusion (Glass and Buenfeld, 2000). The 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) (Bertolini *et al*, 2004; Neville, 2011). The binding capacity can be increased through the use of SCMs, such as PFA and GGBS, due to the generation of additional C-S-H (calcium silicate hydrate) through secondary hydration (Dhir *et al*, 1996; Dhir *et al*, 1997; Glass *et al*, 1997; Glass and Buenfeld, 2000). Microstructural analysis of GGBS has shown its ability to form higher quantities of Friedel's salt compared to CEM I concretes (Luo *et al*, 2003). 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 ion content (Dyer, 2014).

1.3.8 PRODUCTION AND PROCESSING TECHNIQUES

More recently, research has investigated the influence of pre-processing coarse CCA to improve the mechanical and durability performance of the resultant concrete, such as: surface pre-treatments with pozzolanic materials to reduce the water absorption of coarse CCA; and acid, thermal and physical techniques to remove the adhered mortar (Akbarnezhad *et al*, 2011; Akbarnezhad *et al*, 2013; Pepe *et al*, 2014; Liang *et al*, 2015; Pedro *et al*, 2015; Pandurangan *et al*, 2016). Although effective, these methods can introduce other negative effects to the material or the environment, such as possible degradation of the aggregate and/or increased energy and water consumption during processing. Zhang *et al* (2015) therefore investigated the use of carbon dioxide (CO_2) treatment to enhance the physical properties of coarse CCA and found that it improved the apparent density, water absorption and crushing value.

Different approaches to CCA concrete production have also been investigated, including the pre-soaking of aggregates, separation techniques and mixing methods. There is contradiction as to the initial ideal moisture state of coarse CCA with oven-dried, air-dried, saturated surface-dried and full saturation all reported to be the best condition when mixing (Poon *et al*, 2004; Ferreira *et al*, 2011; Mefteh *et al*, 2013; Brand *et al*, 2015; Pickel *et al*, 2017). Separation by means of advanced dry recovery and air jigging, and mixing methods combining the cementitious materials with coarse CCA before the addition of water have all been shown to be beneficial to the fresh and hardened properties of concrete (Brand *et al*, 2015; Lotfi *et al*, 2015; Ambros *et al*, 2017).

Matias *et al* (2014) investigated the use of superplasticisers on the durability of structural CCA concretes. Interestingly, it was found that the concrete specific density and water absorption properties (both by immersion and capillary action) were not influenced by the use of superplasticisers. The effectiveness of superplasticisers also reduced with an increasing coarse CCA content, resulting in a reduced workability. Regardless of this, superplasticisers were found to improve compressive strength, shrinkage strain and the resistance to carbonation and chloride ion ingress.

Sources of CCA may be subjected to contamination, either from exposure to chemicals during its service life or when being stored prior to reuse. Debieb *et al* (2010) found that high chloride and sulphate ion concentration in coarse CCA can be detrimental to the durability performance of structural concrete, particularly in relation to early initiation of reinforcement corrosion. In this situation, soaking aggregates for 2 weeks prior to use can produce clean, uncontaminated CCA suitable for use in concrete production without an increased risk of corrosion.

Silva e*t al* (2014) proposed that the measurement of water absorption and oven-dried density of coarse CCA be necessary to provide some indication of potential impact on the resultant concrete performance. This research led to the proposal of a classification model to categorise coarse CCA to promote selective demolition practices, with Type A having better potential performance (Figure 1.8).

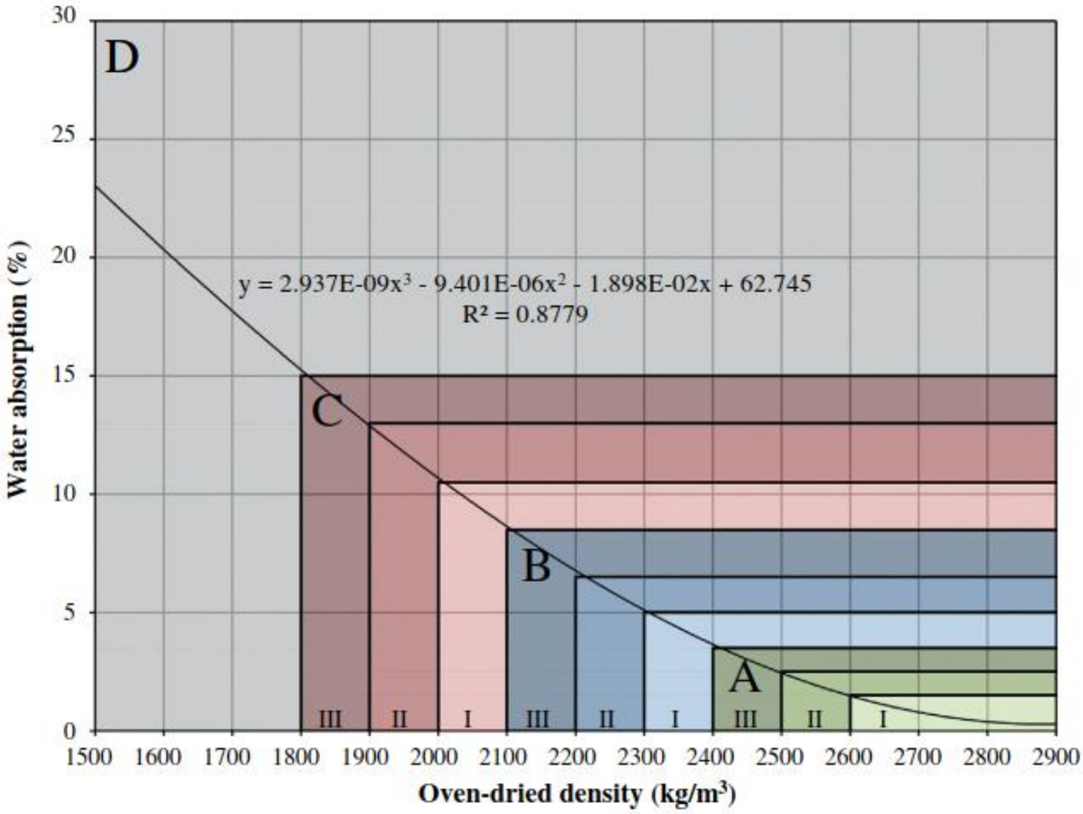

Figure 1.8 Coarse CCA classification model (Silva *et al*, 2014)

1.3.9 IDENTIFIED GAPS IN KNOWLEDGE

The review of literature has identified the following important points, which have been used to refine the EngD research programme:

1. Large quantities of CDW are available in the UK and across Europe. The majority of CDW is used in non-structural applications such as: general fill material, road base layers and low grade concretes.

2. There is strong evidence to support a positive shift in the way the construction industry approaches responsible sourcing and the re-use of CDW in new construction projects, however some ambiguities still exist in the classification of coarse RA in European specification standards.

3. The acceptable replacement level for coarse CCA in British and European standards is 20% and 30% respectively. There is a more cautious approach to the specification of coarse CCA when designing concrete for highways structures which suggests that major asset owners are less likely to utilise a material which may compromise the integrity of the structure or increase the risk of early deterioration.

4. The mechanical performance of structural CCA concrete has been well investigated in previous studies and therefore this research will focus on durability performance. Testing specimens for compressive cube strength is considered to be an important factor to determine the compliance with characteristic strength as a quality control measure and is standard protocol in the construction industry.

5. The limited availability of published research on the effect of coarse CCA on the durability performance of structural concrete highlights that further research is required if a more robust framework for the implementation of coarse CCA is to become a possibility.

6. The majority of work typically analyses coarse CCA from one source, which is often not defined or lacks characterisation (unknown properties and/or original constituents), so ambiguities and uncertainties exist over the role of the CCA and underlying mechanisms. Recommendations for the characterisation of coarse CCA sources are therefore required to strengthen the conclusions of future research.

7. Chloride-induced corrosion is the most common cause of deterioration to reinforced concrete infrastructure. The addition of SCMs have been shown to be beneficial in aggressive chloride environments due to the reduced porosity of the cement matrix, improved quality of the ITZ and/or the increased chloride binding capacity of concrete.

In addition to the identified gaps in knowledge, the research of innovative techniques to improve the quality and performance of coarse CCA is increasingly popular. In recent years, this has gained more traction with a stronger focus on improving the physical properties of coarse CCA. The RE acknowledges that this emerging and interesting subject domain has great potential for future research, however was not considered part of this EngD research programme.

2 AIM AND OBJECTIVES

This section sets out the aim and individual objectives for the research programme together with a justification for each choice.

2.1 BACKGROUND

As the nature of the EngD programme is to undertake unique research relevant to industry, the overall aim and objectives were developed over time through discussions with the industrial sponsor and academic supervisors. With a keen interest for development and innovation, AECOM continually seek to improve sustainability on new construction projects by responsibly sourcing materials.

As summarised in section 1.3.9, there is strong evidence to support a positive shift in the way the construction industry approaches responsible sourcing and the re-use of CDW in new construction projects. The available quantity of CDW is increasing annually, and RA producers are continually looking for new ways to improve the quality and performance of their aggregates to move towards higher value applications (Barritt, 2015; NFDC, 2016). Further research into the effect of coarse CCA on durability performance is required before a more robust framework for the implementation of coarse CCA can become a possibility. This gap in the international knowledge base is highlighted by the existing limitations imposed by European and British standards (30% and 20% replacement levels of natural aggregates respectively) for particular exposure classes (BSI, 2013b; BSI 2015a; BSI, 2015b). This limitation can reduce to 0% in cases of aggressive environments.

The review of existing literature suggests that studies have investigated the effect of coarse CCA's on different transport mechanisms in a variety of exposure conditions. SCMs have also been shown to be beneficial in the majority of environmental conditions; however ambiguities and uncertainties still exist. The majority of existing work typically analyses coarse CCA from one source, which is often not defined or lacks characterisation (unknown properties and/or original constituents). It is envisaged that characterisation of coarse CCA before utilisation in structural concrete may strengthen the analysis and conclusions of future research and help to address industry concerns and poor perceptions. For the purpose of this thesis, a single source of coarse CCA hereon in may refer to concrete obtained from a specific region, site and/or structural element.

Chloride-induced corrosion is the most common cause of deterioration of reinforced concrete structures, resulting in significant annual maintenance costs (NACE International, 2012; NAO, 2014). Chloride ion ingress of reinforced concrete usually occurs through exposure to marine environments or when de-icing salts are applied to highway structures during routine winter maintenance. The overall aim of the research programme therefore focused on the key transport mechanisms involved with chloride ion ingress in real-scale reinforced concrete structures (absorption and diffusion), the resistance to chloride ion ingress and the risk of corrosion initiation in different chloride exposure conditions (XD/XS) (BSI, 2013b).

This research involved quantitative data collection from a laboratory programme, following an in-depth review of existing literature. The minimum requirements for the submission of the EngD thesis is three accepted and published peer-reviewed papers (including at least one journal paper), which effectively distribute the findings of the research. The RE and the research team agreed throughout the research programme that the quantity and quality of work undertaken could produce more publications than this required minimum.

2.2 AIM

The aim was to investigate the effect of coarse CCA and SCMs on the durability performance of structural concrete, with particular emphasis on the key transport mechanisms of concrete, namely resistance to water and chloride ion ingress and the risk of corrosion initiation.

Avoiding the issue of on-site blends of multiple concrete types and undertaking characterisation of the coarse CCA before manufacture of test concrete would also strengthen the analysis and hence the conclusions that could be drawn. In this case, the majority of coarse CCA sources were obtained from a single known location or structural element and were not contaminated.

The successful completion of this aim contributes to a deeper understanding of the effect of coarse CCA on durability performance and should lead to a more rational and informed approach when specifying its inclusion in structural concrete. Also, the research has generated rigorous and significant data and knowledge which will help address a common poor perception of coarse CCA in the industry and help overcome barriers when considering the wider implementation in higher value applications.

2.3 OBJECTIVES

In order to achieve the aim of the research programme, the following four objectives were identified:

Objective 1 Conduct an in-depth critical literature review to identify the state-of-the-art on the use of CCA and SCMs in structural concrete and their effect on durability performance.

Objective 2 Identify current practices in the demolition and construction industry to highlight the common perceptions and barriers to the wider implementation of CCA in higher value applications. This includes the engagement of UK industry, professional bodies and research groups to understand the current and accepted levels of incorporation in construction.

Objective 3 Undertake an extensive laboratory programme using a variety of concrete mix designs, with different sources of coarse CCA and SCMs in order to obtain a large amount of empirical data for analysis.

Objective 4 Provide scientific evidence on the effect of coarse CCA on the durability performance of structural concrete, and produce high quality conference and journal papers which effectively distribute the findings of this research.

2.4 JUSTIFICATION OF THE OBJECTIVES

The reason for selecting the individual objectives was to break down the aim of the research into more manageable and identifiable tasks which could be effectively monitored with time. It was believed that the four objectives developed could be accomplished within the four-year time frame provided (Figure 2.1).

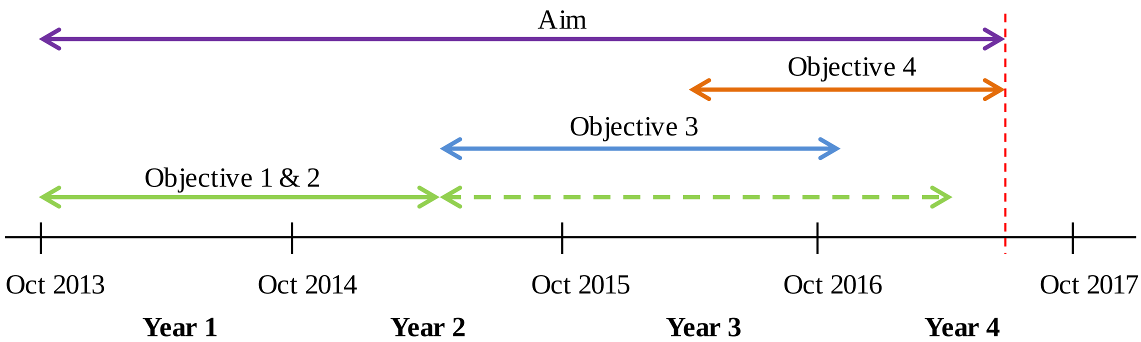

Figure 2.1 EngD project timeline

The critical literature review and identification of current practices (objectives 1 and 2) were adopted as the initial tasks to broaden the understanding of the use of CCA in industry and in structural concrete, and highlight the common perceptions in design, construction and demolition. This included a review of the aggregates market, engagement with key research groups, professional bodies and construction and demolition contractors, and a critical analysis of the existing literature and international knowledge base. This process was hugely important to the EngD programme as it provided the fundamental basis for the development of research in this area. Additionally, this helped to define the overall research programme and identified a lack of knowledge in a specific area compared to the wider subject field of recycled materials in concrete. It was discussed that objectives 1 and 2 should take approximately 12 to 18 months in order to assess properly the subject area, and help to define a laboratory programme that would provide novel and unique data that would benefit research and industry. Objectives 1 and 2 would also be a continual process throughout the EngD programme to capture new research developments in the subject area as it became available.

Objective 3 was arguably the most crucial component of the research programme as it would provide the empirical data that would compare different coarse CCA sources in a variety of concrete mix designs produced with Portland cement in combination with SCMs. It was established early on that obtaining field data may be difficult due to the fact that a limited number of structures in the UK exist where coarse CCA has been used as a construction material in structural concrete, and in these particular cases it would be rare that any would have experienced any physical deterioration in the timescale for the EngD. It was therefore decided that all of the experimental work would be laboratory-based and should last approximately 12 to 18 months, dependent upon the test methods selected. This will be discussed further in Section 3.3.

Objective 4 was chosen to comply with the requirements for submission of the EngD thesis as three accepted and published peer-reviewed papers (including at least one journal paper) are required. The analysis and discussion of the data combined graphical analysis of the numerical data, statistical analysis and a comparison of the findings against relevant literature. This will also be discussed further in Section 3.3.

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3 METHODOLOGY

This section describes the consideration of various approaches that could be used to effectively complete the research programme, and also details the methods chosen to meet the individual objectives and the justification for each. Full details of the experimental testing methods employed for each of the publications can be found in Appendices B to F.

3.1 METHODOLOGICAL CONSIDERATIONS

This research programme comprises one aim, broken down into four distinct objectives. Considerations for the methodological approach for each objective were analysed prior to commencement.

The word 'research' can be defined as *'a systematic investigation to establish facts or principles or to collect information on a subject'* (Collins English Dictionary, 2017). Many different models and written approaches exist when conducting research and collecting data, including the work of Brewer (2007), who states that research can be conducted in a number of ways including: surveys of public opinion, observational techniques, action research, archival/desk studies and/or scientific experiments involving hypothesis testing. Further guidance on the approaches to data collection is widely available in literature (Northey and Jewinski, 2012; Naoum, 2013). Research approaches can be broken down into specific typologies as shown in Figure 3.1.

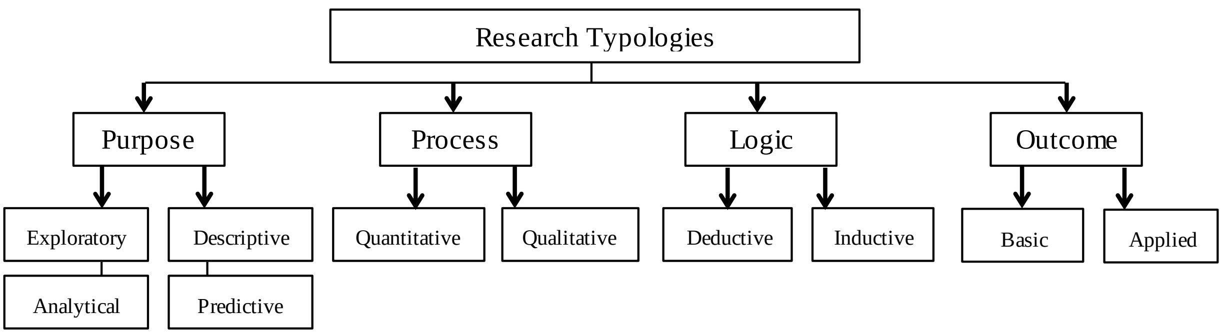

Figure 3.1 Research Classifications (Hussey and Hussey, 1997)

These classifications are summarised and described in Table 3.1, with a focus on their application specifically to research and development within the construction industry.

Table 3.1 Definition of research classifications (Brewer, 2007; Collis and Hussey, 2014; Fellows and Liu, 2015)

	Research classification	Description
Purpose	Exploratory	Exploring theoretical considerations to discover possible hypotheses. An array of possibilities is often established before hypotheses can be produced.
	Descriptive	To identify and record all elements of a process or system from a particular perspective (surveys/case studies), and usually results in categorisation. This process can be described in a narrative, chronological or organisational sense (Dunleavy, 2003).
	Analytical	This approach attempts to explain the data by analysis. This involves the determination of trends and an attempt to measure them. Where possible the variables need to be closely controlled.
	Predictive	This approach determines the likelihood of a specific phenomenon to reoccur elsewhere. It is therefore useful for testing what-if scenarios.
Process	Quantitative	Quantitative approaches adopt existing theory and literature to determine aims and objectives with proposed hypotheses. These approaches generally address questions such as; how much and how many? And is often in the form of numerical data.
	Qualitative	Qualitative approaches involve an exploration of the subject domain to improve understanding (in some cases with no prior hypothesis). Qualitative research tends to lead to quantitative research and is often used to develop new ideas and seeks to find out why things happen the way they do (Harrison *et al*, 2007). This approach is critical to develop knowledge in the construction industry.
Logic	Deductive (Top down)	This approach develops hypotheses form existing theory and literature. Tests are then developed to test the hypotheses.
	Inductive (Bottom up)	General patterns are determined from particular observations. Hypotheses are then established following the confirmation of trends and a theory is produced.
Outcome	Basic (Pure)	This relates to the discovery of theories and laws of nature. Development and innovation cannot exist without pure research however on its own it is unlikely to be of any benefit to society.
	Applied	Applied research relates to end users and practical applications. Both are equally as important in the construction industry. Applied research often relates to problem-solving which can be ‘closed’ or ‘open’ dependent on the simplicity of identification and solution.
	Instrumental*	This classification involves the calibration of research equipment or data sets. It uses theoretical considerations to evaluate the accuracy of measurements.
	Explanatory*	Used to answer a particular question or explain a specific issue. In comparison to exploratory studies the subject domain is often more defined. Is often a follow on from exploratory research.
	Interpretive*	Compares findings against a theoretical framework or model and is often used when empirical data cannot be collected.

***Additional research classifications as identified by Fellows and Liu (2015)**

In addition to the outcome of 'basic' and 'applied' research, Phillips and Pugh (2005) suggest three further classifications: exploratory, testing-out and problem solving (Table 3.2).

Table 3.2 Definition of research classifications (Phillips and Pugh, 2005)

Research classification	Description
Exploratory	As above, this type of research is used to explore theoretical considerations to discover possible hypotheses, and is typical when little is known about a subject domain. Likely solutions are often tested in the hope that something useful will be discovered.
Testing-out	The limits of previously proposed hypothesis are evaluated in this type of research. Variables are tested to determine if the same theories apply for all scenarios. This process can be continuous as a wide variety is often available, but generally looks to improve the performance/specification of concepts, products or materials.
Problem solving	This type of research looks to find a solution to real world problems in research and industry. The solutions may be readily available or will be based on new and innovative concepts. This often involves input from multiple disciplines and cannot rely solely on academic research.

All of the aforementioned definitions and approaches are worth consideration before embarking upon a doctoral research programme. Phillips and Pugh (2005) recommend that for a PhD or doctorate, the testing-out research approach is the most appropriate given the constraints on time and available funding usually encountered. In addition to this, Brewer (2007) states that a researcher '*needs to establish a clear, precise research question that is neither too narrow nor too broad'* which will ultimately influence the research methods adopted. Burnard and Morrison (1994) suggest this can be achieved by brainstorming ideas to refine the specific research question. Alternatively, the use of analogies, relevance trees and morphological analysis techniques have been shown to be effective (Howard and Sharp, 1983; Collis and Hussey, 2014).

3.2 METHODOLOGY DEVELOPMENT

With a clearer understanding of the suitable methodological approaches for doctoral research, the methodology for the chosen subject domain could be refined. The review of methodological considerations in Section 3.1 highlight that the research objectives can be defined in relation to the purpose, process and logic classifications, whereas the aim requires definition in relation to the outcome of the research. A summary of the adopted approaches for the objectives and a justification for each one can be seen in Table 3.3.

Table 3.3 Justification of adopted research classifications

Objective	Adopted approach	Justification
1 – Critical literature review	Purpose – Exploratory/ Descriptive Process – Qualitative Logic - Deductive	The purpose of the literature review was to identify existing theories, research methods and hypotheses, and examine the extent to which coarse CCA has been used on previous case studies in structures. This process was mostly to improve understanding of the subject domain to identify gaps before quantitative research could be undertaken (objectives 3 and 4). As coarse CCA is a commonly used construction material for lower grade applications, theories and hypotheses regarding performance are likely to exist.
2 - Identify current practices in the demolition and construction industry	Purpose – Descriptive/ Analytical Process – Qualitative Logic – Inductive	The purpose of identifying current practices within industry was to identify existing trends and common perceptions. This process was mostly to improve understanding of the subject domain before quantitative research could be undertaken (objectives 3 and 4). It was generally accepted that a poor perception of coarse CCA exists in industry; however it is not necessarily clear as to why. An inductive approach looked to identify possible hypotheses from existing trends.
3 - Extensive laboratory programme to obtain empirical data 4 - Provide scientific evidence on the effect of CCA on the durability performance of structural concrete	Purpose – Analytical Process – Quantitative Logic – Deductive	The collection of a large quantity of numerical data and dissemination of the findings clearly relates to analytical and quantitative approaches. As a number of studies regarding durability performance of coarse CCA in structural concrete already exist, a deductive approach would be required test existing theories to develop hypotheses.

It is clear from Table 3.3 that the approach to research (the purpose) differs for each objective as the project progresses. In order to conduct the research (the process) a combination of qualitative and quantitative approaches to research are required to complete the project objectives. The logic is predominantly deductive throughout, with some inductive reasoning required for identification of the current practices in the demolition and construction industry. Fellows and Liu (2015) define how a combination of both qualitative and quantitative research can be used effectively to deliver conclusions and recommendations (Figure 3.2).

The theory and literature will be established primarily through completion of objective 1 (and subsequently objective 2), whereas the combination of qualitative and quantitative data will be obtained through completion of objectives 2, 3 and 4. It is deemed that this methodological model will be the best approach for the research project proposed to achieve the aim.

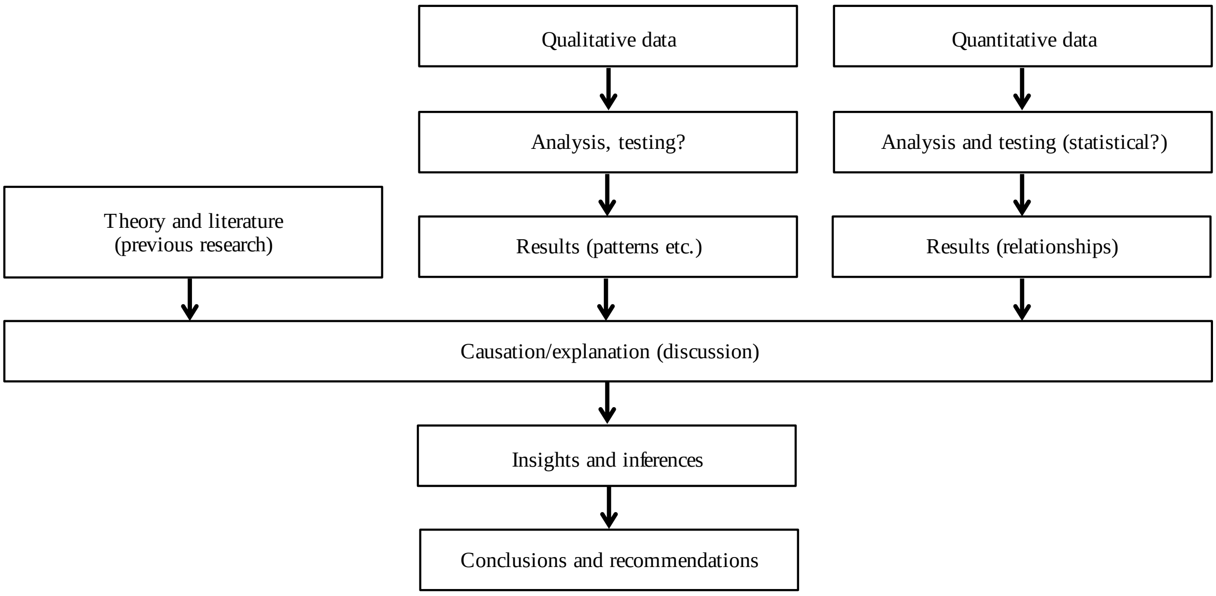

Figure 3.2 Triangulation of qualitative and quantitative data (Fellows and Liu, 2015)

The main purpose of the overall CICE EngD programme is to improve collaboration and innovation between the construction industry and academia, and to provide innovative solutions to existing real world problems. In this case, the 'applied' and 'problem solving' approaches would seem the most appropriate outcomes. As is acknowledged, 'applied' research cannot be achieved without prior 'basic' research, although if the theories and laws have already been established for a particular subject domain, then 'basic' research is unlikely to feature. 'Problem solving' research is crucial to the ideology of the EngD programme, however 'testing-out' research, recommended for PhD projects when time and funding is limited, is also applicable to materials and products testing which is a common subject domain within construction.

The aim of the research project, as identified by the review of existing literature, was to investigate the effect of coarse CCA and SCMs on the durability performance of structural concrete. The use of coarse CCA in structural concrete is a relatively new concept within the construction industry; however, the use of secondary and recycled materials used in the construction industry has gained traction since the 1950's (Figure 1.1), and so theories and laws are already well established. 'Applied' research therefore, is deemed the most appropriate outcome for this particular research project. A combination of 'testing-out' and 'problem solving' approaches would also be beneficial in achieving the aim as it looks to address a real world problem by testing an array of variables to optimise the sustainable credentials of structural concrete. 'Instrumental', 'explanatory' and 'interpretive' approaches were not considered appropriate for this type of research and so were dismissed.

At quarterly intervals throughout the EngD programme the adopted approaches in Table 3.3 were reviewed to ensure the objectives were achieved in accordance with the project timeline (Figure 2.1). Additionally, conferences and PhD workshops contributed to the refinement of methodological approaches, in particular the test methods adopted to collect quantitative data. The presentation of results encouraged discussion with other researchers and industry leaders to gain invaluable feedback.

3.3 METHODS

The chosen methods used to complete each objective, in accordance with the adopted approaches, are summarised below:

Objective 1 A critical review of existing literature was used to identify existing theories, research methods and hypotheses, and examine the extent to which coarse CCA has been used on previous case studies in structures. This was achieved through searching in high impact journal papers that publish research based on concrete, recycling, sustainability, aggregates and durability. Books were also identified, published by authors well known in the subject domain of concrete durability (e.g. Dyer and Neville). It was expected that this approach would yield a significant quantity of literature that would require reviewing and arranging based on appropriate and relevant content. This process was mostly to improve understanding of the subject domain and determine appropriate test methods for objective 3. Section 1.3 highlights the extent of the relevant literature obtained throughout the EngD programme.

Objective 2 The current practices within industry were identified to determine existing trends and common perceptions amongst professionals. This was achieved by finding and reviewing reports published by professional bodies and organisations that associate themselves with sustainability within the construction and demolition industry such as WRAP, the Department for Environment, Food and Rural Affairs (DEFRA), the Concrete Society and the Environment Agency. Correspondence and personal communication with industry experts was also critical to establish an understanding of common perceptions. This was achieved by engaging with professionals at continuing professional development (CPD) events, seminars, webinars and conferences. Informal discussions were also undertaken with professional bodies and organisations, including: Dorton Group Ltd, NFDC, British Precast, Aggregate Industries Ltd, AR Demolition Ltd, DSM Demolition Ltd, John Barritt Consulting Ltd and Responsible Solutions Ltd. This process was mostly to improve understanding of the subject domain before quantitative research could be undertaken (refer to sections 1.3.1 and 1.3.2).

Objective 3 The collection of a large quantity of numerical data was was arguably the most crucial component of the research programme. Objectives 1 and 2 provided the basic understanding of appropriate durability test methods that are commonly used in research and industry that could be utilised. It was established early in the research programme that all of the experimental work would be laboratory-based due to the lack of real-scale structures currently constructed using coarse CCA. Tables 3.4 and 3.5 explain the chosen test methods for concrete and aggregate samples and the characterisation of coarse CCA sources respectively. The test methods were adapted throughout the EngD programme as different sources of coarse CCA were obtained, and as it became clear characterisation was an important factor (refer to Section 4). The Building Research Establishment (BRE) method of mix design was used to determine the mix constituents for all concretes mixes produced (BRE, 1997).

Objective 4 The production of high quality conference and journal papers would effectively disseminate the findings of the research (refer to Appendices B to F). Statistical analysis strengthened the findings/hypotheses and hence improved the reliability of results. It is beneficial to publish research in well-respected journals with a high impact factor, and at conferences that have experienced and well-known scientific committees as these tend to attract a wider, more-informed audience upon publication. Elsevier's Construction and Building Materials (Journal Impact Factor (JIF) of 3.17 (3.71 over 5 years) and SCImago Journal Rank (SJR) of 1.49) and the ICE - Construction Materials (SJR of 0.26) were chosen as the preferred publications for this research as they have a history of publishing articles related to improving the sustainability of structural concrete.

Table 3.4 Justification of chosen test methods for concrete testing

Concrete testing		
Test method	Standard reference	Justification
Compressive cube strength	(BSI, 2009a)	To determine compliance of mixes with the characteristic ($f_{c,cube}$) and target mean strength and to determine the suitability of the BRE mix design method to produce structural CCA concrete. 100mm³ specimens were produced to match commonly adopted practices in the UK construction industry for quality control purposes.
Surface resistivity	(Concrete Society, 2004; AASHTO, 2015)	To determine the quality of the microstructure of concrete, indicated by the electrical surface resistivity.
Bulk resistivity	N/A	To determine the quality of the microstructure of concrete, indicated by the electrical bulk resistivity.
Absorption by capillary action	(BSI, 2002)	To determine the sorptivity of concrete with no external pressures applied. This is the key transport mechanism of water and chloride ion ingress when concrete is in a dry state.
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	(NordTest, 1999)	To determine the migration of chloride ions in concrete when an electric field is applied. Migration techniques provide a quick indication of a concrete's ability to resist chloride ion ingress.
Accelerated corrosion	(NordTest, 1989)	To determine the time to corrosion and cracking when an electric field is applied. Migration techniques provide a quick indication of a concrete's ability to resist chloride ion ingress.
Unidirectional natural diffusion	(BSI, 2015c)	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	(Concrete Society, 2004; ASTM, 2009)	The results can provide an indication of the risk of corrosion initiation. Close interval half-cell measurements (50mm spacing) can assist in identifying localised areas of anodic activity (Christodoulou *et al*, 2014).
Chloride ion concentration profile	(Concrete Society, 2004; BSI, 2015d)	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 by linear curve fitting (Poulsen, 1995).
Chloride ion ingress (depth)	(Meck and Sirivivatnanon, 2003)	This test provides a quick indication of the chloride ion ingress depth, indicated by the formation of white precipitate on the surface of freshly split concrete.
Aggregate testing		
Test method	Standard reference	Justification
Water absorption and particle density	(BSI, 2013c)	To determine the 30 minute and 24 hour water absorption characteristics and particles density of all aggregates used in testing. This not only provides an indication of potential durability performance, but also is used to design the concrete mixes.

Table 3.5 Justification of chosen test methods for characterisation of the CCA sources

Characterisation of CCA sources		
Test method	Standard reference	Justification
Petrographic analysis	(Concrete Society, 2010b; ASTM, 2014)	To determine the aggregate type, cement type, possible presence of admixtures and amount of segregation, microcracking and voids. Also, to provide an estimate of the mix constituents, cement content, water-cement ratio, slump and 28 day strength.
Alkali, cement and chloride ion content	(BSI, 2015d)	To determine possible sources of contamination in the obtained CCA sources. The cement content provides an indication of the original cement composition for comparison with the estimate from petrographic analysis.
Compressive strength of cores	(BSI, 2009b; BSI, 2010)	To determine the equivalent in-situ characteristic strength, for comparison with the estimate from petrographic analysis.
Water absorption and particle density	(BSI, 2013c)	To determine the 30 minute and 24 hour water absorption characteristics and particles density of CCA sources. This not only provides an indication of potential durability performance, but also is used to design the concrete mixes.

Background information on the test methods detailed in Tables 3.4 and 3.5, including the reasoning, references to literature, interpretation of results and possible limitations, are available in the published papers (refer to Appendices B to F).

The BRE method of mix design is a well-established and simplified process for determining the constituents of normal concrete mixes. To achieve the required compressive strength, a value for water/cement ratio is estimated for an appropriate test age and cement and aggregate type. The free water content, cement content and aggregate content are then determined using the tables in the handbook (BRE, 1997). The particle size distribution of fine and coarse aggregates is not considered in this mix design method, although it is acknowledged that variations in the aggregate grading could cause changes in the properties of concrete. In this study, the BRE method has been adopted which was not originally intended for coarse CCA concretes. The mix constituents were determined following the normal method and then natural coarse aggregates were replaced with coarse CCA by mass. Alternatively, the coarse natural aggregates could have been substituted by volume based on the bulk density of aggregates.

In this study, the target mean strength was determined based on the mean compressive cube strength of the control concrete batch. The characteristic strength was then determined by subtracting the margin, calculated from the expected variability of concrete. A standard deviation of 8 N/mm^2 was adopted as previous variability data was unavailable (BRE, 1997). For normal concrete mixes produced in a laboratory environment a lower standard deviation may be expected. A consistence class of S2 was adopted for the target slump (between 40mm and 100mm) in accordance with BS EN 12350-2 (BSI, 2009c; BSI, 2015a).

Additionally, when analysing results, the statistical analysis of data was undertaken using the Student's t-test to determine the effect on sample means when coarse CCA sources were included, based on a 10% decrease in performance. A 10% decrease in performance was considered to be significant as this is greater than any expected human or batch reproducibility error. The results of concrete produced with coarse CCA were compared against the results of the respective control concrete for each binder type to calculate a probability of a significant detrimental effect. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect. It is considered that statistical analysis can be useful in strengthening the findings of research and improving the reliability of results.

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4 THE RESEARCH UNDERTAKEN

This section provides a discussion of the research undertaken to achieve the objectives in Section 2.3, and references the publications which have resulted from this research.

Objectives 1 and 2 were completed in accordance with the methodological approaches in Table 3.3 and the resultant findings are discussed in Section 1.3. It was identified at an early stage of the research that collection of data from real-scale structures would be difficult due to the lack of availability of structures produced with coarse CCA, but also the limited quantity that would be exhibiting signs of physical deterioration (corrosion/cracking etc.). The research therefore focused on obtaining a large quantity of data based on a laboratory programme using various CCA sources.

The research conducted to achieve objectives 3 and 4 was refined throughout the EngD programme, through discussions with the supervisory team and attendance at PhD workshops and conferences. As the research progressed it became apparent that the work could be sub-divided into 3 work packages based on the type of coarse CCA source obtained. As stated, a single source of coarse CCA may refer to concrete obtained from a specific region, site and/or structural element.

4.1 WORK PACKAGE 1

Work package 1 was an initial testing programme that aimed to broaden the understanding of the effects of coarse CCA in structural concrete and develop the requirement for further research.

4.1.1 MATERIALS AND TESTING

Before the practical laboratory work could begin, it was critical to obtain a source of coarse CCA at the earliest opportunity to undertake initial tests which would confirm the need for the research.

The first coarse CCA source was obtained from a recycling plant in Plymouth, UK owned by Dorton Group Ltd. The material was ready-crushed to a 40mm down product (maximum aggregate size 40mm) which required further sieving to obtain the aggregate sizes suitable for concrete (4/20mm) (Figure 4.1). The exact origin of the material was unclear as demolition arisings are often grouped together at aggregate recycling plants when crushed, and later re-sold as a backfill or general fill material. This aggregate source is representative of the majority of coarse CCA sold from aggregate recycling plants in the UK. It was established later in work package 1 that it would be difficult to characterise the mixed coarse CCA source using techniques such as petrographic analysis, as the location of the source materials were unknown. 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.

Figure 4.1 Coarse CCA obtained from aggregate recycling plant in Plymouth, UK

The effect of coarse CCA on the compressive cube strength and durability properties of structural concrete was examined using 3 binder types: CEM I (100% Portland cement), CEM

III/A (50% Portland cement, 50% GGBS) and CEM II/B-V (70% Portland cement, 30% PFA). The BRE method of mix design was adopted to determine the mix constituents (BRE, 1997). A water-binder ratio of 0.5 was chosen to produce a concrete with characteristic and target mean strengths of 35MPa and 49MPa respectively (a reduced water-binder ratio of 0.4 was used for the CEM II/B-V concretes as recommended by the BRE method of mix design). The characteristic strength was chosen to produce a structural concrete in accordance with the recommendations for XD3/XS3 exposure conditions in BS 8500-1 (BSI, 2015a). The source of mixed coarse CCA was incorporated at 20% increments, up to 60% replacement of natural aggregates. The coarse aggregate size proportions of 4/10mm and 10/20mm for both natural aggregate and CCA were added at a ratio of 1:2 respectively (BRE, 1997). A yield calculation was undertaken to account for the different densities of materials, to ensure a constant volume of concrete.

The resulting two publications can be found in Appendices B and C. Paper 1 was presented at the fib Symposium 2016, performance-based approaches for concrete structures in Cape Town, South Africa, and Paper 2 has been published in the Proceedings of the ICE – Construction Materials (Dodds *et al*, 2016b; Dodds *et al*, 2017b). The results from the test methods (Table 3.4) were divided between the publications as shown in Table 4.1.

Table 4.1 Concrete testing undertaken as part of Work Package 1

Paper 1 – Appendix B Theme: Effect of coarse CCA on compressive cube strength, microstructure and water and chloride ion migration of structural concrete	Paper 2 – Appendix C Theme: Effect of coarse CCA on chloride ion resistance and time to corrosion initiation of structural concrete
Compressive cube strength	Half-cell potential mapping
Surface resistivity (28 days)	Surface resistivity (regular intervals)
Absorption by capillary action	Chloride ion concentration profile
Rapid chloride migration	Chloride ion ingress (depth)
-	Unidirectional natural diffusion

Structural beams (500 x 100 x 100mm) were cast as part of work package 1 to undertake corrosion monitoring when subjected to cyclic wetting/drying with 3% chloride ion solution.

It was known that this type of testing would be continued throughout the EngD programme and the findings published at a much later date (those presented in Appendix C), compared to the majority of results established at 28 days (those presented in Appendix B).

An additional 10kg/m³ of binder was added to the mix for an increase in coarse CCA of 20% in accordance with the recommendation for crushed aggregates in the BRE method of mix design compared to rounded aggregates. It was established that increasing the cement and water content dependent on aggregate type reduces the sustainable benefits of coarse CCA. It also makes it more difficult to compare the results of concrete mixes as they have slightly different compositions, and so it was decided that the cement content would be kept constant in later work packages.

4.1.2 PAPER 1 – APPENDIX B

One source of mixed coarse CCA was incorporated into structural concretes with 3 different binder types. The concrete microstructure was analysed as well as its resistance to water and chloride ion ingress.

The results revealed that low quantities of mixed coarse CCA, even as low as 20%, can have a detrimental effect on compressive cube strength and durability performance, similar to the findings of other published research (Limbachiya *et al*, 2000; Etxeberria *et al*, 2007; Limbachiya *et al*, 2012; Soares *et al*, 2014; Bravo *et al*, 2015b). There is a general consensus among researchers that the detrimental effect on performance is due to the increased water absorption of the coarse CCA. In this study all of the concrete mixes tested achieved the characteristic strength at 28 days (Figure 4.2).

The statistical analysis (Student's t-test for difference in sample means) highlighted that the increase in surface resistivity and resistance to chloride ion migration, and reduction in the water absorption of coarse CCA structural concrete, due to the addition of both PFA (30%)

and GGBS (50%) was statistically significant when compared to CEM I concretes (up to 60% replacement of natural aggregate). The increase in surface resistivity at 28 days is shown as an example of the beneficial effects of SCMs (particularly GGBS at 50%) in Figure 4.3. This finding is in agreement with the literature summarised in Table 1.7, and it has been shown that SCMs generally improve the durability performance of coarse CCA concrete through a reduction in the porosity of the cement matrix, improved quality of the ITZ and/or an increase the chloride binding capacity of concrete (Dhir *et al*, 1996; Dhir *et al*, 1997; Bertolini *et al*, 2004; Bapat, 2013). Further analysis and discussion is presented in Appendix B.

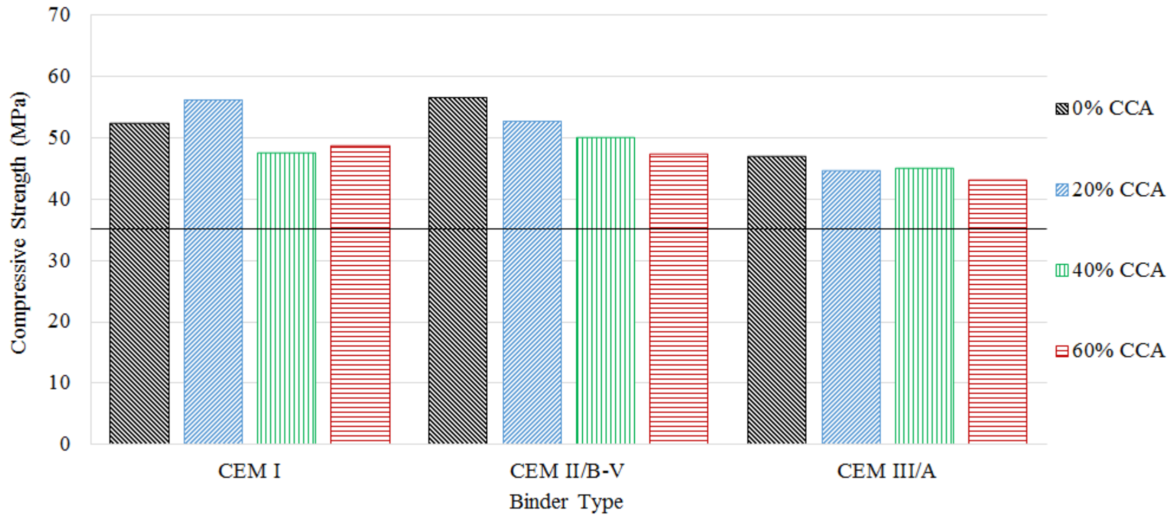

Figure 4.2 Compressive cube strength at 28 days

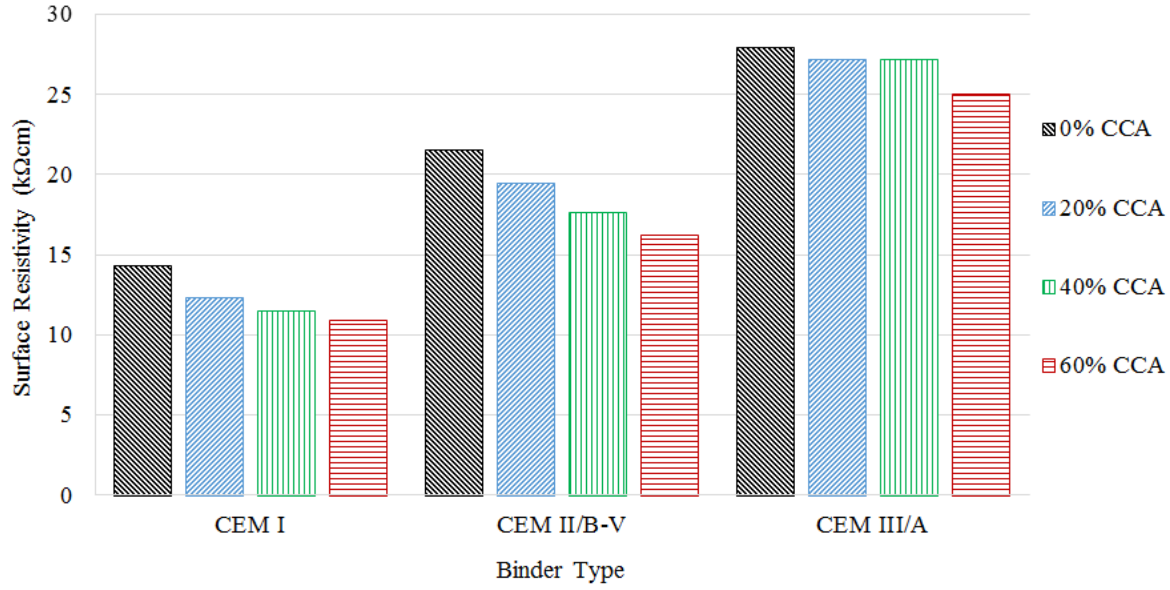

Figure 4.3 Surface resistivity at 28 days

4.1.3 PAPER 2 – APPENDIX C

The probability of corrosion initiation of the same structural concretes discussed in Paper 1 were monitored over time whilst the concrete was subjected to cyclic wetting/drying with 3% chloride ion solution using a well-established electrochemical test method. Destructive sampling was undertaken following 12 months exposure to determine the chloride ion ingress resistance and predicted time to corrosion initiation, compared against the results of natural diffusion tests. To the authors knowledge, no literature on coarse CCA concrete currently exists where electrochemical and destructive testing have been used to analyse and predict the time to corrosion initiation.

In the majority of cases the interpretation criteria for electrochemical tests suggested a low risk of corrosion initiation for all concrete types (Concrete Society, 2004a; ASTM, 2009; AASHTO, 2015). Only three cases of possible corrosion activity were identified, as indicated by a half-cell potential reading less than -284mV (vs. Ag/AgCl 0.5M) (Figure 4.4).

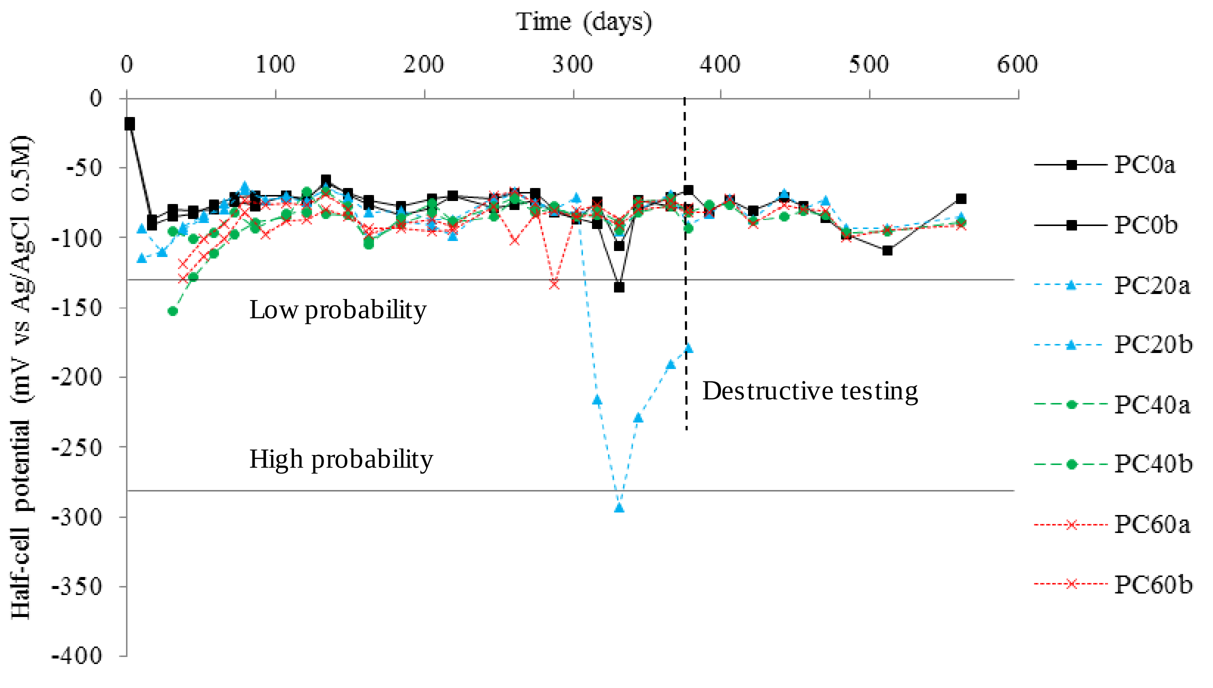

Figure 4.4 Half-cell potential development over time, CEM I concrete

The majority of half-cell potentials remained above the recommended threshold for a low probability of corrosion initiation, greater than -134mV (vs. Ag/AgCl 0.5M), even for coarse CCA contents up to 60% replacement of natural aggregates. The results of destructive testing after a 12 month exposure period confirmed that no corrosion initiation had taken place. Dust samples for chloride ion analysis were collected at 25mm intervals and a chloride profile was produced to determine the apparent chloride diffusion coefficient by linear curve fitting and predicted time to corrosion initiation (Poulsen, 1995). The chloride ion ingress was also measured using the colourmetric technique as indicated by the formation of white precipitate forming on the surface of the concrete (Meck and Sirivivatnanon, 2003).

The results indicated that both CEM II/B-V and CEM III/A concretes performed better than the CEM I concrete at resisting chloride ion ingress. The predicted time to corrosion initiation shown in Table 4.2 increased beyond 120 years for concretes produced with SCMs, with coarse CCA contents up to 60% replacement of natural aggregates, which is well in excess of the 50 year design life adopted for this study. The results of unidirectional natural diffusion by ponding also indicated that SCMs improved the resistance to chloride ion ingress by diffusion. Further analysis and discussion is presented in Appendix C.

Table 4.2 Prediction of time to corrosion initiation

	CCA Content (%)			
Binder Type	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+

4.1.4 LESSONS LEARNT

The following conclusions were drawn which helped refine work package 2:

1. A coarse CCA source of known location would be preferable so that further characterisation can be conducted to better predict the effect of materials. It may also

be beneficial to collect larger sections of demolished concrete of the same source if possible to undertake some compressive core testing.

2. The cement and water content of coarse CCA concretes should be kept constant to maximise the associated sustainable benefits.

3. CEM III/A concretes outperformed CEM II/B-V and CEM I concretes in all durability tests performed. Further tests should be conducted for different replacement levels of GGBS.

4. Coarse CCA, up to 60% replacement of natural aggregates, was found to achieve the characteristic strength and perform well in durability tests. Higher quantities should be tested up to 100% replacement of natural aggregates to determine if this hypothesis remains true.

4.2 WORK PACKAGE 2

Work package 2 was a follow on testing programme that aimed to refine the requirement for further research before a laboratory programme was undertaken.

4.2.1 MATERIALS AND TESTING

A second source of coarse CCA was obtained from a 1970's office building in Leicester, UK. The material was ready-crushed to a 40mm down product and required further sieving to obtain the aggregate sizes suitable for concrete (4/20mm) (Figure 4.5). Although the material was obtained from one demolition site it was still difficult to determine if different structural elements had been mixed as part of the crushing process. This source is representative of the type of coarse CCA that is re-used on demolition sites as a general fill material, or transported from site to nearby aggregate recycling plants for further processing. The material was characterised by determining the cement content, water absorption and particle density of random samples of the coarse CCA, and extracting cores from larger sections for compressive strength. Tests were conducted for potential contamination problems in the form of alkali and chloride ion content. Petrographic analysis was also undertaken 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 4.6). The key findings of characterisation can be found in Appendix D.

Figure 4.5 Coarse CCA obtained from demolition site in Leicester, UK

Figure 4.6 Section of CCA source concrete for petrographic analysis

The effect of coarse CCA on the compressive cube strength and durability properties of CEM I (100% Portland cement) and CEM III/A (50% Portland cement, 50% GGBS) structural concretes were examined using the BRE method of mix design to determine the mix constituents (BRE, 1997). A water-binder ratio of 0.5 was chosen to produce a concrete with a characteristic and target mean strength of 39MPa and 53MPa respectively. The characteristic and target mean strengths were adjusted to comply with the average compressive cube strength of CEM I concrete with 100% natural aggregates. The source of coarse CCA was incorporated at 20% increments, up to 100% replacement of natural aggregates. The coarse aggregate size proportions of 4/10mm and 10/20mm for both natural aggregate and CCA were added at a ratio of 1:2 respectively (BRE, 1997). A yield calculation was undertaken to account for the different densities of materials, to ensure a constant volume of concrete.

The publication resulting from work package 2 in Appendix D was presented at the 1st International Conference on Construction Materials for Sustainable Future in Zadar, Croatia (Dodds *et al*, 2017c).

4.2.2 PAPER 3 – APPENDIX D

A single source of coarse CCA was incorporated into CEM I and CEM III/A structural concretes in order to determine the effect on concrete microstructure and its resistance to water and chloride ion ingress at various ages.

Similar to work package 1, the results showed that low quantities of coarse CCA, even as low as 20%, can have a detrimental effect on compressive cube strength and durability performance. The results of compressive cube strength showed that CEM III/A concretes produced with a coarse CCA content above 60% did not achieve the characteristic strength at 28 days (Figure 4.7).

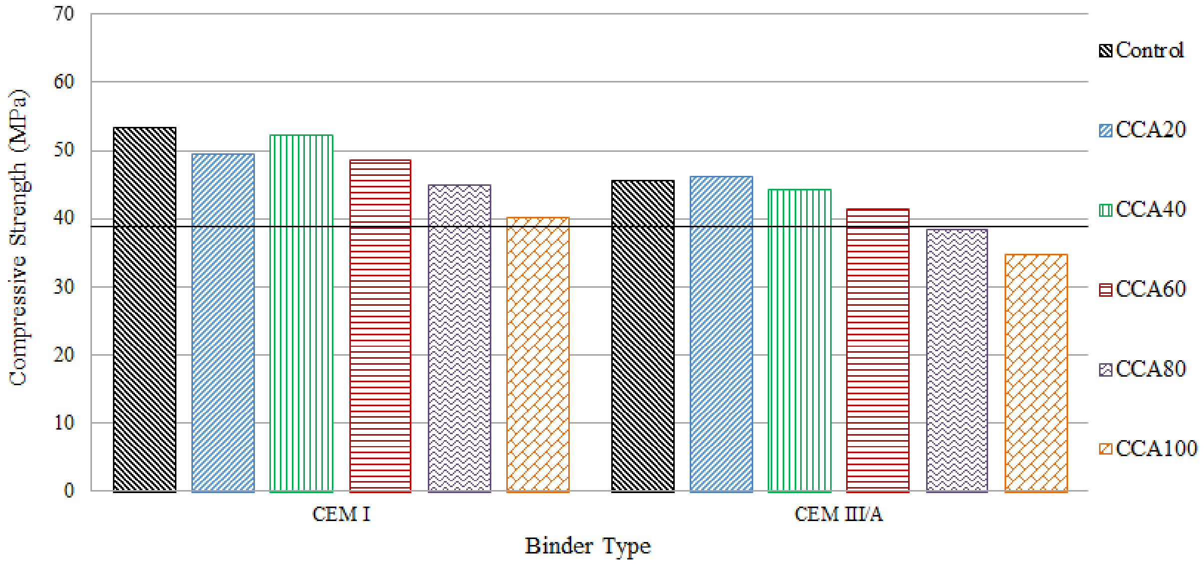

Figure 4.7 Compressive cube strength at 28 days

All concretes, however, achieved the characteristic strength at 56 days due to the latent hydraulic effects of GGBS (Dhir *et al*, 1996; Bapat, 2013). This suggests that 60% coarse CCA inclusion is acceptable for CEM I and CEM III/A concretes without increasing the risk of a non-compliant concrete (i.e. not achieving the specified characteristic strength).

The results of surface resistivity, absorption by capillary action and rapid chloride migration demonstrate that GGBS can significantly improve the microstructure and resistance to water and chloride ion ingress of structural concrete due to the reduced porosity of the cement matrix, improved ITZ and the increased chloride binding capacity of the material (Dhir *et al*, 1996; Glass *et al*, 1997; Glass and Buenfeld, 2000).

More importantly, a structural CEM III/A concrete incorporating up to 60% coarse CCA performed better than the control CEM I concrete produced with 100% natural aggregates by a factor of 3 to 4 and 2 to 3, for surface resistivity and rapid chloride migration respectively (Figures 4.8 and 4.9). Only two concretes (CEM I with 20% CCA and CEM III/A with 40% CCA) were found to be an exception to this finding in terms of the capillary absorption (Figures 4.10 and 4.11).

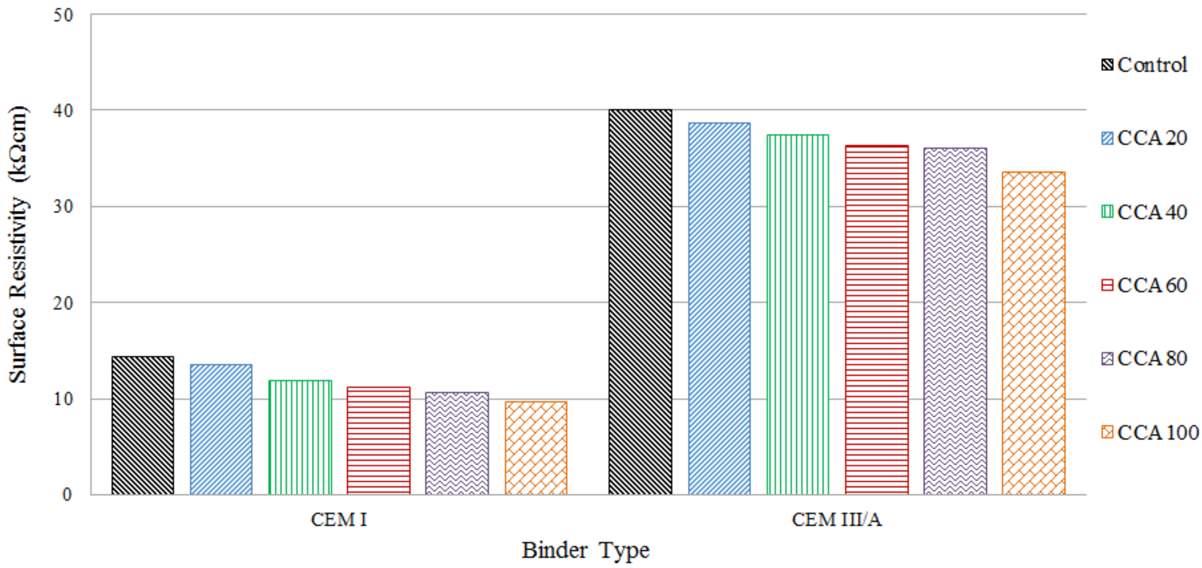

Figure 4.8 Surface resistivity at 28 days

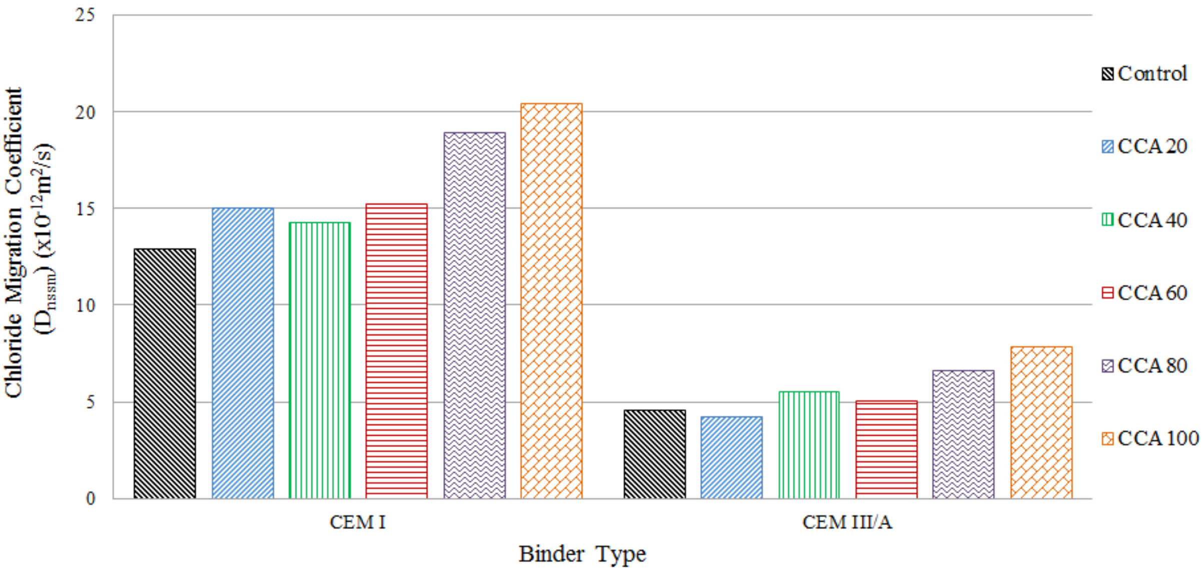

Figure 4.9 Rapid chloride migration coefficient at 28 days

Based on these results, it is concluded that up to 60% coarse CCA can be adopted in structural concrete - provided that GGBS (at 50% replacement of Portland cement) is also incorporated - as it has been demonstrated that the resulting concrete is resistant to chloride environments. Further analysis and discussion is presented in Appendix D.

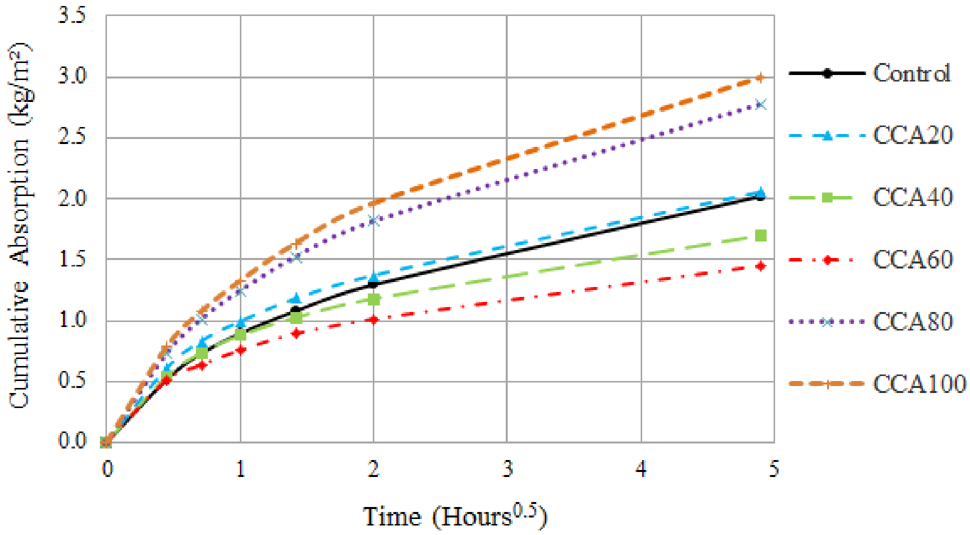

Figure 4.10 Cumulative sorption at 28 days for CEM I concrete

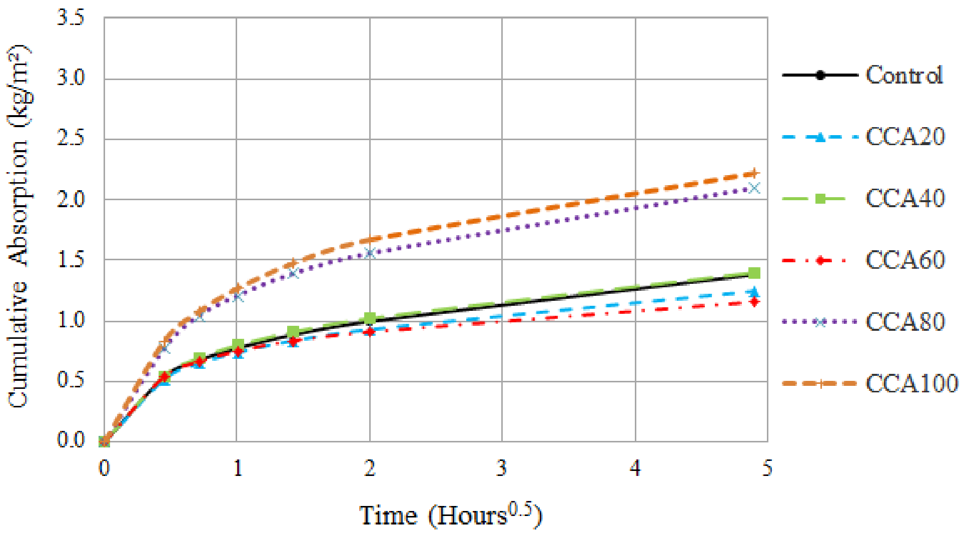

Figure 4.11 Cumulative sorption at 28 days for CEM III/A concrete

4.2.3 Lessons learnt

The following conclusions were drawn, which also helped refine work package 3:

1. It would be beneficial to obtain coarse CCA sources that represent a range of concrete strengths and compositions from specific known structural elements. In reality, the segregation of specific elements may not be the most practical approach for demolition contractors.

2. The characterisation of coarse CCA (presented in Appendix D) has been shown to be beneficial in predicting potential performance and should be used to strengthen the conclusions of future research.

3. The simple, short term durability tests can be good indicators of concrete performance when compared against the CEM I control concretes made with 100% natural aggregates. These tests tend to be undertaken at 28 days to obtain quick results, however it is also important to understand how the coarse CCA concrete performs at an age more representative of long term durability such as 56 and 91 day tests.

4. The inclusion of GGBS at 50% has been shown to be effective at improving the durability performance of concrete, but also increases the risk of a non-compliant concrete (achieving the characteristic strength at 28 days) when replacement levels of coarse CCA exceed 60%. Different replacement levels of GGBS require testing to determine the balance between achieving the characteristic strength, producing a durable concrete and maximising the sustainability credentials.

5. The incremental increase in coarse CCA content should be increased to 30%, 60% and 100% as it has been shown that up to 60% coarse CCA can be suitable for structural concrete.

4.3 WORK PACKAGE 3

Work package 3 was the final laboratory programme undertaken over a period of 12 months that provided a large quantity of data for publication in a high impact journal.

4.3.1 MATERIALS AND TESTING

Throughout the research programme it became increasingly evident that it would be a challenge to find a demolition site where the contractor was sympathetic to the need to obtain uncontaminated concrete from specific structural components. Following an extensive search, three sources of coarse CCA were obtained from selected components of reinforced concrete structures from two demolition sites in the East and West Midlands, UK (Table 4.3). It was also difficult to convince the contractor to undertake the crushing of selected components as this may incur on-site delays to the demolition programme. In this case, larger sections of reinforced concrete beams, footings and floor slabs were separated by the contractor on site and brought to the laboratory to be individually processed (Figures 4.12 and 4.13). The steel reinforcement was removed and a primary jaw crusher reduced the CCA to a 40mm down product (Figure 4.14). The resultant material was sieved into 4/10mm and 10/20mm coarse size increments. Obtaining sources of CCA in this manner is not necessarily a typical approach for current demolition practices; it was however important for this study as the material characteristics and original constituents could be better quantified.

Table 4.3 CCA sources obtained from selected components

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

Figure 4.12 Segregated sections of CCA from demolition sites in the East and West Midlands, UK

Figure 4.13 Reinforced concrete ground floor slab sections of CCA

Figure 4.14 Micro-crusher used to produce a 40mm down product from larger sections

The material was characterised by determining the cement content, water absorption and particle density of random samples of the coarse CCA, and extracting cores from larger sections for compressive strength testing. The results of characterisation are presented in Appendix E. Tests were conducted for potential contamination problems in the form of alkali and chloride ion content. Petrographic analysis was also undertaken 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.

The full results of characterisation are presented in Appendix E and F. In summary it was found that little correlation exists between the water absorption/particle density, equivalent in-situ strength and the petrography results. Little correlation also exists between the cement content, equivalent in-situ strength and estimated cement content. Collectively however, 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 compressive cube strength and durability performance of structural concrete. Sources A and C have similar compositions, with source A having a higher estimated cement content, a better visual grading of coarse aggregates and no evidence of microcracking.

The effect of coarse CCA on the compressive cube strength and durability properties of structural concrete was investigated. Forty different CEM I and CEM III/A concretes were produced to achieve a characteristic and target mean strength of 44MPa and 58MPa respectively with a water/binder ratio of 0.5, using the BRE method of mix design to determine the mix constituents (BRE, 1997). The characteristic and target mean strengths were adjusted to comply with the average compressive cube strength of CEM I concrete with 100% natural aggregates. The coarse CCAs were incorporated at 30%, 60% and 100% replacement of natural aggregates. The coarse aggregate size proportions of 4/10mm and 10/20mm for both natural aggregate and CCA were added at a ratio of 1:2 respectively (BRE, 1997). GGBS was incorporated at 36%, 50% and 65% to replace Portland cement by mass to produce a range of CEM III/A concretes. A yield calculation was undertaken to account for the different densities of materials, to ensure a constant volume of concrete.

The concrete mixes were coded by the numeric GGBS content, followed by A, B or C for the relevant CCA source and the numeric coarse CCA content. For example, a mix denoted as 36A-60 refers to a concrete produced with 36% GGBS and CCA source A at 60%.

The two resulting publications are in Appendices E and F. Papers 4 and 5 have been published in Construction and Building Materials (Dodds *et al*, 2017d,e). The properties reported were divided between the publications as shown in Table 4.4.

Table 4.4 Concrete testing undertaken as part of Work Package 3

Paper 4 – Appendix E Theme: Effect of coarse CCA on compressive cube strength, microstructure and water ingress of structural concrete	Paper 5 – Appendix F Theme: Effect of coarse CCA on rapid chloride migration and accelerated corrosion
Compressive cube strength	Rapid chloride migration
Surface resistivity	Accelerated corrosion
Bulk resistivity	-
Absorption by capillary action	-
SEM analysis	-

4.3.2 PAPER 4 – APPENDIX E

This study investigated the effects of three sources of coarse CCA from known structural components on the compressive cube strength, microstructure and water ingress of structural concrete at various ages.

The characteristic strength of 44MPa at 28 days was achieved by 24 of the 40 concrete mixes. CEM III/A concretes (up to 50% GGBS replacement level) produced with coarse CCA contents up to 60% for sources A and C, and 30% for source B, achieved the characteristic strength. In comparison 37 of the 40 concretes achieved the characteristic strength by 91 days (Figure 4.15), with only the 65B-100 concrete having a statistically high probability of non-compliance. Therefore, if the characteristic strength at 28 days is of particular importance (as is usually the case in the construction industry), it is recommended that the GGBS and coarse CCA content be restricted to 50% and 30% respectively. If a different approach is adopted whereby the long term 91 day compressive cube strength performance is assessed for compliance, then higher quantities of coarse CCA content can be utilised, producing a more sustainable structural concrete. In this case the coarse CCA content may be increased to 60% without significantly increasing the risk of not achieving the characteristic strength, which is higher than previously reported values of 25-50% (Etxeberria *et al*, 2007; Padmini *et al*, 2009; Tabsh and Abdelfatah, 2009; Bravo *et al*, 2015a).

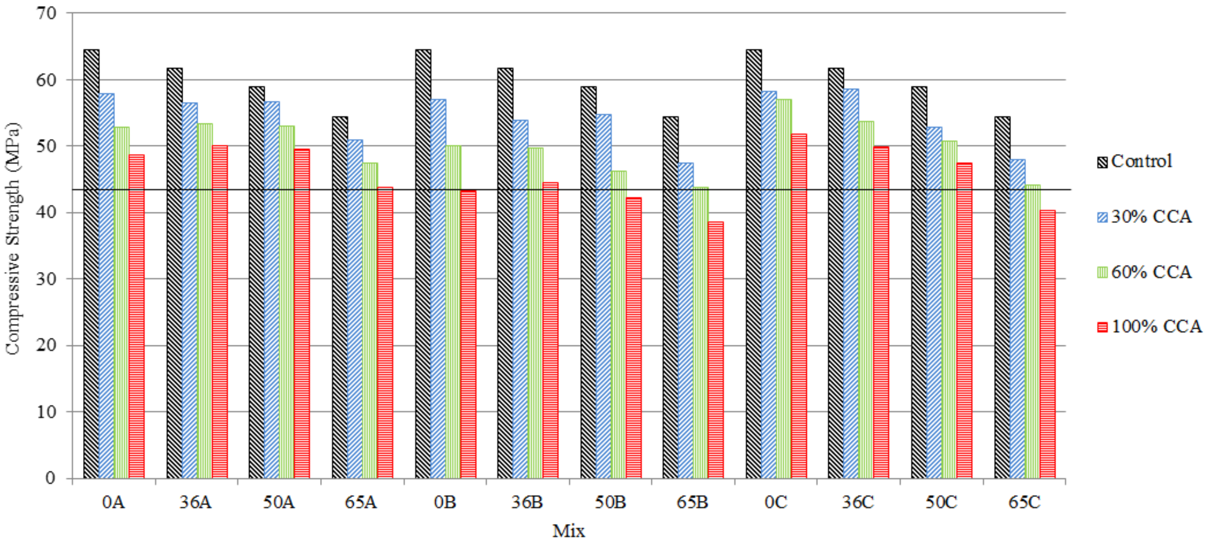

Figure 4.15 Compressive strength at 91 days

The results of surface and bulk resistivity and absorption by capillary action have shown 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 concrete (Figures 4.16 and 4.17). The inclusion of coarse CCA generally reduced the surface and bulk resistivity and resulted in an increase in 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 (Limbachiya *et al*, 2012; Pedro *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Lofty and Al-Fayez, 2015; Bravo *et al*, 2015b). 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. This is significantly higher than previously reported values of

25-50% (Limbachiya *et al*, 2012; Kou and Poon; 2013; Soares *et al*, 2014; Zega *et al*, 2014; Lofty and Al-Fayez, 2015).

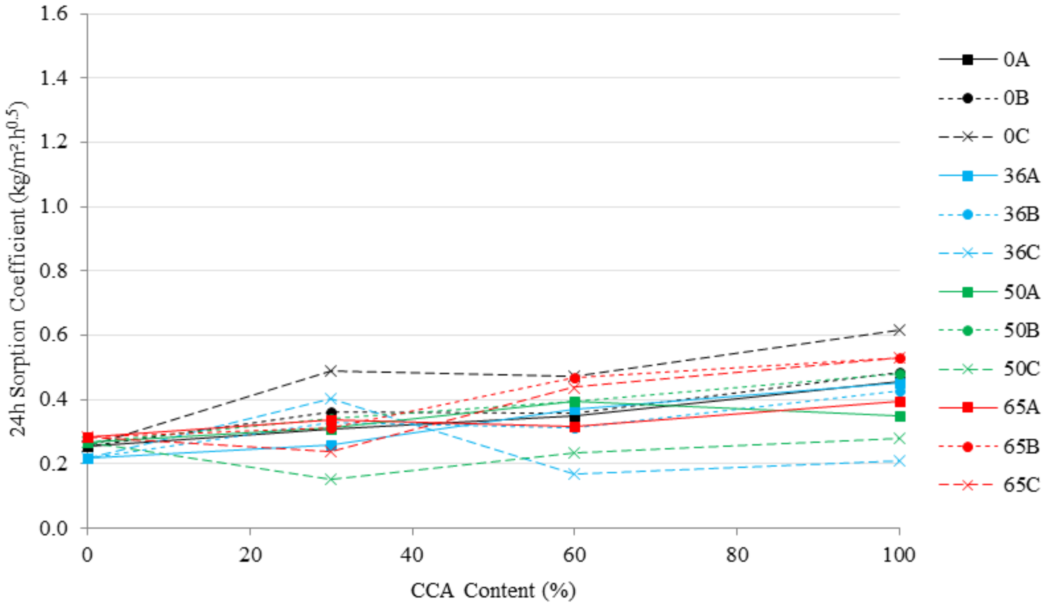

Figure 4.16 24hr Sorption coefficient at 28 days

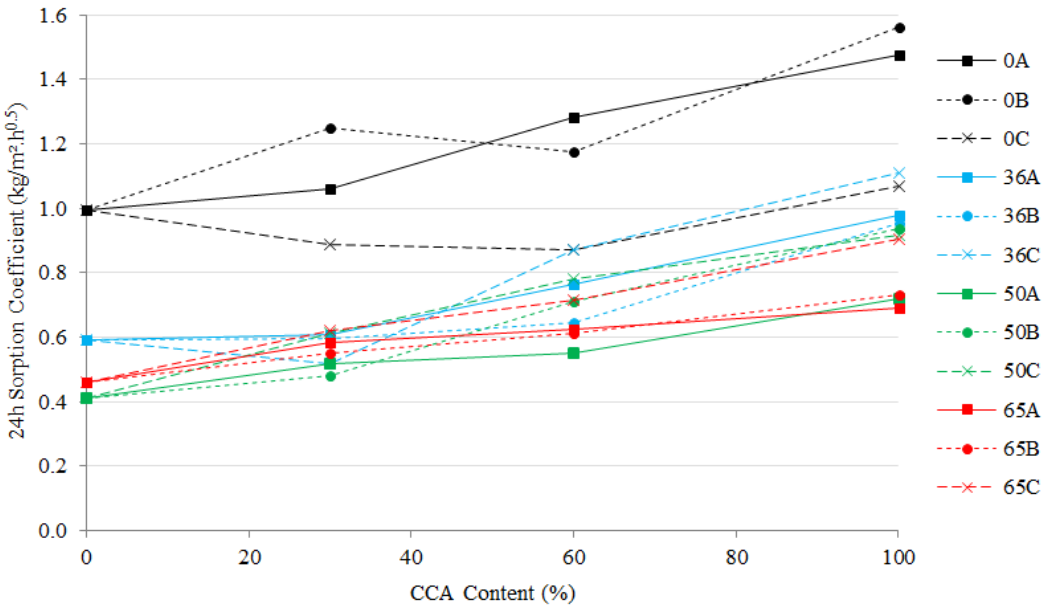

Figure 4.17 24hr Sorption coefficient at 91 days

BS8500 provides guidance for cover depth and concrete mix design proportions based on the binder type and environmental exposure conditions (BSI, 2015a,b). It suggests that the cover depth 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.

The SEM analysis of the microstructure of concrete, particularly the quality of ITZ between the new cement matrix and aggregates, revealed no additional voids due to the release of air from coarse CCA in this case (Figure 4.18). This result contradicts previously published work in this field (Leite and Monteiro, 2016), and further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes.

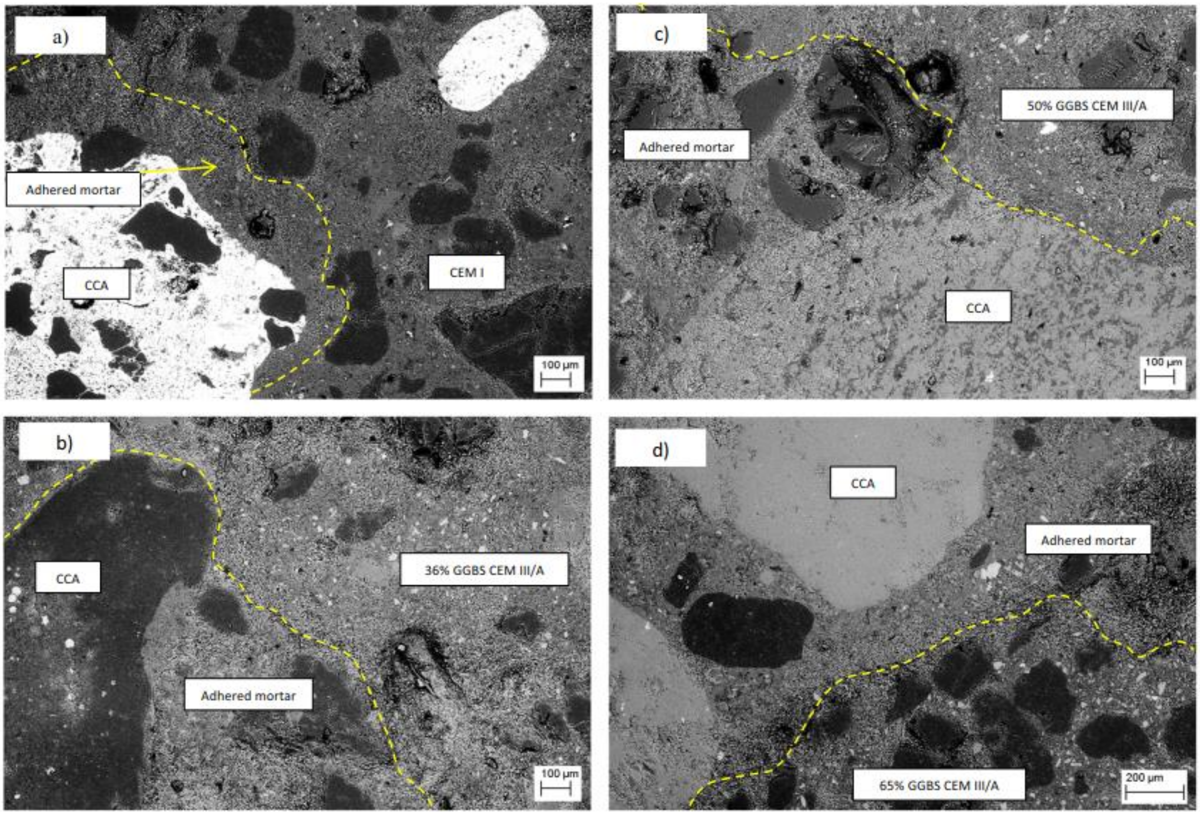

Figure 4.18 SEM high resolution images for a) CEM I, b) 36% GGBS, c) 50% GGBS and d) 65% GGBS CCA concretes

Taking a holistic review of the combined results, source B CCA was found to be the poorest performing aggregate for the majority of tests and concrete types, followed by sources A and C respectively. It is recommended that sources of coarse CCA be tested in a similar manner before inclusion within structural concrete to foresee any potential risks to mechanical and durability performance. In particular the results of water absorption, chemical analysis and petrographic analysis had a good correlation to potential performance. Further analysis and discussion is presented in Appendix E.

4.3.3 PAPER 5 – APPENDIX F

Testing the same structural concrete mixes as in Paper 4, an investigation was conducted into the effects of three sources of coarse CCA from known structural components on the rapid migration coefficient and accelerated time to corrosion initiation and cracking at various ages.

Six unreinforced and four reinforced concrete cylinders (200mm × 100mm diameter) were cast for each mix. In the reinforced specimens, steel reinforcing bars (12mm in diameter) were placed centrally, with a 50mm cover depth to the base of the cylinder. For accelerated corrosion, the test was terminated when a visible crack was observed (greater than 0.3mm), as this can be indicative of a failure of the protective concrete cover (Figure 4.19) (BSI, 1992; Raupach, 1996; Concrete Society, 2004a,b; Concrete Society, 2010a). Upon termination of the test, specimens were split axially along the crack plane and the minimum concrete cover was measured.

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 indicated by an increase in the chloride migration coefficient and a reduced time to corrosion initiation and cracking. Nevertheless, 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 (Figures 4.20 and 4.21). This highlights the beneficial latent hydraulic effects of GGBS at increasing the resistance to chloride ion ingress, particularly at later ages (Dhir *et al*, 1996; Glass *et al*, 1997; Glass and

Buenfeld, 2000; Reddy *et al*, 2002; Bapat, 2013), 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.

Figure 4.19 Typical cracking of 200mm × 100mm diameter reinforced concrete cylinder

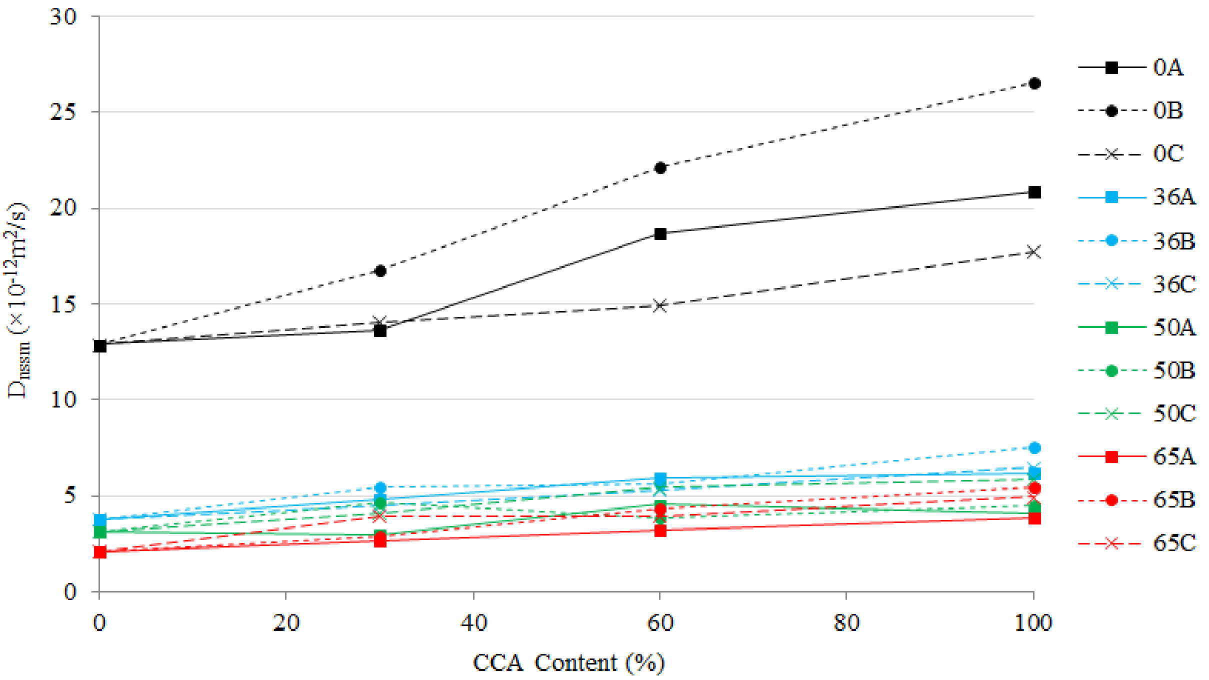

Figure 4.20 Rapid chloride migration coefficient (D_{nssm}) at 91 days

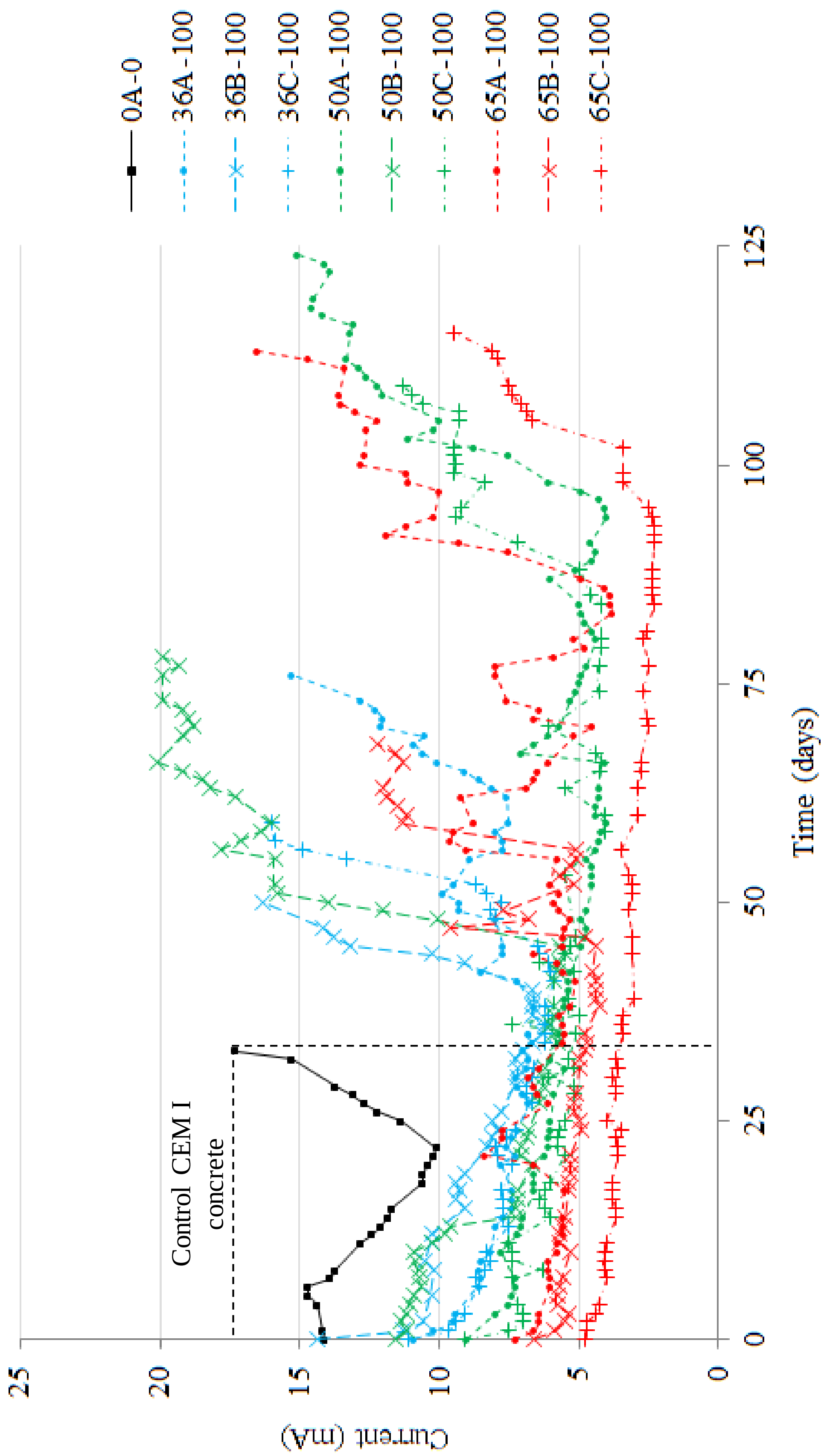

Figure 4.21 Time to corrosion initiation and cracking (91 days)

The current (mA) for CEM I concretes at 91 days was higher than at 28 days, particularly after corrosion has initiated; the corrosion initiation and cracking also occurred at a faster rate. Contrary to this, the 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. A similar observation was made on 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 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. Similar to Paper 4, source B CCA was found to be the poorest 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 on the rapid chloride migration coefficient. The results of water absorption, chemical analysis and petrographic analysis were found to have a good correlation to potential performance.

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5 FINDINGS & IMPLICATIONS

This section explains the key findings from the research, discusses the contribution to the existing international knowledge base and the potential wider impact on the industrial sponsor. It also makes recommendations for further research and provides a critical review of the research.

5.1 KEY FINDINGS OF THE RESEARCH

The key findings of the complete EngD programme, undertaken in accordance with the methodology described in Section 3 are summarised below. The detailed findings are presented in the published research papers in Appendices B to F which collectively contributed to the project aim and objectives.

5.1.1 CRITICAL LITERATURE REVIEW

The main findings of the critical review of literature are as follows:

1. The limited availability of published research on the effect of coarse CCA on the durability performance of structural concrete demonstrated that further research is required if a more robust framework for the implementation of coarse CCA is to become a possibility in the future. This research therefore focused on durability performance, with particular emphasis on chloride ion ingress and corrosion initiation.

2. The majority of published work analyses coarse CCA from a single source, which is often not defined, has been produced in a lab environment, and/or lacks characterisation (unknown properties and/or original constituents). Recommendations for the characterisation of coarse CCA sources are therefore required to strengthen the conclusions of future research, alongside the testing of coarse CCA sources that are representative of circa 40+ year old demolition arisings.

3. Chloride-induced corrosion is the most common cause of significant deterioration to reinforced concrete infrastructure (Concrete Society, 2004a,b; NACE International, 2012, NAO, 2014). This therefore became the main focus of the research in relation to durability performance.

4. The addition of SCMs have been shown to be beneficial in aggressive chloride ion environments due to the reduced the porosity of the cement matrix, improved quality of the ITZ and/or the increased chloride binding capacity of concrete (Dhir *et al*, 1996; Dhir *et al*, 1997; Neville, 2011).

5.1.2 CURRENT INDUSTRY PERCEPTIONS

1. Large quantities of CDW are available in the UK and across Europe (Monier *et al*, 2011; NFDC, 2016). The majority of CDW is utilised in non-structural applications such as: general fill material, road base layers and low grade concretes.

2. There is strong evidence to support a positive shift in the way the construction industry approaches responsible sourcing and the re-use of CDW in new construction projects, to optimise the quality and utilisation of recycled aggregates (EC, 2008; Environment Agency and WRAP, 2013; Barritt, 2015; MPA, 2016).

3. In the UK and other developed countries, where recycling rates are high, situations may still arise where coarse CCA may be a suitable replacement material in structural concrete, such as: a specific project/client requirement; improved project sustainability credentials; a good quality, consistent source of CCA is available on-site; and/or where there is a short supply of natural aggregates (Filho *et al*, 2013; Hassan *et al*, 2016; Yehualaw and Woldesenbet, 2016; McGinnis *et al*, 2017).

4. The current allowable replacement level for coarse CCA in British and European standards is 20% and 30% respectively, for certain exposure classes (BSI, 2013b; BSI,

2015a,b). There is a more cautious approach to the specification of coarse CCA when designing concrete for highways structures which suggests that major asset owners are less likely to use a material which may compromise the integrity of the structure or increase the risk of early deterioration (DMRB, 2007; MCHW, 2014, MCHW, 2016).

5. In addition to testing concrete specimens for durability performance, testing for compressive cube strength is considered to be an important factor to determine the compliance with characteristic strength as a quality control measure and is standard protocol in the UK construction industry (BSI, 2009a).

5.1.3 Effect of coarse CCA and SCMs

Section 4 provides further detail on the work packages and laboratory testing undertaken to determine the main findings, as summarised below. Further detail is provided in Appendices B to F.

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. GGBS in itself is a by-product of the steel production industry which further improves the sustainable credentials of structural concrete.

3. The results presented in Appendices B and C also indicate that the use of PFA (at 30% replacement of Portland cement), to produce CEM II/B-V concretes, allows higher proportions of coarse CCA to be included; however, it was found to perform worse than CEM III/A concretes for all test methods adopted. The inclusion of PFA was also only tested for one source of coarse CCA, up to 60%, with unknown constituents therefore it is difficult to conclude whether similar effects would be observed for all CEM IIB-V concretes.

4. Throughout the experimental programme it was established that SCMs have a beneficial effect on the durability performance of structural concrete, as confirmed by findings 2 and 3 above. For the majority of test methods adopted, the improved performance was much greater than the detrimental effect of coarse CCA, which suggests that the selection of SCMs is more important than the type and origin of coarse aggregates used.

5.1.4 SUITABLE REPLACEMENT LEVEL OF COARSE CCA

The following recommendations for suitable replacement levels are based upon the statistical analysis of empirical data presented in Section 4 and Appendices B to F, and can be summarised as follows:

1. 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. Replacement levels above 30% increase the risk of a non-compliant concrete with the specified characteristic strength, as confirmed by the statistical analysis. 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.

2. 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.

3. As previously stated, the inclusion of PFA was also only tested for one source of coarse CCA, up to 60%, with unknown constituents therefore it is difficult to conclude whether similar replacement levels are suitable for CEM IIB-V concretes without further research.

5.1.5 CHARACTERISATION

1. The results of water absorption, and chemical and petrographic analysis, as presented in Appendices E and F for sources of coarse CCA with known compositions had a good correlation with the compressive cube strength and 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.

2. Although further characterisation of source materials would incur a higher initial cost to a project, the data collected provides valuable information regarding the potential impact on mechanical and durability performance, which could ultimately lead to a more robust framework for the implementation of suitable coarse CCA in structural concrete.

5.1.6 FUTURE OF COARSE CCA

1. The quantities of coarse CCA are increasing annually and utilisation in higher value applications is becoming a popular alternative as there is a potential to increase profit (Barritt, 2015; WRAP, 2015a, MPA, 2016). 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.

5.2 CONTRIBUTION TO THEORY AND PRACTICE

1. This research has clearly demonstrated that the existing limitations in British and European standards are stringent (20% and 30% coarse CCA respectively), particularly when coarse CCA structural concrete is to be exposed to aggressive chloride ion environments. Higher quantities of coarse CCA (up to 60%) have been shown to be suitable, which is more than double the existing allowance in national specification standards. This study highlights the requirement for stronger collaboration between academia and the construction industry to develop new best practice guidelines and legislation, and encourage the increased specification of coarse CCA in structural concrete.

2. A wide variety of tests have been conducted as part of the research programme to give a more comprehensive and credible assessment of the overall durability of coarse CCA concrete with SCMs. The chosen durability tests looked to assess the effect of coarse CCA on key liquid transport mechanisms associated with water and chloride ion ingress, namely: absorption by capillary action, diffusion and migration. The simpler, short term durability tests (such as measuring the water absorption by

capillary action, surface and bulk resistivity and rapid migration) are useful in determining the potential performance of coarse CCA structural concretes at early ages (28 and 91 days), and could be used in addition to compressive cube strength results to determine suitability. This holistic approach to testing is supported by the recent industry interest in moving to performance-based specifications for durable concrete.

3. A particular novelty of this research comes from collecting coarse CCA sources that are representative of 40+ years old demolition arisings, from known structural elements, and attempting to characterise the materials before use. It is recommended that characterisation, in the form of water absorption, and chemical and petrographic analysis, be undertaken to strengthen the conclusions of future research and to provide some indication of potential performance in construction. It is hoped that this approach will lead to a better understanding of the materials being specified and help to address the poor perception of coarse CCA in structural concrete. The recommendation for characterisation also highlights the benefits of segregating good quality reinforced concrete sources on demolition sites.

4. It has been shown that the selection of SCMs is more important for concrete durability than the type and origin of coarse aggregates used, as the majority of coarse CCA structural concretes with SCMs in this study outperformed the control concrete with natural aggregates. This finding is in agreement with the majority of existing literature on the beneficial effects of SCMs on concrete durability (Table 1.7).

5.3 IMPACT ON THE SPONSOR

AECOM has supported the research comprehensively throughout the entirety of the EngD and has stated from the outset that it was not critical for the research project to be of commercial gain. Instead, the research has provided the following benefits to the industrial sponsor:

1. The research has led to deeper understanding of coarse CCA and has provided recommendations for the wider implementation into structural concrete applications. This would not have been possible without the collaboration between the industrial sponsor and Loughborough University, which highlights the importance of strong relations between academia and industry when conducting high level research.
2. The findings of the research have not yet been incorporated into a real industry project, whereby structural concrete has been specified with quantities of coarse CCA beyond the limitations imposed by design standards. In this case, AECOM has not directly benefitted in terms of commercial competitiveness; however, the company brand has been associated with this innovative research through conference presentations and the production of high quality publications which generates discussion. In May 2017, this project was also nominated for the ICE West Midlands Awards and was highly commended in the 'Studies and Research' project category. This demonstrates AECOM's commitment to improving sustainability and providing innovative solutions which may potentially help to win work for AECOM in the future. It is likely that the recommendations may be implemented in a trial scheme which would require subsequent long-term durability and corrosion monitoring to compare against laboratory findings from this research. It is hoped that the results would correlate well to those obtained in the laboratory and help improve the general perception of coarse CCA to encourage its use in structural applications.

3. Throughout the EngD programme AECOM were able to incorporate a RE into their design team, who may bring a different perspective to a chosen design solution as they have close links with academia and the current developments in research. This again highlights the benefit of collaboration between academia and industry.

4. Following on from the EngD, it is envisaged that there will be opportunities to publish articles in well-established civil engineering and concrete production magazines, as well as internal publications within AECOM, to further raise the profile and awareness of the findings of research.

5.4 IMPACT ON 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. Segregation would help when re-using the material on site or transporting to a recycling plant for further processing as the resultant material would be suitable for higher value applications. To make this a possibility, the requirement of segregation would need to be clearly communicated to the demolition contractor at an early stage so that any additional costs and risk can be accounted for. 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. In reality, segregation can be difficult for demolition contractors due to time and space constraints on site, which typically results in mixed CCA and poor quality materials. Furthermore, the selection of suitable structural components for segregation would need to be undertaken by a competent individual and supervised

throughout; the segregation of demolition arisings may therefore only be possible at particular sites.

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. The sustainability benefits of coarse CCA are optimised when transportation distances are kept to a minimum (Georgopoulos and Minson, 2014). 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 for use. In this case, situations may arise whereby coarse CCA is the preferred replacement materials for natural aggregates in structural concrete when a quality, consistent source is available nearby or on site.

5.5 RECOMMENDATIONS FOR FURTHER RESEARCH

The recommendations for further research are as follows:

1. The novelties of this research come from collecting coarse CCA sources that are representative of circa 40+ years old demolition arisings, from known structural elements, and attempting to characterise the materials before utilisation, which has yielded positive results. It is acknowledged that further research is required to test a wide range of coarse CCA sources, including commercially available sources from recycling plants, mixed demolition arisings and those from specific structural elements, and analyse their effect on durability performance subject to different exposure conditions. This research is crucial if the current perceptions and approaches to the specification of coarse CCA are to change. There is also an opportunity to use a volumetric method to replace the coarse natural aggregates with CCA in comparison to replacement by mass, which is a common approach for lower density aggregates.

2. It was observed in work package 1 that the inclusion of GGBS (at 50% replacement of Portland cement) performed better than PFA (at 30% replacement of Portland cement) in all durability tests conducted, and so it was decided that the remaining research would focus on incorporating GGBS at varying levels of replacement (Appendices B and C). Further research is required to establish the durability performance of coarse CCA structural concrete using varying levels of other SCMs including PFA, Silica Fume and Metakaolin, but also tertiary blends that combine these SCMs and further reduce the quantity of Portland cement. The research can also examine various water-cement ratios, different sources of coarse CCA and natural aggregates and attempt to produce acceptable performance criteria for coarse CCA concretes.

3. This research did not compare CEM I and CEM III/A concretes of equivalent strength at 28 days as the binder content was kept constant for all concretes throughout. There is an opportunity for further research into the durability performance of coarse CCA concretes made with a high binder content which may further improve durability performance. The specification of higher binder contents however may offset the sustainability benefits of coarse CCA.

4. The results presented in Appendix C based on the measurement of chloride ion ingress when structural reinforced concrete specimens are subject to cyclic wetting/drying warrant further investigation. Following 18 months of corrosion risk monitoring it was found that no corrosion had occurred and that the probability of corrosion initiation was low based on commonly used interpretation criteria. Ponding of these specimens with 3% chloride ion solution will be continued beyond the completion of the EngD programme with the objective of obtaining long-term monitoring data and a more accurate prediction of time to corrosion initiation. These results may eventually be

analysed for correlations against apparent diffusion coefficients obtained from the rapid chloride migration testing to determine if simpler shorter-term tests can be used to predict potential performance.

5. A key finding of the investigation of the microstructure of structural concrete using SEM analysis techniques found that no additional voids around the ITZ were evident in the case of the three coarse CCA sources tested, suggesting that any observed detrimental effect may be due to other causes. This finding contradicts similar previously published work in this field and it is recommended that further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes, as this finding may not be a true representation of all coarse CCA sources.

6. Further work is also required on innovative processing techniques that can improve the performance of coarse CCA, as demonstrated by more recent studies (Section 1.3.8). Research of this nature is critical to the wider implementation of coarse CCA in higher-value applications, but should also focus on realistic and sustainable practicable solutions that do not have an adverse effect on the environment.

5.6 CRITICAL EVALUATION OF THE RESEARCH

The research programme and its associated conclusions and recommendations are based on the findings of a large-scale laboratory programme. The limitations listed below are not an attempt to detriment the research work undertaken but provide clarity on the constraints encountered. It is important to acknowledge the limitations of the work in order to reflect on how best to interpret and implement the findings.

1. As previously stated, it was identified at an early stage of the research that collection of data from real-scale structures would be difficult due to availability of structures produced with coarse CCA, but also the limited quantity that would be exhibiting

signs of physical deterioration. The majority of findings in other published work are based on structural concrete produced in a laboratory environment, which may not be representative of in-situ site-based structural concrete. This research however, did incorporate coarse CCA sources that are representative of 40+ years old demolition arisings, with known and unknown compositions.

2. The findings of the research are also based upon coarse CCA sources in CEM III/A structural concretes at a water/binder ratio of 0.5. The water-binder ratio and replacement levels of Portland cement with GGBS were chosen based on commonly adopted values when designing structural concrete. It is acknowledged that a wider range of water/binder ratios and replacement levels of Portland cement with various SCMs would also comply with the durability recommendations provided in BS 8500 for different exposure conditions, which require further investigation.

3. The five coarse CCA sources obtained were found to cover a broad range of compressive strengths. These sources are not necessarily representative of all demolition arisings available and more sources require testing to better understand the likelihood of variability in results.

4. The data collected from reinforced concrete specimens subjected to cyclic wetting/drying was undertaken over a period of 18 months. This is a relatively short period of time when compared to the rate of chloride ion ingress in real-scale structures. Longer periods of testing would be preferred to confirm the low risk of corrosion initiation; however the sampling time was limited due to time constraints of the EngD programme.

5. The conclusions and recommendations of the research are based on the results of well-established durability test methods that cover the different transport mechanisms of

concrete. A variety of test methods were adopted as this provides a holistic analysis of the effect of coarse CCA on durability performance. Additional test methods are available which could not be undertaken due to time and cost restraints of the project.

6. The 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 results are compared against a reference concrete. 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. 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 ion ingress data on similar structural CCA concretes.

Overall, this research has highlighted that sustainable structural CEM III/A concretes can be a viable option for future responsibly sourced projects, provided that a reliable and consistent source of coarse CCA can be obtained. Characterisation of coarse CCA sources has been recommended in the form of water absorption tests, and chemical and petrographic analysis to provide an indication of potential performance before specification in structural concrete. The findings presented are a significant and positive outcome for the wider implementation of coarse CCA into structural concrete applications and should be considered when specifying the re-use of demolition concrete arisings.

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APPENDIX A LIST OF ADDITIONAL PUBLICATIONS

- Dodds, W. Christodoulou, C. Goodier, C.I. Austin, S.A, 2014. *Performance evaluation of galvanic anodes through laboratory testing and on-site monitoring*. IN: Bjegovic, D., Beushausen, H., Serdar, M. (eds). *Proceedings of the RILEM International Workshop on Performance-Based Specification and Control of Concrete Durability*, Zagreb, Croatia, 11th – 13th June 2014, pp175-182.

- Dodds, W. Christodoulou, C. Goodier, C, 2016. *Hybrid anode concrete corrosion protection – independent study*. Proceedings of the Institution of Civil Engineers - Construction Materials. Ahead of print. DOI: 10.1680/jcoma.16.00024.

- Dodds, W. Christodoulou, C. Goodier, C. Atkins, C. Preston, J, 2017. *Discussion: Hybrid anode concrete corrosion protection – independent study*. Proceedings of the Institution of Civil Engineers - Construction Materials. Ahead of print. DOI: 10.1680/jcoma.17.00026.

- Dodds, W. Goodier, C. Austin, S. Christodoulou, C. Dunne, D. Chan, M, 2017. *The effect of fine crushed concrete aggregate on the durability of structural concrete*. IN: De Schutter, G. De Belie, N. Janssens, A. Bossche, N.V.D. (eds). *RILEM Proceedings PRO 107 - XIV DBMC – 14th International Conference on Durability of Building Materials and Components*, Ghent, Belgium, 29th – 31st May 2017, pp 125-126.

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APPENDIX B PAPER 1

Full Reference

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D. Fitt, M. Snowden, P, 2016. *Durability performance of structural concrete made with coarse recycled concrete aggregates*. IN: Beushausen, H. (ed.). Performance-based approaches for concrete structures: Proceedings (fib Symposium 2016), Cape Town, South Africa, 21-23rd November 2016. ISBN: 978-2-88394-120-5. https://dspace.lboro.ac.uk/2134/23683.

Abstract

There is often a poor perception of the durability of concrete made with recycled concrete aggregates (RCA), as well as concerns regarding performance variability and contamination of the source material. Additional research regarding the addition of RCA in structural concrete is therefore required to more clearly determine the limits of its suitability.

The influence of RCA on the mechanical properties of concrete has been well investigated; the effect on durability however, is less well understood. Chloride ions can be particularly detrimental to the durability of reinforced concrete and BS 8500 currently allows RCA in strength classes up to C40/50 for structures unlikely to be exposed to de-icing salts and marine environments during their design life. This research investigated the effect of coarse RCA in combination with supplementary cementitious materials on the resistance to chloride ingress of concrete in terms of surface resistivity, sorptivity and rapid chloride migration testing. Compressive cube testing was conducted to determine compliance with characteristic and target mean strengths.

The results indicate that a higher replacement of natural aggregates with RCA causes a reduction in the resistance to water and chloride ingress, possibly due to the higher water absorption characteristics of the RCA. PFA and GGBS reduced the rate of water and chloride ingress compared to Portland cement concretes for all coarse RCA increments tested.

Keywords – Recycled concrete aggregates (RCA), durability, chloride ingress, corrosion

Paper type – Conference

1 INTRODUCTION

Recycled aggregates (RA) have become an increasingly popular construction material to replace virgin aggregates since the beginning of the 1980's. Approximately 13.5 and 18.8 million tonnes of hard demolition arisings became available in the UK in 2013 and 2014 respectively (NFDC, 2015). UK government statistics suggest that low amounts of demolition waste are now sent to landfill, and that the recycling target of 70% by 2020 for the demolition and construction industry has already been achieved (DEFRA, 2015). The increase in recycling of demolition materials in recent years has been accelerated by government strategies and industry best practice guidance (BERR, 2008; WRAP, 2009; WRAP 2015).

Recycled concrete aggregates (RCA) are mainly utilised in general fill, road base/sub-base materials and low-grade concrete, as the quality of these aggregates are generally of less importance (WRAP, 2008). A recent study has shown that the sustainability benefits of RCA are soon diminished when the material has to be transported long distances, and virgin aggregates become the preferred option (Georgopoulos and Minson, 2014). It is important to improve the general perception of RCA so that it can be incorporated into a wider variety of applications, including structural concrete.

It is a general perception that the inclusion of RCA requires an increased cement content to compensate for the lower quality of aggregates (Georgopoulos and Minson, 2014; Agrela et al, 2013). In recent years pilot schemes, and also major construction projects globally, have included RCA without the need for additional cement by incorporating supplementary cementitious materials (SCMs) (Messari-Becker et al, 2014; Filho et al, 2013). These case studies have found that the carbon footprint and environmental impact of projects could be significantly reduced, which has led to the need for research to better understand the effects of these aggregates.

The European standard for concrete specification provides recommendations for coarse RCA ($d \geq 4$mm) 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, 2013). This limit can be increased to 50% if no reinforcing steel or embedded metal is present. If the source of the RCA is unknown or does not conform to the criteria of Type A aggregates (>95% concrete products, unbound aggregate and natural stone) (BSI, 2002a) then the replacement allowance for the majority of exposure classes, including chlorides, reduces to 0%. The UK standard for the specification of concrete allows crushed concrete aggregate (CCA) in concrete up to strength class C40/50, except when the structure is likely to be exposed to chlorides. The 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 (BSI, 2015a,b).

A review of research work has highlighted a general consensus that RCA has a detrimental effect on the mechanical properties of concrete (WRAP, 2007; Ajdukiewicz and Kliszczewicz, 2002). The extent largely depends upon the replacement quantity, and the quality of the original concrete. Some studies have shown that RCA can be successfully incorporated at 30% for structural applications, without impacting the compressive strength (Limbachiya et al, 2000; Etxeberria et al, 2007).

The effect on durability is less well understood and requires further investigation, particularly when the RCA concrete is exposed to aggressive chloride environments, increasing the risk of corrosion to steel reinforcement. Recent research suggests water and chloride permeability increases proportionally with RCA content due to the increased water absorption of the aggregates (Lofty and Al-Fayez, 2015; Bravo et al, 2015; Soares et al, 2014; Pedro et al, 2014; Kwan et al, 2012). However, it has been shown that SCMs can significantly improve the durability performance of concrete made with RCA, due to the reduced porosity of the cement matrix and interfacial transition zones of aggregates (Hwang et al, 2013; Limbachiya et al, 2012; Somna et al, 2012; Berndt, 2009; Ann et al, 2008). Some SCMs can also increase the chloride binding capacity of concrete which reduces the free chloride content within the pores (Bapat, 2013). A wider variety of RCA sources, water/cement ratios and cement combinations requires investigation to improve our understanding of the trade-off between cement and aggregate sources.

The aim of this study was to examine one source of RCA with different cement combinations and its resistance to water and chloride ingress. The compressive strength was tested to determine compliance with the characteristic and target mean strength.

2 RCA COMPOSITION

RCA from a commercial recycling facility in Plymouth, UK, from mixed sources of concrete, was crushed to a 40mm down product including 0-4mm fines. The fines content and larger aggregates (>20mm) were sieved out to leave coarse RCA conforming to Type A recycled aggregates suitable for concrete production (BSI, 2013). RCA samples were analysed for cement content, alkali content and chloride content testing to BS 1881:124 (BSI, 2015c). The results are summarised in Table 1.

Given that the age, composition and source of the concrete were unknown, some assumptions were made regarding the original mix design. A concrete density of 2400kg/m³ was assumed, thus the data in Table 1 suggests a cement content between 265kg/m³ to 310kg/m³ in the original concrete(s), which may be representative of structural concrete. This however is not a sufficient indicator of the quality of the original concrete. An alkali content of up to 0.4% can be beneficial for strength development of concrete but quantities higher than 0.6% can cause expansive reactions of the aggregate (Neville, 2011). In this case the alkali content is lower than 0.6% and unlikely to cause contamination problems in the new concrete.

The chloride levels of the RCA are relatively low and are comparable to readings taken from non-contaminated reinforced concrete structures. This therefore indicates that the concrete structures that the RCA was obtained from were not exposed to severe chloride environments. It is generally accepted that a threshold level of chloride below 0.4% by weight of cement represents a low risk of corrosion initiation. (Concrete Society, 2004).

Table 1 - Laboratory analysis of RCA

Cement content (%) by mass of dried sample	Sample 01	11.1
	Sample 02	12.8
Alkali content (%) by mass of dried sample	Sample 01	K_2O – 0.12 Na_2O – 0.02
	Sample 02	K_2O – 0.19 Na_2O – 0.03
Chloride content (%) (acid soluble) by mass of dried sample	Sample 01	0.03
	Sample 02	0.02
	Sample 03	0.01

3 METHODOLOGY

A C28/35 concrete was cast as part of an initial testing programme to determine the effect of RCA on the durability performance of concrete. The BRE mix design method (BRE, 1997) was adopted for the design of concrete mixes to achieve characteristic and target mean strengths of 35MPa and 49MPa respectively. Portland cement (CEM I) and GGBS (50% - CEM III/A) concrete mixes were tested at a water-binder ratio of 0.5, and PFA (30% - CEM IIB-V) mixes at a ratio of 0.4, with a reduced water content for PFA mixes following the recommendations in the BRE mix design method (BSI, 2013). The water-binder ratios were chosen to comply with the recommendations for XD3/XS3 exposure classes in Table A.4 of BS8500-1 (BSI, 2015a). Coarse RCA was incorporated at 20%, 40% and 60% to replace natural coarse aggregates (rounded quartzite river gravel) by mass. An additional cement content was added to compensate for the inclusion of coarse RCA (10kg/m³ per 20% RCA) following the recommendations for crushed aggregates in the BRE mix design method. Table 2 details the test methods adopted to investigate the effect of coarse RCA on the durability properties of concrete.

Table 2 - Test methods

Test	Justification
Compressive cube strength (BSI, 2009)	To determine compliance of mixes with characteristic and target mean strengths and to analyse the effect of coarse RCA on compressive strength.
Surface resistivity (AASHTO, 2015)	To determine the effect of coarse RCA on electrical resistivity of concrete, to provide an indication of its ability to resist chloride ion penetration.
Absorption by capillary action (BSI, 2002b)	To determine the effect of coarse RCA on the sorptivity of concrete with no external pressures applied. This is the key transport mechanism of water and chloride ingress when concrete is in a dry state.
Rapid Chloride Migration (NordTest, 1999)	To determine the effect of coarse RCA on the chloride migration coefficient in concrete. The results cannot be directly compared to natural diffusion tests, however provides a rapid indication of durability performance.

Statistical analysis of the results was undertaken using t-tests to determine the effect on sample means when coarse RCA and SCMs were added. Probabilities were calculated based on a detrimental effect on performance by 10% when compared to the control concrete for each cement combination.

4 ANALYSIS OF RESULTS

4.1 COMPRESSIVE STRENGTH

Tests were conducted on 100mm cube samples at 7, 28 and 56 days. The results show that the inclusion of coarse RCA does have an increasing detrimental effect on compressive strength at both 28 and 56 days for all cement combinations tested, except for 20% RCA in Portland cement concrete (Figures 1 and 2 respectively). The target mean strengths (49MPa) for Portland cement and PFA concretes were met for lower levels of RCA inclusion (up to 40%), however was not achieved for any of the GGBS concretes at 28 days. In all cases the characteristic strength (35MPa) at 28 days was easily achieved.

A left-tailed t-test was used to determine if the addition of coarse RCA had a detrimental effect (10% decrease) on sample means. A high probability ($p>0.733$) was obtained for coarse RCA contents above 20% in the PFA concrete at 28 days. A lower probability was observed in Portland cement and GGBS concretes at 28 days ($p<0.384$ and $p<0.135$ respectively). The highest probability calculated for the concrete to decrease below the 28 day characteristic strength of 35MPa was $p=0.006$.

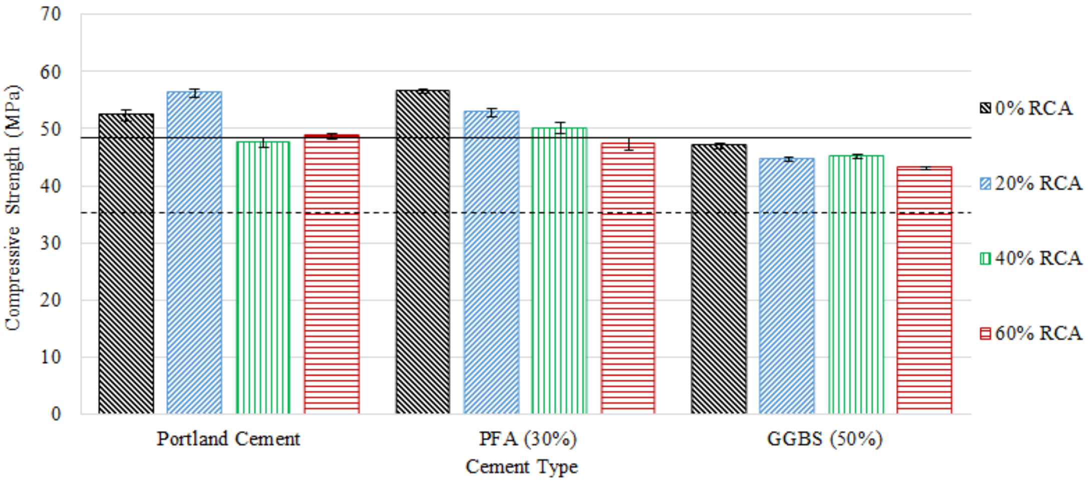

Figure 1 - 28 day compressive cube strength

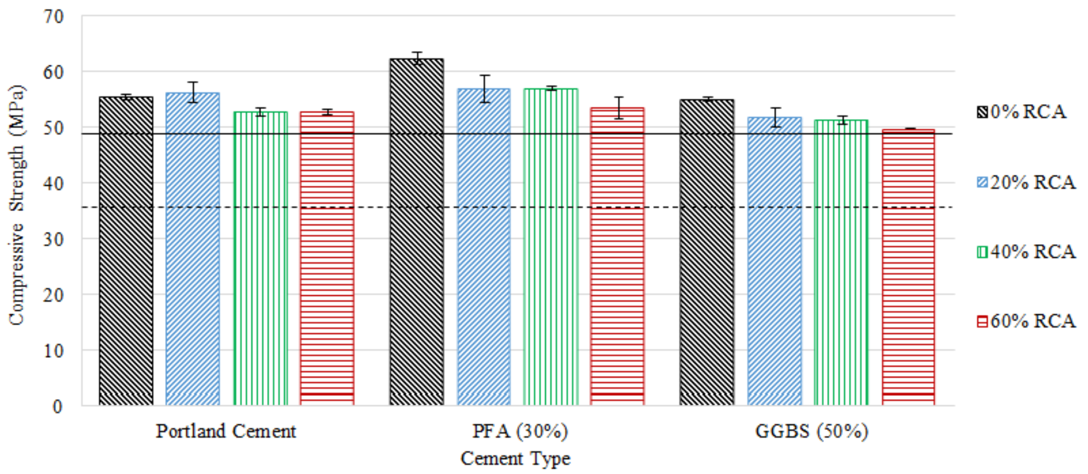

Figure 2 - 56 day compressive cube strength

4.2 SURFACE RESISTIVITY

The surface resistivity of cylindrical specimens (200mm x 100mm diameter) was measured at 28 days; a relatively quick method for assessing the microstructure and subsequent transport properties of concrete (Angst and Elsener, 2014). The results of surface resistivity testing are commonly interpreted following recommendations in Tables 3 and 4. A lower resistivity indicates a more porous concrete microstructure as it allows a higher current to pass between the probes at the surface. The results of the surface resistivity test are shown in Figure 3.

Table 3 - Interpretation of Wenner probe readings (Concrete Society, 2004)

Resistivity (kΩcm)	Interpretation
>20	Low corrosion rate
10-20	Low to moderate corrosion rate
5-10	High corrosion rate
<5	Very high corrosion rate

Table 4 - Interpretation of Wenner probe readings (AASHTO, 2015)

Resistivity (kΩcm)	Interpretation
<12	High chloride ion penetration
12-21	Moderate chloride ion penetration
21-37	Low chloride ion penetration
37-254	Very low chloride ion penetration
>254	Negligible chloride ion penetration

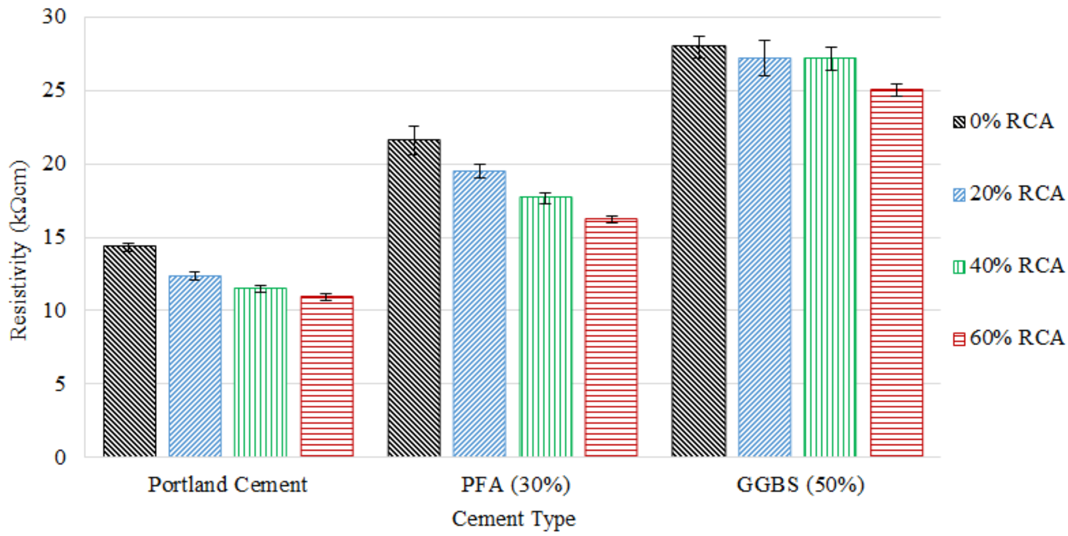

Figure 3 – Concrete surface resistivity at 28 days

The results show that the Portland cement concrete has the lowest surface resistivity followed by PFA and GGBS concretes respectively. The addition of coarse RCA had an increasing detrimental effect on the surface resistivity of the concrete, however all mixes tested remained within the low to moderate chloride ion penetration/corrosion rate range, even with up to 60% coarse RCA content. Statistical analysis showed a particularly high probability ($p>0.929$) that the surface resistivity would decrease by more than 10% when more than 20% coarse RCA content is included in the Portland cement and PFA concretes. A much lower probability was calculated for the GGBS concrete ($p<0.290$) with up to 60% coarse RCA content.

4.3 ABSORPTION BY CAPILLARY ACTION

Kropp *et al* (1995) describe sorptivity as the *'transport of liquids into porous solids due to surface tension acting in capillaries'*. The sorptivity is influenced by the characteristics of the liquid and solid material it is in contact with, particularly the radius, tortuosity and continuity of the capillaries. The concrete specimens (50mm x 100mm diameter slices) were sealed on all sides except the surface to be exposed to the water; therefore the capillary suction phenomenon is considered to be in non-steady state as no evaporation of liquid can take place. Cumulative absorption was measured at 28 and 120 days (Figures 4 and 5 respectively) and the sorption coefficient determined from the gradients (Table 5). Higher sorption coefficients were observed at 120 days compared to the 28 day readings for all cement combinations tested.

Low probabilities ($p<0.047$) were calculated for the total cumulative absorption (kg/m^2) to increase by more than 10%, when coarse RCA was included up to 60% for the 28 day readings. In contrast, higher probabilities of increased absorption ($p>0.563$) were observed at 120 days for the same effect. This suggests that the inclusion of RCA had a more detrimental effect on sorption at later ages. Statistical analysis of the data also showed that the inclusion PFA and GGBS reduced the probability ($p<0.008$) of a significant detrimental effect on the concrete.

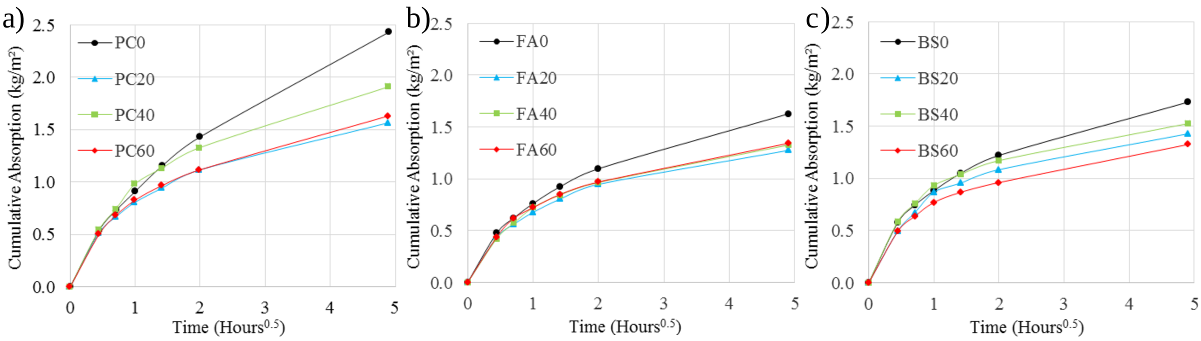

Figure 4 – Cumulative absorption at 28 days for a) Portland cement, b) PFA, c) GGBS concrete

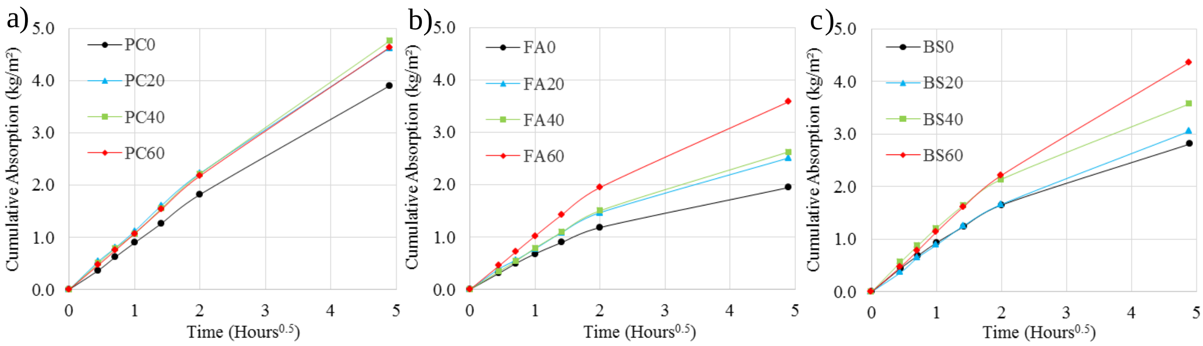

Figure 5 – Cumulative absorption at 120 days for a) Portland cement, b) PFA, c) GGBS concrete

Table 5 - Sorption Coefficients for all concretes tested

	Portland Cement				PFA				GGBS			
RCA Content (%)	0	20	40	60	0	20	40	60	0	20	40	60
28 Day Sorption Coefficient ($kg/m^2.h^{0.5}$)	0.50	0.32	0.39	0.33	0.33	0.26	0.27	0.27	0.35	0.29	0.31	0.27
120 Day Sorption Coefficient ($kg/m^2.h^{0.5}$)	0.80	0.94	0.97	0.95	0.40	0.51	0.54	0.73	0.57	0.62	0.73	0.89

4.4 RAPID CHLORIDE MIGRATION

Migration of chloride ions occurs when an electric field is applied across a concrete specimen (50mm x 100mm diameter slice), causing the negatively charged chloride ions to move towards the anode (Claisse, 2014). The non-steady state migration coefficients have been calculated from average penetration depths and are shown in Figure 6.

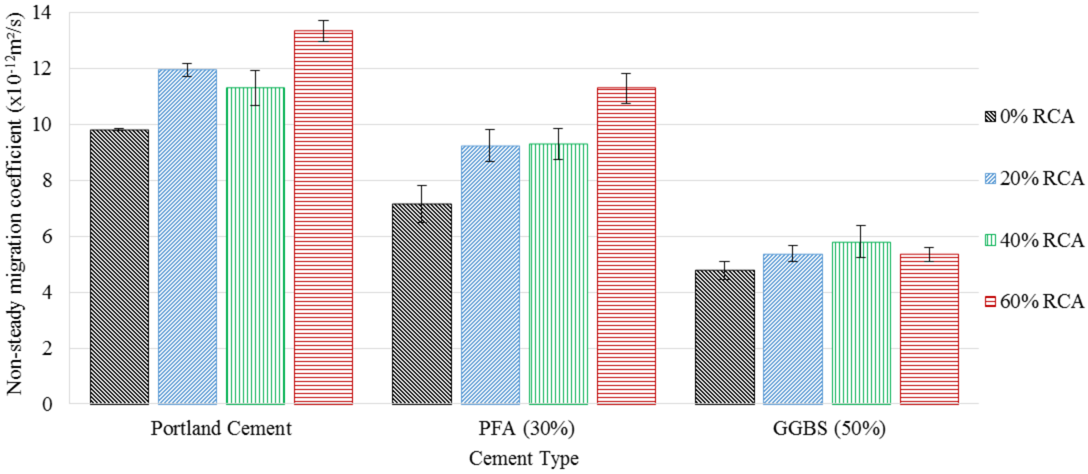

Figure 6 - Rapid chloride migration at 28 days

The results show that the inclusion of coarse RCA content generally had an increasing detrimental effect on the migration coefficient of concrete. Statistical analysis showed a particularly high probability ($p>0.727$) that the migration coefficient would increase by more than 10% when more than 20% coarse RCA content was included in the Portland cement and PFA concretes. A slightly lower probability was calculated for the GGBS concrete ($p<0.588$) with up to 60% coarse RCA inclusion. Statistical analysis of the data also showed that the inclusion of PFA and GGBS reduced the probability ($p<0.043$) of a significant detrimental effect on the concrete.

5 DISCUSSION

5.1 COMPRESSIVE STRENGTH

The statistical tests for 28 day results provide strong evidence that coarse RCA is detrimental to the compressive strength of concrete at higher increments than 20% in PFA and Portland cement concretes, similar to the findings of other published research work (Etxeberria *et al*, 2007; Ajdukiewicz and Kliszczewicz, 2002; Limbachiya *et al*, 2000). The particularly low probability of RCA causing a detrimental effect on compressive strength in GGBS concretes suggests that it is the most suitable replacement material. In this case, the extremely high probability for all concretes to achieve the 28 day characteristic strength suggests that the BRE method of mix design is suitable for designing concrete of sufficient strength with coarse RCA up to 60%. Figure 2 shows that the target mean strengths for all concretes was achieved after 56 days; this is particularly important for the concrete containing GGBS and higher levels of RCA inclusion (>40%). The benefits of SCM's are also demonstrated in Figures 1 and 2 with the continuing development of concrete strength due to pozzolanic and latent hydraulic effects.

5.2 SURFACE RESISTIVITY

Figure 3 shows that as the coarse RCA content increased the concrete surface resistivity in all cement combinations tested reduced, probably due to the RCA concrete having a more porous and open microstructure, as suggested by the higher water absorption of the aggregates (Pedro *et al*, 2014; Kwan *et al*, 2012). The inclusion of both PFA and GGBS increased the surface resistivity of concrete; however, the statistical analysis suggests that GGBS is more beneficial in reducing the porous microstructure of concrete and hence increasing resistivity. It should be noted that a reduced water-binder ratio for the PFA concretes would also contribute to an increased surface resistivity.

5.3 ABSORPTION BY CAPILLARY ACTION

The inclusion of both PFA and GGBS had a beneficial effect on the sorption coefficient of the concrete for all increments of coarse RCA tested, possibly due to the reduced porosity of the cement matrix (Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). The difference in probability values between 28 and 120 days suggests that the inclusion of RCA had a more detrimental effect on sorption at later ages. This is possibly due to the hydration process of the cement paste which has reduced the size and continuity of the capillaries in the concrete. The natural aggregate and RCA then becomes the more dominant pathway for the water ingress rather than the surrounding cement paste. Hydration of the cement paste also caused an increase in cumulative absorption due to increased surface tension effects of the smaller pores. The increased water absorption of the RCA therefore contributes to the increase in absorption by capillary action of the concrete. This finding is in agreement with the work of other published research in this field (Lofty and Al-Fayez, 2015; Bravo *et al*, 2015; Soares *et al*, 2014).

5.4 RAPID CHLORIDE MIGRATION

The results show that the migration coefficient can be reduced with the inclusion of both PFA and GGBS for all increments of coarse RCA tested, in agreement with other published work, and is possibly due to the reduced porosity of the cement matrix (Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). The probability values calculated for Portland cement, PFA and GGBS concretes suggest that GGBS is the more suitable replacement material for reducing the detrimental effect on the migration coefficient. This is possibly due to the combined effect of reduced porosity and the chloride binding capacity of the cement paste when a high quantity of GGBS is included within the mix (Bapat, 2013).

6 CONCLUSIONS

The results show that the inclusion of RCA has a slightly detrimental effect on the compressive strength of concrete. Statistical analysis of the results showed that for the concrete mixes tested in this study, the BRE method of mix design is suitable for designing concrete of sufficient strength with coarse RCA up to 60%. In all cases the characteristic strength was exceeded at 28 days. The benefits of SCMs on compressive strength are usually seen at later ages due to pozzolanic and latent hydraulic effects.

The results of the tests to investigate the effect of coarse RCA on the surface resistivity, resistance to water and chloride ingress of concrete has highlighted that RCA contents, even as low as 20%, have a detrimental effect on the durability of concrete. However, statistical analysis has highlighted that the addition of PFA (30%) and GGBS (50%) can significantly increase the surface resistivity and resistance to chloride migration whilst reducing water absorption of the RCA concrete for all replacement levels tested (up to 60%) which is in agreement with other published work in this field. The GGBS concrete performed better than the PFA and Portland cement concretes in all the test methods due to the combined effect of reduced porosity of the cement matrix and the chloride binding capacity.

These findings suggest that RCA could be a viable option for new structural concrete, even when the structure is likely to be exposed to chlorides during its service life, provided that a suitable level of SCM is incorporated. This conclusion is valid, provided that: a reliable and consistent source of RCA is obtained with no known sources of contamination or deleterious materials present; and the durability recommendations for minimum cement content, maximum water-cement ratio and minimum cover to reinforcing steel are met (BSI, 2015a).

7 ACKNOWLEDGEMENTS

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APPENDIX C PAPER 2

Full Reference

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D, 2017. *Corrosion risk assessment of structural concrete with coarse crushed concrete aggregate*. Proceedings of the Institution of Civil Engineers - Construction Materials. Ahead of print, DOI: https://doi.org/10.1680/jcoma.17.00056.

Abstract

Crushed concrete aggregates (CCA) are an increasingly popular replacement for natural aggregates in structural concrete due to industry demands for more recycled, low carbon 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 them 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.
Results showed that the CEM II/B-V and CEM III/A concretes produced with up to 60% coarse CCA outperformed the control CEM I concrete with 100% natural aggregates, and had a lower risk of corrosion initiation. For 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. It is recommended that further monitoring is required over longer periods to determine the corrosion initiation risk.

Supplementary cementitious materials (SCMs) 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; a significant outcome for the potentially wider implementation of coarse CCA into structural concrete applications.

Keywords – Crushed concrete aggregates (CCA), recycled concrete aggregate (RCA), corrosion risk, durability, chloride ion ingress

Paper type – Journal

1 INTRODUCTION

The recycling of demolition concrete is an increasingly important debate in the construction industry, particularly with the move towards a more sustainable way of sourcing materials (DEFRA, 2015; WRAP, 2015; NFDC, 2016;).

In the UK, a high proportion of demolition concrete known as crushed concrete aggregate (CCA), formerly referred to as recycled concrete aggregate (RCA), is utilised as general fill, sub-base material or within low grade concrete, as the quality and performance is generally of less importance (Barritt, 2015). Certain situations however, may arise where CCA may be a suitable replacement material for structural concrete such as: a specific project/client requirement, improved project sustainability credentials, a good quality, consistent source of CCA is available on site, and/or where there is a short supply of NA (Filho et al, 2013; Hassan et al, 2016; Yehualaw and Woldesenbet, 2016). Chloride ion ingress is the most common cause of early deterioration to reinforced concrete 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 reinforced concrete structures exposed to aggressive chloride environments, particularly the risk of corrosion initiation during its service life; hence coarse CCA is limited for structural applications (BSI, 2013; BSI, 2015a,b). Furthermore, it is not evident whether higher replacement levels of natural aggregates produces 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 which 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 (Kropp, 1995; Glass *et al*, 2000). 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 (Kropp, 1995; Concrete Society, 2004a; Alonso and Sanchez, 2009; Angst *et al*, 2009). Once the steel is exposed to the chloride ions, the corrosion can then aggressively propagate as ‘pitting’ occurs, producing further acidity from corrosion products (Bertlolini *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).

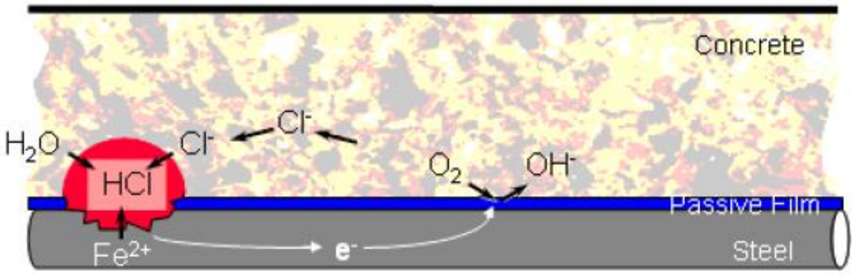

Figure 1 - Electrochemical process of chloride induced corrosion (Glass *et al*, 2006)

Non-destructive testing, such as half-cell potential surveys and surface resistivity, 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 (Concrete Society, 2004a).

Half-cell potentials are interpreted following the ASTM recommendations in Table 1 for saturated Copper/Copper Sulphate ($Cu/CuSO_4$) and Silver/Silver Chloride (Ag/AgCl/0.5M KCl) reference electrodes (ASTM, 2009).

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

Voltage vs $Cu/CuSO_4$ (mV)	Voltage vs Ag/AgCl/0.5M KCl (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

Surface resistivity tests can provide an indication of the microstructure of concrete as a measure of the flow of ions between 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 20kΩcm is associated with a low corrosion rate and chloride ion penetration.

Table 2 - Interpretation of four-point Wenner probe readings (AASHTO, 2015; Concrete Society, 2004a)

Concrete Society Technical Report 60		AASHTO T358	
Resistivity (kΩcm)	Interpretation	Resistivity (kΩcm)	Interpretation
<5	Very high corrosion rate	<12	High chloride ion penetration
5-10	High corrosion rate	12-21	Moderate chloride ion penetration
10-20	Low to moderate corrosion rate	21-37	Low chloride ion penetration
>20	Low corrosion rate	37-254	Very low chloride ion penetration
-	-	>254	Negligible chloride ion penetration

There are limitations to both methods as the results can be affected by the ambient relative humidity, temperature, pH value of the concrete pore solution and oxygen availability (Concrete Society, 2004a ; Assouli *et al*, 2008; Holmes *et al*, 2011; Angst and Elsener, 2014). 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; Concrete Society, 2004a). The results are often interpreted by the Concrete 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 0.1M 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.

Table 3 - Interpretation of chloride ion concentration (Concrete Society, 2004a)

Threshold levels (%) by mass of cement	Interpretation
>1.0	High corrosion risk
<1.0 and >0.4	Medium corrosion risk
<0.4	Low corrosion risk

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 upon 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 which predominantly leads to the formation of Friedel's salt (calcium chloroaluminate hydrate) (Neville, 2011; Bertolini *et al*, 2004). 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 (Dhir *et al*, 1996; Dhir *et al*, 1997; Glass *et al*, 1997; Glass and Buenfeld, 2000; Reddy *et al*, 2002; Andrade and Bujak, 2013; Bapat, 2013; Dunne *et al*, 2015; Lollini *et al*, 2016).

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 (Ryu and Monteiro, 2002; Neville, 2011). 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 (Kwan *et al*, 2012; Pedro *et al*, 2014; Soares *et al*, 2014; Bravo *et al*, 2015; Lofty and Al-Fayez, 2015). 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 natural aggregates. The general consensus is that replacement levels above 30% coarse CCA cause a detrimental effect to the transport properties of CEM I concrete, which is commonly attributed to the increased water absorption of the aggregates (Limbachiya *et al*, 2012; Soares *et al*, 2014; Zega *et al*, 2014; Lofty and Al-Fayez, 2015). 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 source 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; Somna *et al*, 2012; Kou and Poon, 2013; Lima *et al*, 2013). Additionally, Dodds *et al* (2017a,b) 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 to CEM I control concretes produced with natural aggregates, whilst still achieving the specified characteristic strength.

The quantity of coarse CCA has been limited to 30% and 20% in Eurocodes and UK standards respectively for structural concrete (BSI, 2013; BSI, 2015a,b). 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 suggests the need for revised practice guidance.

However, there is limited research into the effect of coarse CCA on the risk of corrosion initiation of structural concretes using common, well-established corrosion monitoring techniques. This study investigates 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 are 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) are unknown (as is virtually all CCA sold from aggregate recycling plants), so it is difficult to characterise the material. The concrete was crushed to a 40mm down product, which was later processed to remove the fines content (d<4mm) and larger aggregates (d>20mm) to obtain a coarse CCA conforming to 'Type A' aggregates suitable for concrete production (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 to the natural aggregates (rounded quartzite river gravel) (Table 5). The particle density of coarse CCA is lower than that of natural aggregates for both coarse size gradings tested. The water absorption of coarse CCA at 24 hours was found to be 3-4 times greater than the natural aggregates, but towards the lower end of the reported range in literature (between 3.6% and 11.6%) which is indicative of a good quality source.

Table 4 - Laboratory analysis of CCA

	Sample No.	(%) by mass of dried sample
Cement content	1	11.1
	2	12.8
Alkali content	1	K_2O – 0.12 Na_2O – 0.02
	2	K_2O – 0.19 Na_2O – 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 mins) (%)	Water absorption (24 hours) (%)
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

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 have been adopted to determine the subsequent corrosion risk of reinforced concrete beams, with a sample size to provide a large surface for chloride ion ponding. The natural diffusion coefficient provides a comparison against the apparent chloride diffusion coefficient. Concrete cubes were exposed as per the European standard (BSI, 2015d).

The concrete was designed using the BRE mix design method to achieve characteristic and target mean strengths of 35MPa and 49MPa respectively (BRE, 1997). The constituents for each mix are summarised in Table 7. Additional binder content was added to compensate for the inclusion of the coarse CCA (10kg/m³ per 20% coarse CCA inclusion) and the water content for the CEM II/B-V mixes reduced following recommendations in the BRE mix design method for crushed aggregates.

Coarse CCA replaced coarse natural aggregates at 20, 40 and 60% by mass. 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% natural aggregate).

Table 6 – Justification of test methods

Exposure	Test method	Standard/reference	Sample size
Combined absorption and diffusion	Half-cell potential	Concrete Society, 2004a; ASTM, 2009	Reinforced concrete beams 500 × 100 × 100mm
	Surface resistivity	Concrete Society, 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 100mm³

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/m³)	390	307	195
PFA (kg/m³)	-	131	-
GGBS (kg/m³)	-	-	195
Water (kg/m³)	195	175	195
Sand (kg/m³)	653	650	653
Coarse 10-20mm (kg/m³)	775	759	775
Coarse 4-10mm (kg/m³)	387	378	387

Two concrete beams (500mm × 100mm × 100mm) were cast for each mix with a 16mm diameter steel reinforcing bar with a top concrete cover of 65mm to comply with the durability recommendations for a 50 year design life in XS3 exposure conditions (BSI, 2015a,b). A 4mm cross-linked polyethylene (XLPE) 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 days before being subjected to 2 days of ponding (wetting) with 3% chloride ion solution, followed by 12 days of drying in the internal lab 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 38,400mm² was created using 15mm high PVC profiles and a silicon-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 (50mm spacing) readings were recorded on the top face of each beam before exposing to the chloride ion solution (dry reading), and immediately after removing the chloride ion solution (wet reading), and an average calculated (Concrete Society 2004a; ASTM, 2009). All ponded chlorinated water was removed with a cloth prior to recording the half-cell potential measurements. Surface resistivity readings were also recorded at 6 locations along the top of the beams, and an average calculated, prior to ponding at approximately 28, 56, 90, 180 and 360 days (Concrete Society, 2004a; AASHTO, 2015).

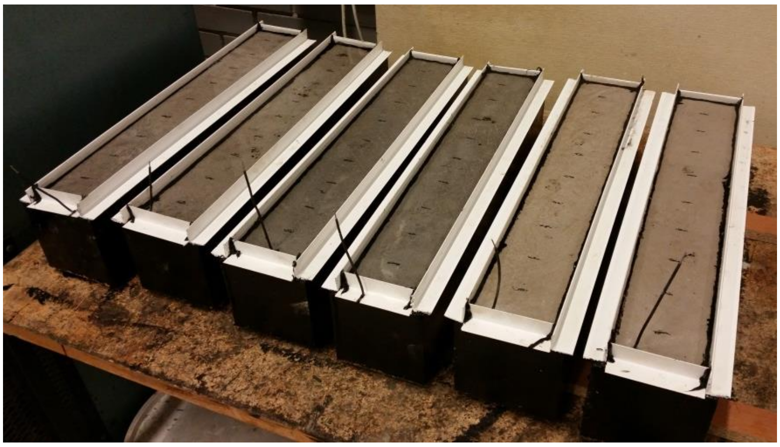

Figure 2 – Reinforced concrete beams prepared for cyclic wetting/drying

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 10mm depth intervals until the steel reinforcement was reached at 65mm (20mm diameter 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 colorimetric 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 second law of diffusion, identified as a chloride ion concentration of 0.4% reaching the surface of the steel reinforcement (Concrete Society, 2004b). The remaining beams were continually ponded and assessed for corrosion initiation risk, when exposed to the same cyclic wetting/drying process.

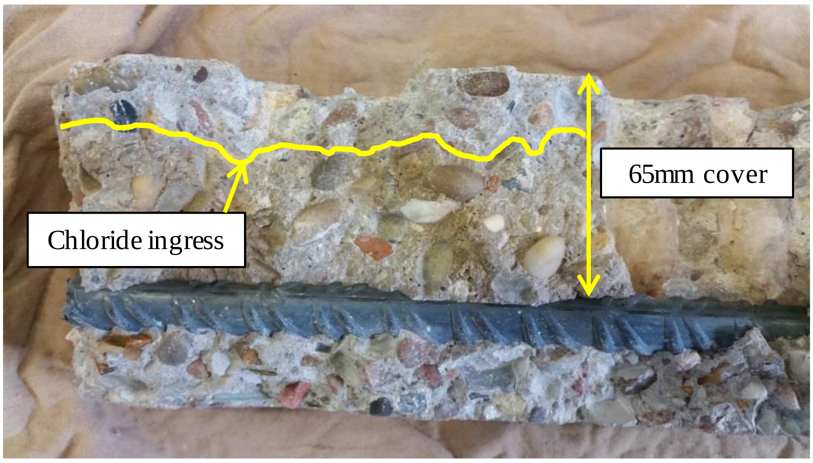

Figure 3 - Visual analysis and measurement of chloride ion ingress, CEM I concrete

Two concrete cubes ($100mm^3$) 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% 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 (Poulsen, 1995; BSI 2015c).

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

5 ANALYSIS OF RESULTS

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

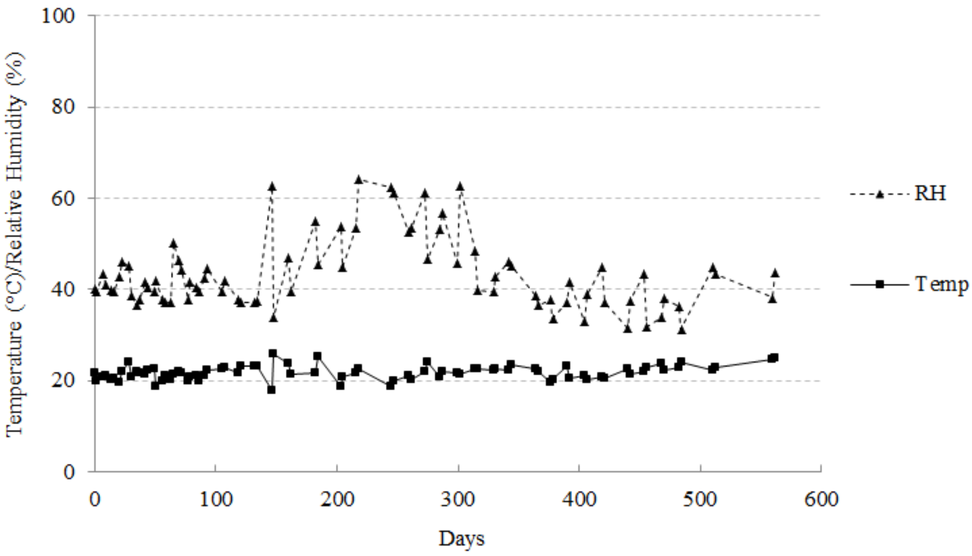

Figure 5 - Monitoring of temperature and relative humidity over time

5.1 CLOSE INTERVAL HALF-CELL POTENTIALS

The half-cell potential of the reinforcing steel was recorded bi-weekly, before and immediately following two days of ponding, which are referred to as the '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 (Concrete Society, 2004a). Therefore, only the 'wet' half-cell potential readings are presented and discussed.

Figures 6 to 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).

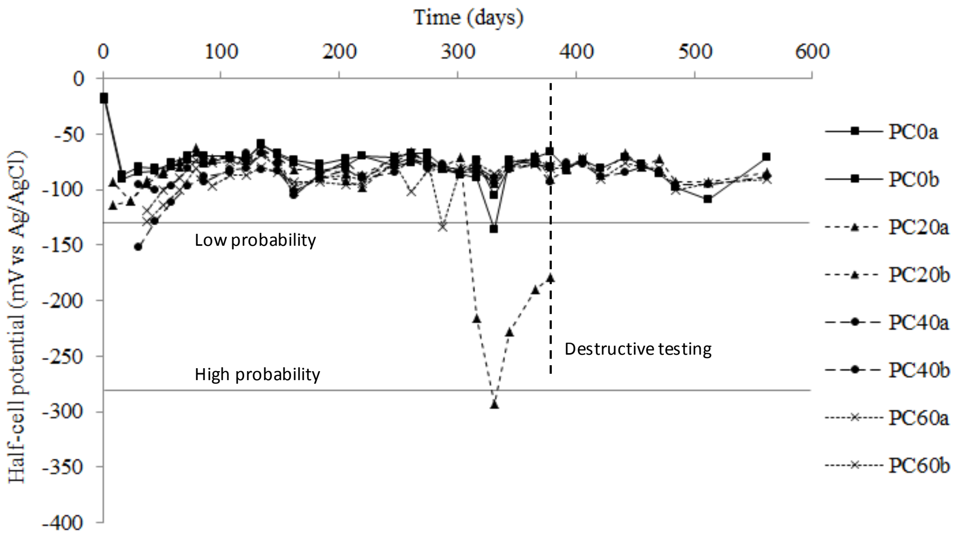

Figure 6 - Development of 'wet' half-cell potential over time, CEM I concrete

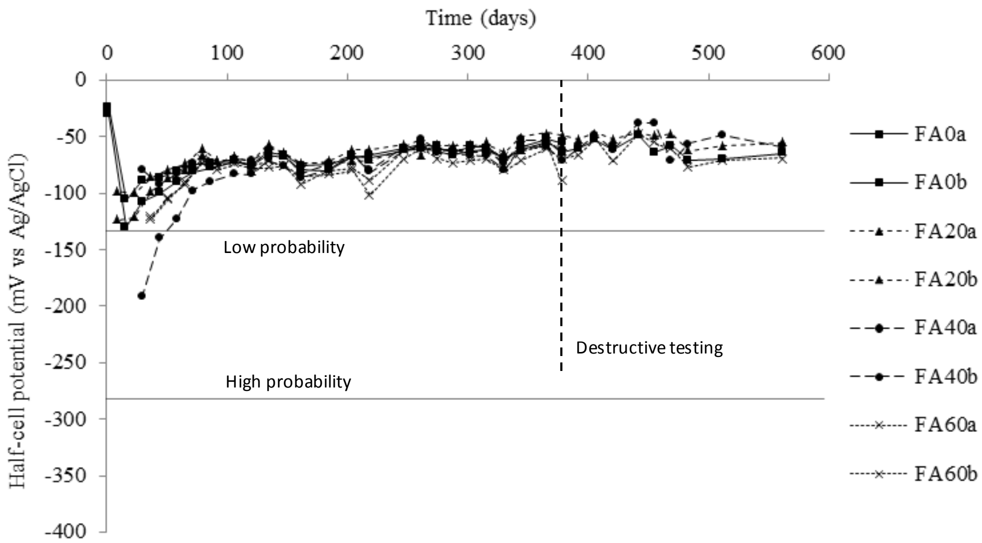

Figure 7 - Development of 'wet' half-cell potential over time, CEM II/B-V concrete

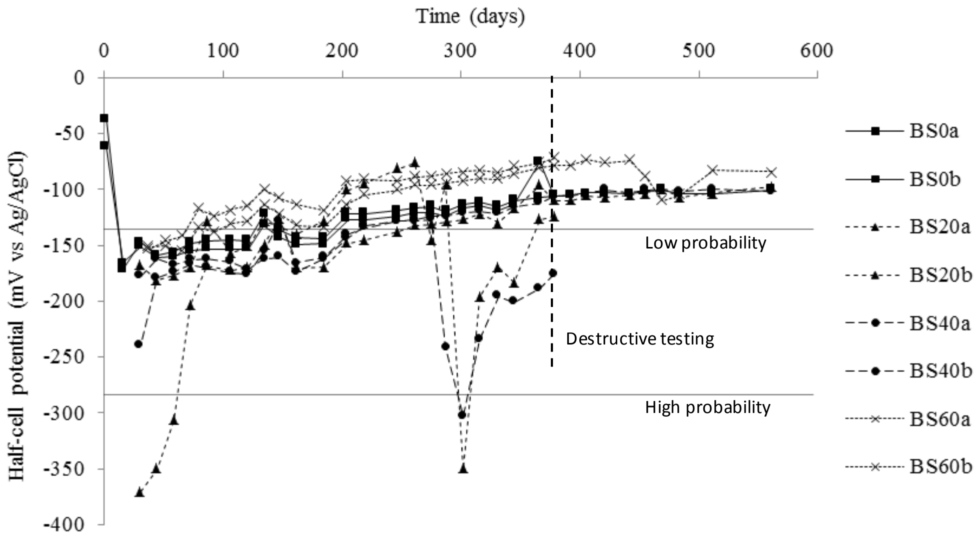

Figure 8 - Development of 'wet' half-cell potential over time, CEM III/A concrete

The majority of half-cell potentials remained above the recommended threshold for a low probability of corrosion initiation (<-134mV), 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 batch, with no particular trend regarding 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; Dhir *et al*, 1997; Glass *et al*, 1997; Glass and Buenfeld, 2000).

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, amongst 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 that of control concretes.

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 days (Concrete Society, 2004a).

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

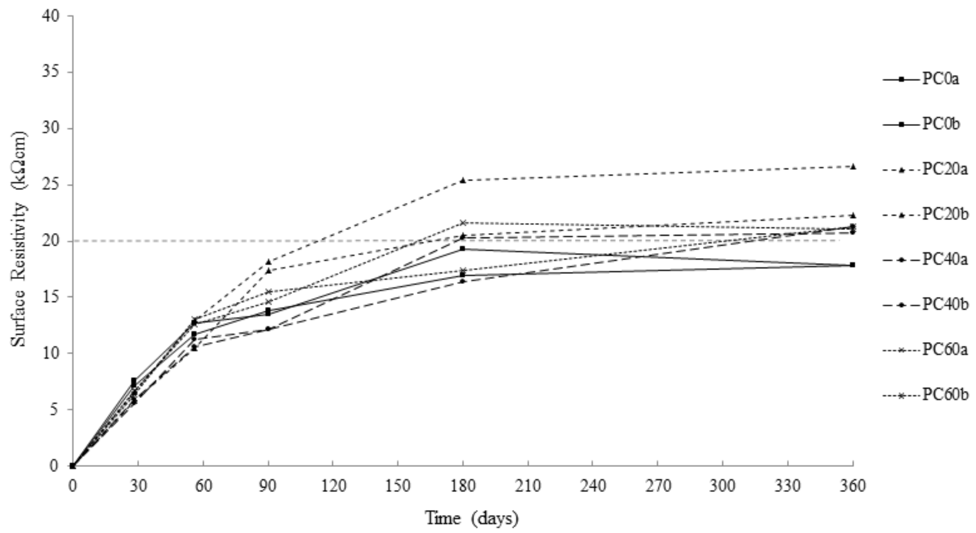

Figure 9 - Development of surface resistivity over time, CEM I concrete

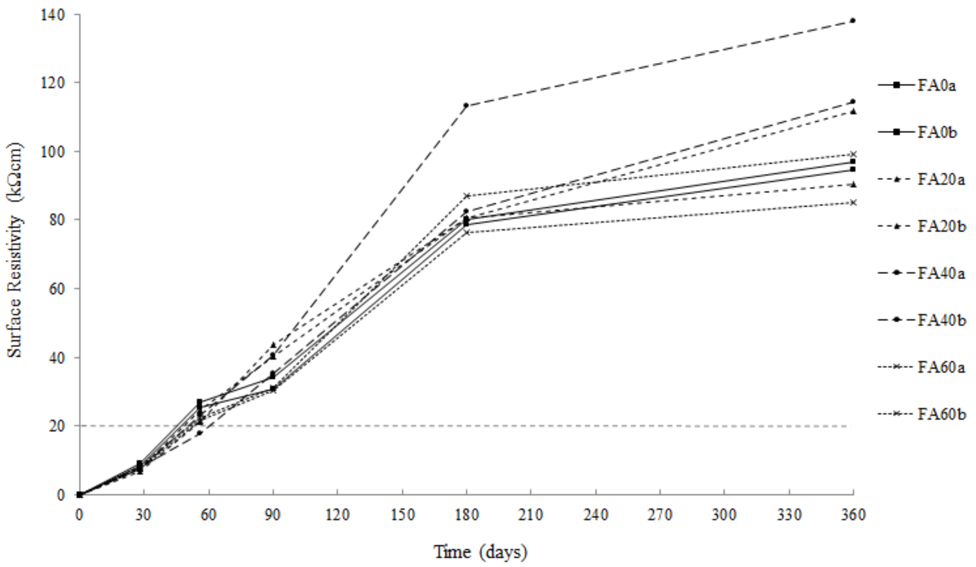

Figure 10 - Development of surface resistivity over time, CEM II/B-V concrete

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, and were approximately 3 to 5 times higher in magnitude than that of the reference CEM I concretes. The majority of CEM II/B-V and CEM III/A concretes achieved the 20kΩcm threshold for low corrosion rate/chloride ion penetration by 56 days. In comparison, the surface resistivity of the CEM I concrete remained much lower, with the majority of results being just above the 20kΩcm threshold for low corrosion rate/chloride ion penetration (AASHTO, 2015; Concrete Society, 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.

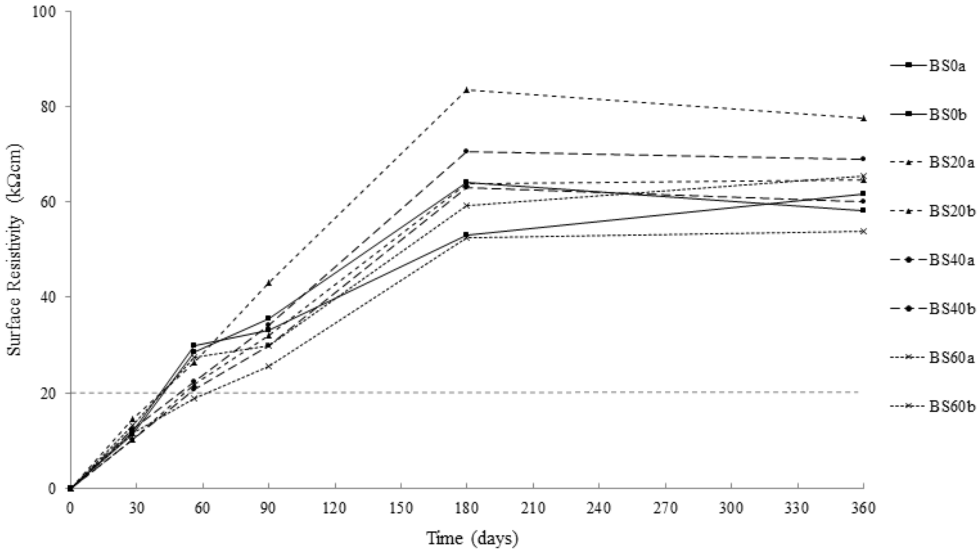

Figure 11 - Development of surface resistivity over time, CEM III/A concrete

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.

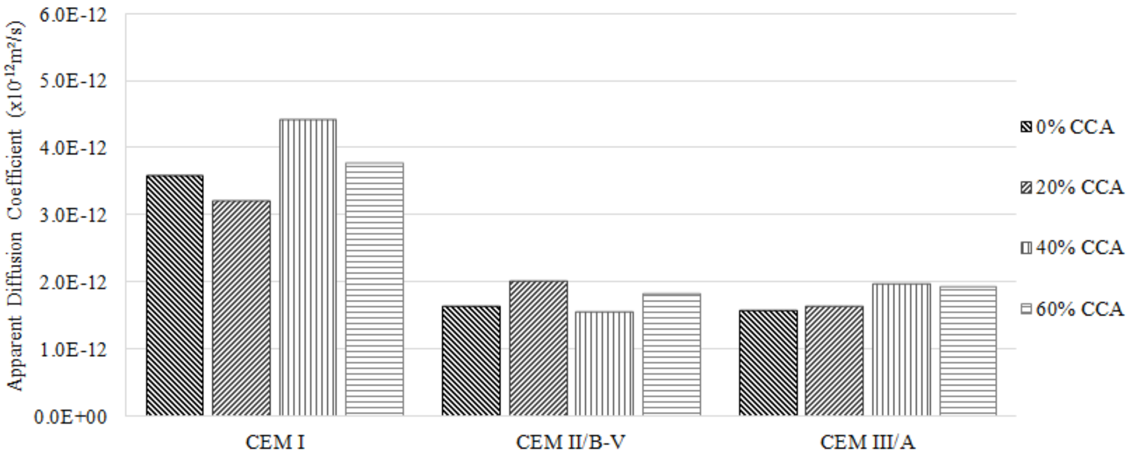

Figure 12 - Apparent diffusion coefficient following 12 month exposure to cyclic wetting/drying

Analysis of the chloride ion ingress resistance and the prediction of time to corrosion initiation shows a strong correlation to the observations already stated. The CEM II/B-V and CEM III/A concretes with up to 60% coarse CCA content have outperformed the control CEM I concrete at resisting the ingress of chloride ions when a combination of absorption and diffusion is occurring simultaneously.

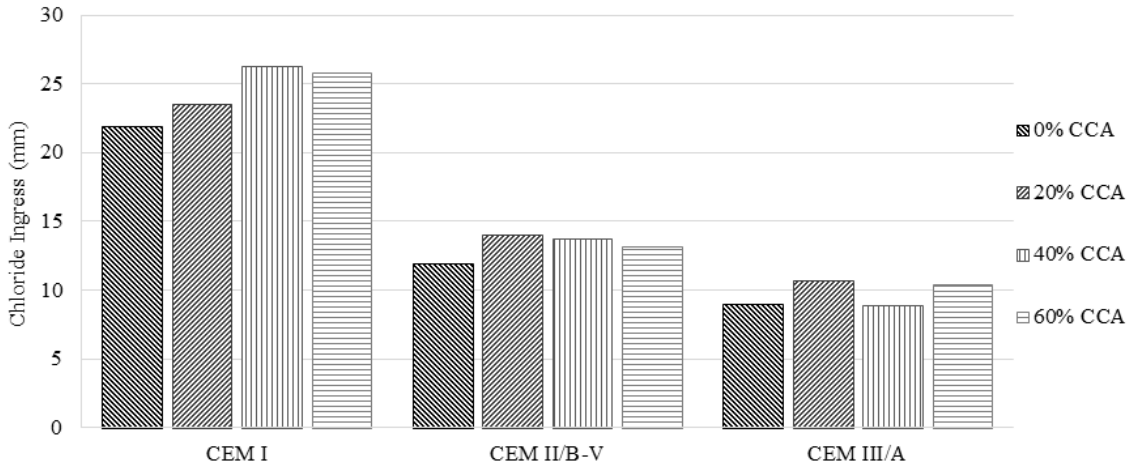

Figure 13 - Chloride ion ingress following 12 month exposure to cyclic wetting/drying

In both cases, the inclusion of SCMs have 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 to the quantity of coarse CCA, which does not appear to have an evident trend in relation to the chloride ion ingress.

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+

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 CCA content have outperformed the control CEM I concrete at resisting the ingress of chloride ions when diffusion is 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.

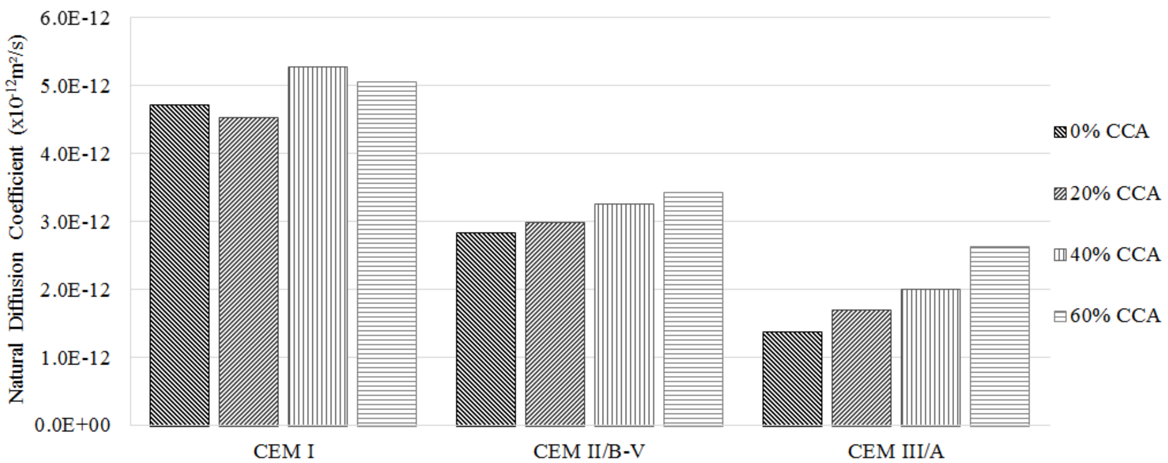

Figure 14 - Natural diffusion coefficients following a 90 day exposure to chloride ion solution

6 DISCUSSION

This study 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. The majority of close interval half-cell potentials and surface resistivity results indicated a low risk of corrosion initiation for all concrete types tested. Only three cases of probable corrosion activity were identified throughout the testing period (Figures 6 to 8), as indicated by a decrease in the half-cell potential below -284mV (Figures 6 and 8). Results of the destructive testing and measurement of chloride ion ingress resistance however, indicated that none had taken place (Figures 12 and 13, Table 8).

For all test methods, the CEM II/B-V and CEM III/A concretes with up to 60% coarse CCA outperformed the control CEM I concrete with 100% natural aggregates. These concretes had lower risks of corrosion initiation compared to control CEM I concretes as indicated by stable half-cell potentials readings above the -134mV threshold for low corrosion initiation risk, surface resistivity readings significantly higher than the 20kΩcm 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 to the quantity of coarse CCA, which largely outweighed any observed detrimental effects. In the majority of 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 finding are in agreement with other published research on the beneficial effects of SCMs and highlights the advantages of their use in combination with coarse CCAs (Dhir *et al*, 1996; Dhir *et al*, 1997; Glass *et al*, 1997; Glass and Buenfeld, 2000).

Dodds *et al* (2017a,b) 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. This study has 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 compared to control CEM I concrete produced with 100% natural aggregates when exposed to aggressive chloride environments. The replacement level of 60% coarse CCA is double the recommended limitation in other published literature and existing European and British standards - a significant outcome for the wider implementation of coarse CCA in structural concrete (Limbachiya *et al*, 2012; Soares *et al*, 2014; Zega *et al*, 2014; Lofty and Al-Fayez, 2015). 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 reinforced concrete 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 reinforced concrete structures. Based upon the analysis of results, and determining the risk of corrosion initiation from a range of test methods, the following conclusions can be made:

1. 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% natural aggregates, and had a lower risk of corrosion initiation.

2. 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,b). For 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.

3. 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.

4. The beneficial pozzolanic and latent hydraulic effects of CEM II/B-V and CEM III/A concretes are 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 large influence on the chloride ion ingress resistance compared to the inclusion of coarse CCA, and largely outweighed any observed detrimental effects.

The findings of this study have complemented existing research by Dodds *et al* (2017a,b) and have further highlighted 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.

8 ACKNOWLEDGEMENTS

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APPENDIX D PAPER 3

Full Reference

Dodds, W. Goodier, C. Austin, S. Christodoulou, C. Dunne, D. Wingrove, E, 2017. *The effect of coarse crushed concrete aggregate on the durability of structural concrete*. IN: Pecur, I.B. Baricevic, A. Stirmer, N. Bjegovic, D. (ed.). 1st International conference on construction materials for sustainable future: Book of abstracts (CoMS 2017), Zadar, Croatia, 19-21st April 2017. ISBN: 978-953-8168-04-8. https://dspace.lboro.ac.uk/2134/24326.

Abstract

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

Keywords – Crushed concrete aggregate, recycled concrete aggregate, durability, water absorption, chloride ingress

Paper type – Conference

1 INTRODUCTION

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

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

With a large quantity of hard demolition arisings becoming available, and an industry shift towards incorporating CCA into a wider variety of higher value applications [6], certain situations may arise where CCA may be a suitable replacement material in structural concrete, such as: a specific project/client requirement, improved project sustainability credentials, a good quality, consistent source of CCA is available on-site, and/or where there is a short supply of natural aggregates (NA) [7,8,9].

The European standard for concrete specification states that *'Type A aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%'* [10]. The British standard permits the inclusion of CCA, up to 20% replacement by mass, in concrete up to strength class C40/50, except when the structure is to be exposed to chlorides [11,12]. The British standard also states that *'these aggregates may be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment'*, which is an ambiguous statement as no performance criteria or limits are included to determine suitability. This highlights uncertainty with respect to incorporating coarse CCA into structural concrete [13]. Further research is therefore required to understand the true effects of coarse CCA on the mechanical and durability properties, if a more robust framework for the use of coarse CCA is to become a possibility in the future.

A review of existing research has highlighted that the effect of CCA on the mechanical properties of structural concrete has been investigated [14-18]. The effect of CCA on long-term durability performance however, is less well established, particularly in relation to chloride ingress and corrosion initiation. The durability of reinforced concrete is primarily influenced by the connectivity, continuity and tortuosity of its pores, as this is how gases, liquids and other substances penetrate the concrete cover to reinforcement [19-21]. The majority of published research on the effect of coarse CCA on concrete durability has focused on rapid migration and absorption test methods to determine acceptable levels of replacement of NA. The general consensus is that 25-30% coarse CCA can be successfully incorporated without detrimentally affecting the transport properties of concrete [22-27]. Quantities up to 75% have been shown to produce structural concrete of adequate quality, however it was noted that higher amounts also increased the variability of durability performance compared to the control concretes [24]. Limbachiya *et al* (2000) established that a replacement level of up to 100% may not have a significant effect on the durability performance of high strength Portland cement (CEM I) concretes, provided the CCA source is obtained from high quality precast concrete sources [18].

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

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

2 METHODOLOGY

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

Statistical analysis was undertaken using t-tests to determine the effect on sample means when coarse CCA was added based on a 10% decrease in performance. A 10% decrease in performance is considered to be significant as this is greater than any expected human or batch reproducibility error. The results of concrete produced with CCA were compared against the results of the control concrete for each binder type to calculate a probability of a significant detrimental effect. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect.

Table 1 - Test method justification

Test	Standard	Justification
Compressive cube strength	BS EN 12390-3 [36]	To determine compliance of mixes with characteristic ($f_{c,cube}$) and target mean strengths and to analyse the effect of coarse CCA on compressive strength.
Surface resistivity	AASHTO T358-15 [37]	To determine the effect of coarse CCA on electrical resistivity of concrete, which provides an indication of its ability to resist chloride ion penetration.
Absorption by capillary action	BS EN 13057 [38]	To determine the effect of coarse CCA on the sorptivity of concrete with no external pressures applied. This is the key transport mechanism of water and chloride ingress when concrete is initially in a dry state.
Rapid Chloride Migration [39]	NT BUILD 492 [39]	To determine the effect of coarse CCA on the chloride migration coefficient in concrete. The results cannot be directly compared to natural diffusion tests; however it provides a rapid indication of durability performance, and is comparative.

3 CCA COMPOSITION

BS EN 206-1 states that a quality source of CCA, of known composition, should be obtained to produce sustainable structural concrete. This is to prevent possible contamination and reduce any detrimental effects [10]. The CCA obtained for this study was from the demolition of a 1970's office building structure in Leicester, UK. Three randomly selected samples were sent for petrographic analysis [40,41] to determine concrete composition and type (Figure 1). Randomly selected samples of coarse CCA were also tested for water absorption properties, and concrete cores from larger sections were obtained to determine compressive strength [42-45].

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

Table 2 - Water absorption properties of CCA and NA

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

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

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

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

The key findings of the petrographic analysis were:

- The concrete was produced with partly-crushed gravel typical of East/South-East England (sandstone, limestone, quartzite and chert), quartz-dominated sand and ordinary Portland cement.
- No evidence of cement replacements or admixtures was detected.
- Estimated water-cement ratio, slump and 28 day strength were 0.58, 30-60mm and 38.5MPa respectively; the latter is similar to that of the determined equivalent in-situ characteristic strength.
- Estimated cement content was 325kg/m³, 13.8% of total weight of concrete.
- There was no obvious segregation, excessive voids, honeycombing or visible microcracking.
- Junctions between aggregates and enclosing binder were tightly sealed, indicative of good quality ITZ.
- Phenolphthalein indicator solution suggests maximum carbonation from the surface was 20-25mm.

4 ANALYSIS OF RESULTS

4.1 COMPRESSIVE CUBE STRENGTH

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

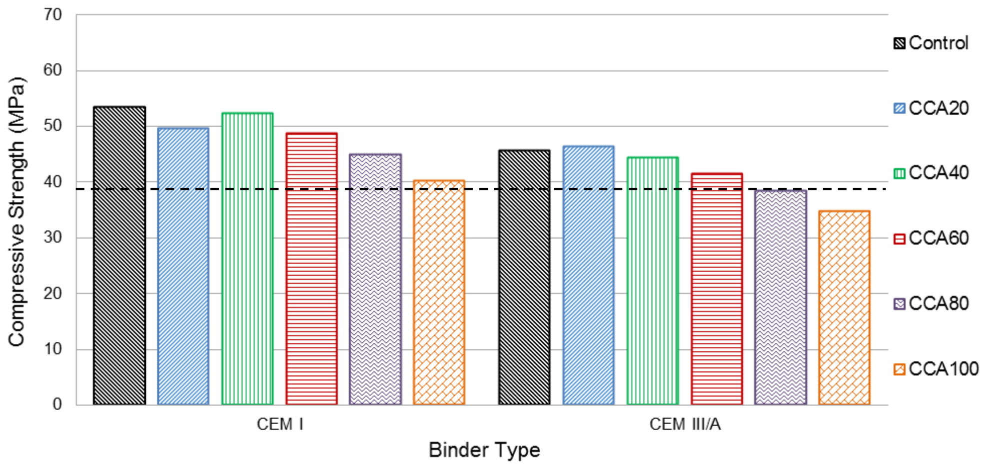

Figure 2 - 28 day compressive cube strengths

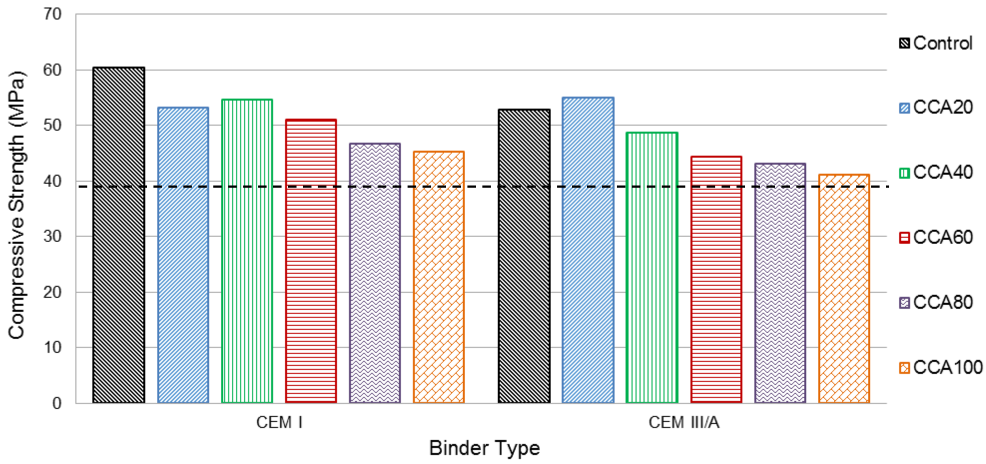

Figure 3 - 56 day compressive cube strengths

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

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

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

4.2 SURFACE RESISTIVITY

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

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

Concrete Society Technical Report 60		AASHTO T358	
Resistivity [kΩcm]	Interpretation	Resistivity [kΩcm]	Interpretation
<5	Very high corrosion rate	<12	High chloride ion penetration
5-10	High corrosion rate	12-21	Moderate chloride ion penetration
10-20	Low to moderate corrosion rate	21-37	Low chloride ion penetration
>20	Low corrosion rate	37-254	Very low chloride ion penetration
-	-	>254	Negligible chloride ion penetration

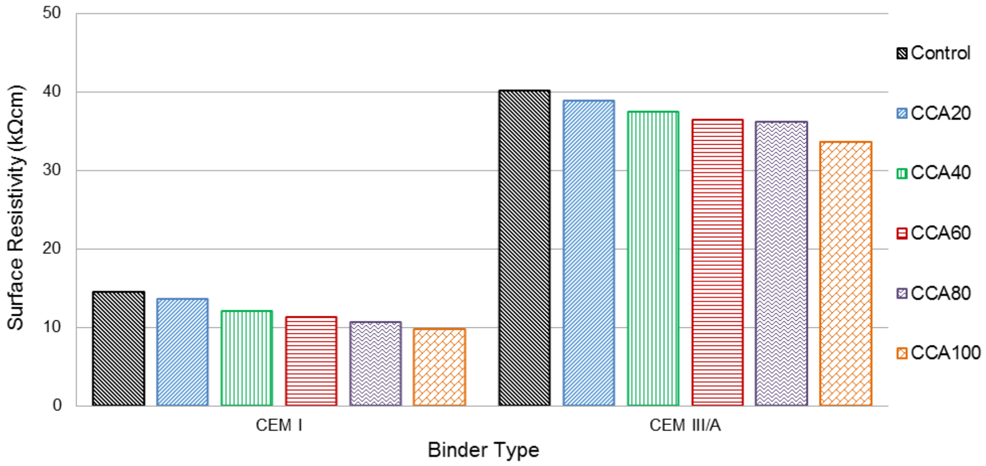

Figure 4 - Concrete surface resistivity at 28 days

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

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

Table 6 - Probability of a detrimental effect on surface resistivity

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

4.3 ABSORPTION BY CAPILLARY ACTION

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

Table 7 - 28 day sorption coefficients for all concretes tested

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

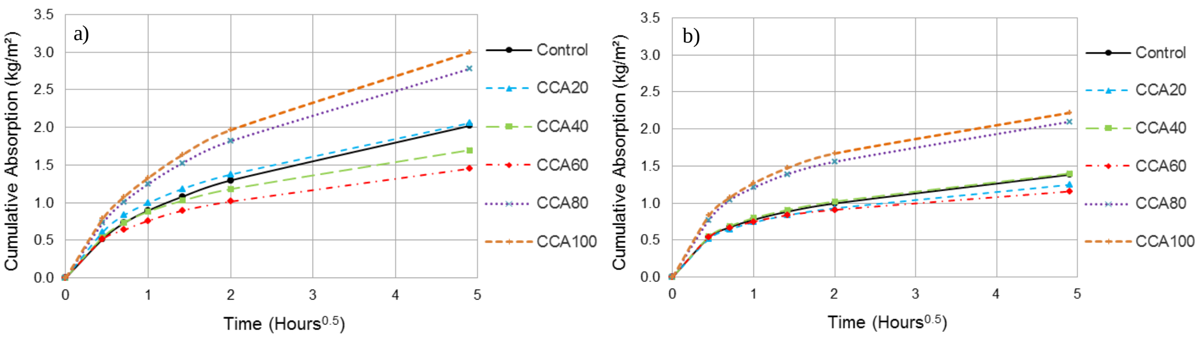

Figure 5 - Cumulative absorption at 28 days for a) CEM I, and b) CEM III/A concrete

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

(Table 8). A structural CEM III/A concrete incorporating up to 60% CCA performed better than the control CEM I concrete.

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

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

4.4 RAPID CHLORIDE MIGRATION

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

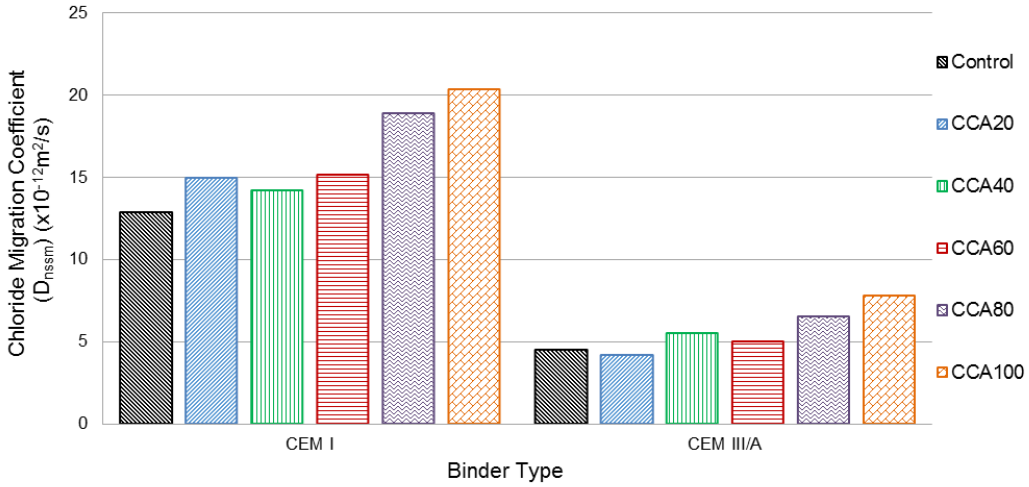

Figure 6 - Chloride migration coefficients at 28 days

The results show that the inclusion of coarse CCA content had an increasingly detrimental effect on the chloride migration coefficient of concrete. CEM III/A concretes were found to provide enhanced resistance to chloride ion penetration compared to CEM I concrete, by a factor of 2 to 3. A structural CEM III/A concrete incorporating up to 100% CCA performed better than the control CEM I concrete. Statistical analysis shows a relatively high probability (highlighted in bold) that the chloride migration coefficient will increase by more than 10% for all CCA contents compared to the control concretes for each binder type; except for the 20% content in CEM III/A concrete (Table 9).

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

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

5 DISCUSSION

5.1 COMPRESSIVE CUBE STRENGTH

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

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

5.2 SURFACE RESISTIVITY

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

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

5.3 ABSORPTION BY CAPILLARY ACTION

The cumulative absorption, sorption coefficients and statistical analysis indicate that higher quantities of coarse CCA (>60%) have a large detrimental effect when compared against the control concretes for each binder type (Figures 5a and 5b, Tables 7 and 8). Some anomalies exist for the lower quantities of CCA replacement for both CEM I and CEM III/A concretes as the cumulative absorption at 24 hours was lower than the respective control concretes. One possibility for the reduced cumulative absorption is that the combination of rounded NA and angular coarse CCA for these mixes reduced the continuity of the capillaries in the cement matrix. In any case, there was a significant increase in the cumulative absorption for CCA contents above 60% for both CEM I and CEM III/A concretes, and the inclusion of GGBS reduced the sorption coefficients at 24 hours due to a reduced porosity of the cement matrix and improved ITZ [28-33]. A structural CEM III/A concrete incorporating up to 60% CCA performed better than the control CEM I concrete, which suggests that up to 60% coarse CCA inclusion is acceptable which is higher than previously reported values [22-27].

5.4 RAPID CHLORIDE MIGRATION

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

6 CONCLUSIONS

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

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

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

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APPENDIX E PAPER 4

Full Reference

Dodds, W. Goodier, C. Christodoulou, C. Austin, S. Dunne, D, 2017. *Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on microstructure and water ingress*. Construction and Building Materials, Volume 145, pp183-195. DOI: 10.1016/j.conbuildmat.2017.03.232. ISSN: 0950-0618. https://dspace.lboro.ac.uk/2134/24801.

Abstract

The use of crushed concrete aggregate (CCA), formerly referred to as recycled concrete aggregate (RCA) is increasing, particularly with a recent push towards sustainable sourcing of materials. Further research is required to understand the effect of coarse CCA on the mechanical properties and durability performance of structural concrete. The electrical resistivity, water absorption by capillary action and SEM analysis of CEM I and CEM III/A concretes were investigated to determine the effects on concrete microstructure and water ingress, together with compliance of characteristic ($f_{c,cube}$) and target mean compressive strengths. The results show that for the three coarse CCA sources tested, the inclusion of coarse CCA generally has a detrimental effect on the microstructure and water ingress of structural concrete. These can be largely overcome through the incorporation of GGBS to produce CEM III/A concretes, allowing higher proportions of coarse CCA to be incorporated. We conclude that the GGBS and coarse CCA content be limited to 50% and 60% respectively, as this reduces the risk of a significant reduction of compressive cube strength and durability performance. The findings suggest 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 CCA can be obtained. This is a positive and significant outcome for the wider implementation of coarse CCA into structural concrete applications.

Keywords – Crushed concrete aggregate (CCA), recycled aggregate concrete (RCA), durability, performance, microstructure, supplementary cementitious materials

Paper type – Journal

1 INTRODUCTION

Crushed concrete aggregates (CCA), formerly referred to as recycled concrete aggregates (RCA) have become increasingly popular to replace virgin aggregates since the 1980's, particularly with a more recent push towards sustainable sourcing of materials (DEFRA, 2015; WRAP, 2015). Approximately 13.6, 18.8 and 21.2 million tonnes of hard demolition arisings were produced in the UK in 2013, 2014 and 2015 respectively, and the quantity is predicted to continue to increase annually (NFDC, 2016). In the UK, a high proportion of hard demolition arisings are utilised as general fill, sub-base material or within low grade concretes, as the quality requirements for aggregates in these applications are generally lower (Barritt, 2015; WRAP, 2009). 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 (Barritt, 2015; Coelho and de Brito, 2013). The UK's Waste and Resources Action Programme (WRAP) provides a framework of quality controls for the production of CCA for use in structural concrete, and all aggregates must conform to the European standard for aggregates in concrete (Environment Agency and WRAP, 2013; BSI, 2013a).

Furthermore, the abundance of natural aggregates (NA) in the UK, does not incentivise designers and contractors to include CCA as a replacement material in structural concrete applications. Certain situations however, may arise where CCA may be a suitable replacement material such as: a specific project/client requirement, improved project sustainability credentials, a good quality, consistent source of CCA is available on site, and/or where there is a short supply of NA (Hassan *et al*, 2016; Yehualaw and Woldesenbet, 2016; Filho *et al*, 2013).

This study investigates the effects of three sources of coarse CCA from known structural elements on the durability performance of structural concrete.

2 BACKGROUND TO CCA

2.1 SPECIFICATION OF CCA IN STRUCTURAL CONCRETE

The European standard for concrete specification states that a Type A coarse aggregate (>95% concrete product; 4/20mm), 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 (BSI, 2013b). The British standard places further limits on the inclusion of coarse CCA, and permits up to 20% replacement by mass, in concrete up to strength class C40/50, except when the structure is to be exposed to chlorides (BSI, 2015a; BSI, 2015b). The British standards also state 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 ambiguous as no performance criteria or limits are included to determine suitability (BSI, 2015a; BSI, 2015b). 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 coarse CCA is to become a possibility.

2.2 EFFECT OF COARSE CCA ON CONCRETE PROPERTIES

The effect of coarse CCA on the mechanical properties of structural concrete has been investigated in recent studies (Silva *et al*, 2016; Bravo *et al*, 2015a; Collery *et al*, 2015; Richardson, 2013; Padmini *et al*, 2009; Tabsh and Abdelfatah, 2009; Etxeberria *et al*, 2007). The effect of CCA on long-term durability performance however, is less well established, particularly in relation to water and chloride ion ingress.

The majority of published research on the effect of coarse CCA on concrete durability has focused on rapid migration and water absorption test methods to determine acceptable levels of replacement of NA. The general consensus is that 25-30% coarse CCA can be successfully incorporated without detrimentally affecting the transport properties of concrete. The detrimental effect is generally attributed to the increased water absorption of the coarse CCA (Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015; Pedro *et al*, 2014; Silva *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Limbachiya *et al*, 2012). 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 (Zega *et al*, 2014). Limbachiya et al (2000) established that a replacement level up to 100% may not have a significant effect on the durability performance of high strength Portland cement (CEM I) concretes, provided the CCA is obtained from a high quality precast concrete source.

Research has shown that the latent hydraulic and pozzolanic properties of supplementary cementitious materials (SCMs) improve the durability performance of CCA concrete. The addition of SCMs reduce the porosity of the cement matrix, improve quality of the interfacial transition zones (ITZ) and increase the chloride binding capacity of concrete (Bapat, 2013; Hwang *et al*, 2013; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008).

Studies of the effects of coarse CCA on structural concrete have shown that CCA content, as low as 20% and 40% for CEM I and CEM III/A concretes respectively, had a significant detrimental effect on the durability performance (Dodds *et al*, 2017; Dodds *et al*, 2016). Statistical analysis also established that the inclusion of SCMs improved the resistance of concrete to water and chloride ion ingress. Dodds *et al* (2017) established that a CEM III/A structural concrete incorporating 60% coarse CCA outperformed the control CEM I concrete for all durability test methods adopted. The observed beneficial effects of SCM's is in agreement with other published work in this field (Faella *et al*, 2016; Singh and Singh, 2016; Goodier *et al*, 2015; Hwang *et al*, 2013; Kou and Poon, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). For example, Berndt (2009) found that CEM III/A concrete (with 50% GGBS) was found to perform best when compared against other replacement levels of SCMs, including 50% fly ash, 70% GGBS and a tertiary blend of 25% fly ash and 25% GGBS.

2.3 KEY TRANSPORT PROPERTIES OF CONCRETE

The durability of reinforced concrete is primarily influenced by its microstructure - the connectivity, continuity, tortuosity and radius of its pores - as this determines how gases, liquids and other substances penetrate the concrete cover to reinforcement (Kropp *et al*, 1995; Ollivier *et al*, 1995). Water and chloride ions can ingress concrete through a combination of transport mechanisms, namely absorption by capillary action, diffusion and permeation

(Tuutti, 1982). Absorption by capillary action and diffusion relate to the transport of liquids and ions by surface tension effects and concentration gradients respectivelty; they are the dominant mechanisms in higher risk exposure classes (under the cyclic wetting and drying of reinforced concrete – denoted XD3 and XS3) (BSI, 2013b). Diffusion is a much slower process as the movement of ions occurs in the pore solution of saturated concrete, whereas absorption by capillary action occurs in a dry or semi-dry state and is considered the fastest transport mechanism (Kropp *et al*, 1995).

Taking measurements of surface resistivity is a well-established and relatively quick method of assessing the microstructure and subsequent transport properties of concretes, where a lower surface resistivity relates to a more porous concrete (Claisse, 2014). The results of surface resistivity are commonly interpreted following the recommendations in Table 1; no recommendations currently exist for bulk resistivity testing. Recent research has shown that strong correlations exist between electrical resistivity (both surface and bulk), water penetration, rapid chloride migration coefficients and diffusion coefficients (Noort *et al*, 2016; Liu *et al*, 2015; Sengul, 2014; Ramezanianpour *et al*, 2011). Some variability in electrical resistivity results can occur due to the inhomogeneity of concrete, location/presence of coarse aggregates, probe spacing and specimen size therefore care should be taken when interpreting results (Ghosh and Tran, 2015; Angst and Elsener, 2014).

Table 1 - Interpretation of four-point Wenner probe readings (AASHTO, 2015; Concrete Society, 2004)

Concrete Society Technical Report 60		AASHTO T358	
Resistivity [kΩcm]	Interpretation	Resistivity [kΩcm]	Interpretation
<5	Very high corrosion rate	<12	High chloride ion penetration
5-10	High corrosion rate	12-21	Moderate chloride ion penetration
10-20	Low to moderate corrosion rate	21-37	Low chloride ion penetration
>20	Low corrosion rate	37-254	Very low chloride ion penetration
-	-	>254	Negligible chloride ion penetration

The transport of liquid in concrete predominantly occurs through the pores of the cement matrix; however aggregates also play an important role. The specific gravity of aggregates (or particle density) can be a good indicator of their water absorption properties and subsequent quality of ITZ between the cement matrix and aggregates, which can accelerate or decrease the rate of ingress of fluids (Neville, 2011; Ryu and Monteiro, 2002). Aggregates with increased water absorption can reduce the ability of cement paste to adhere to the surface of aggregates, and in turn the quality of the ITZ (Lofty and Al-Fayez, 2015; Bravo *et al*, 2015b; Soares *et al*, 2014; Pedro *et al*, 2014; Kwan *et al*, 2012). Research has shown that a strong correlation exists between the water absorption and oven-dried density of coarse CCA which could be used as a prediction model to determine the quality of CCA (Silva *et al*, 2014). Microscopic imaging techniques such as scanning electron microscopy (SEM) and X-ray microtomography can help analyse the microstructure of concrete. Some researchers have used these techniques to analyse the cement matrix, aggregates and ITZ quality of concretes, confirming that CCA itself has an increased porosity and has a detrimental effect on the ITZ, primarily due to the release of air from CCA as water is absorbed during the early curing process which creates additional voids (Leite and Monteiro, 2016; Tam *et al*, 2005).

3 METHODOLOGY

The effect of coarse CCA on the compressive cube strength and durability of structural concrete was investigated. Forty different CEM I and CEM III/A concretes were produced to achieve a characteristic ($f_{c,cube}$) and target mean strength of 44MPa and 58MPa respectively by the BRE mix design method (BRE, 1997). The concretes were produced in accordance with BS 1881-125 (BSI, 2013c) and all specimens were cured in water at a temperature of (20±2°C) until testing. The constituents for each mix are summarised in Table 2. The free water-binder ratio and the cement content were selected to comply with the recommendations for XD3/XS3 exposure classes in accordance with BS8500-1 (BSI, 2015a). Three sources of coarse CCA (4/20mm) of known composition were incorporated at 30%, 60% and 100% to replace the coarse NA by mass and will be referred to 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 included 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, a mix denoted as 36A-60 refers to a concrete produced with 36% GGBS and CCA source A at 60%.

Table 2 - Mix design constituents

	Mix Design			
Constituents	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/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

Concrete cubes (100mm³) and cylinders (200mm × 100mmØ) were cast according to the test methodology detailed in Table 3. The test methods were chosen to investigate the effect of different sources of coarse CCA on the microstructure of structural concrete and its ability to resist water ingress. Compressive strength testing was undertaken to determine compliance with characteristic ($f_{c,cube}$) and target mean strengths.

Statistical analysis was undertaken using t-tests to determine the effect on sample means when coarse CCA sources A, B and C were added based on a 10% decrease in performance. A 10% decrease in performance is considered to be significant as this is greater than any expected human or batch reproducibility error. The results of concrete produced with CCA were compared against the results of the respective control concrete for each binder type to calculate a probability of a significant detrimental effect. The results from the three sources were also compared. A statistical result of 0.999 relates to a 99.9% confidence of a significant detrimental effect.

Table 3 - Test method justification

Test	Standard	Justification
Compressive cube strength	BS EN 12390-3 (BSI, 2009a)	To determine compliance of mixes with the characteristic ($f_{c,cube}$) and target mean strength, to analyse the effect of coarse CCA on compressive strength and to determine the suitability of the BRE mix design method to produce structural CCA concrete. 100mm³ specimens were produced to match commonly adopted practices in the UK construction industry for quality control purposes.
Surface resistivity	AASHTO T358-15 (AASHTO, 2015)	To determine the effect of coarse CCA on the microstructure of concrete, indicated by the electrical surface resistivity.
Bulk resistivity	N/A	To determine the effect of coarse CCA on the microstructure of concrete, indicated by the electrical bulk resistivity.
Absorption by capillary action	BS EN 13057 (BSI, 2002)	To determine the effect of coarse CCA on the sorptivity of concrete with no external pressures applied. This is the key transport mechanism of water and chloride ingress when concrete is in a dry state.
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.

4 AGGREGATE PROPERTIES

The European standard for concrete specification states that a quality source of CCA, of known composition, should be obtained to produce sustainable structural concrete. This is to prevent possible contamination and reduce any detrimental effects (BSI, 2013b). Further aggregate and concrete testing, as detailed in Table 4, was conducted for each CCA source to determine the original concrete compostition and characteristics.

Table 4 – Aggregate and concrete testing of CCA sources

Test	Standard	Justification
Alkali, cement and chloride content	BS 1881-124 (BSI, 2015c)	To determine possible sources of contamination in the obtained CCA sources. The cement content provides an indication of the original cement composition.
Petrographic analysis	ASTM C856-14 (ASTM, 2014); Concrete Society TR 71 (Concrete Society, 2010)	To determine the aggregate type, cement type, possible presence of admixtures and amount of segregation, microcracking and voids. Also, to provide an estimate of the mix constituents, cement content, water-cement ratio, slump and 28 day strength.
Compressive strength of cores	BS 6089 (BSI, 2010); BS EN 12504-1 (BSI, 2009b)	To determine the equivalent in-situ characteristic strength.
Water absorption and particle density	BS EN 1097-6 (BSI, 2013d)	To determine the 30 minute and 24 hour water absorption characteristics and particle density of coarse CCA and NA.

Three sources of CCA were obtained from selected components of reinforced concrete structures from two demolition sites in the East and West Midlands, UK (Table 5). Larger sections of reinforced concrete beams, footings and floor slabs were separated by the contractor on site and brought to the laboratory to be processed. The steel reinforcement was removed and a primary jaw crusher reduced the CCA to a 40mm down product. The resultant material was sieved into 4/10mm and 10/20mm size increments, conforming to a ‘Type A’ aggregate suitable for concrete production (BSI, 2013a; BSI, 2013b). Obtaining sources of CCA in this manner is not necessarily a typical approach for current demolition practices; it was however important for this study as the material characteristics and original constituents could be better quantified.

Table 5 – CCA sources obtained

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

The water absorption and particle density of the NA (rounded quartzite river gravel) and CCA are summarised in Table 6. The particle densities of the three sources of CCA are lower than that of NA for both coarse size increments tested, indicating a lower density microstructure. The water absorption of CCA ranged between 6 and 10 times greater than the NA. A higher water content was added during mixing to account for the short-term water absorption of coarse CCA in accordance with the BRE mix design method (BRE, 1997). The water absorption of coarse CCA at 24 hours in other studies has been reported to be between 3.6% and 11.6%, dependent on the original source of concrete (Bravo *et al*, 2015b; Lofty and Al-Fayaz, 2015; Pedro *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Hwang *et al*, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt *et al*, 2009; Ann *et al*, 2008). The CCA sources in this study fall within the expected range, with source B having the highest water absorption, followed by sources C and A respectively; therefore it may be expected that source B will have the biggest effect on the durability performance of structural concrete (Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015; Pedro *et al*, 2014; Silva *et al*, 2014; Soares *et al*, 2014; Kwan *et al*, 2012).

Table 6 - Water absorption characteristics and particle density of aggregates

Source	Size (mm)	Water Absorption: 30 minutes [%]	Water Absorption: 24 hours [%]	Saturated and surface-dried (SSD) particle density [Mg/m³]
NA	10/20	0.63	0.90	2.59
	4/10	1.07	1.16	2.57
	0/4	0.42	0.54	2.61
A	10/20	4.72	4.81	2.40
	4/10	6.50	6.80	2.30
B	10/20	6.18	6.75	2.35
	4/10	8.15	8.33	2.31
C	10/20	4.85	5.30	2.33
	4/10	6.08	6.41	2.27

CCA samples from each source were analysed for cement, alkali and chloride contents (Table 7) in accordance with BS 1881-124 (BSI, 2015c) and were found to be within acceptable limits and hence unlikely to cause contamination problems in the new concrete (Neville, 2011; Concrete Society, 2004). The cement content is highest for source B, followed by A and C.

Table 7 - Laboratory analysis of CCA

Source	Cement content [%]	Alkali content [%] K_2O/Na_2O	Chloride content [%] by mass of dried sample/cement
A	12.2	0.07/0.07	<0.01/0.08
B	17.1	0.09/0.15	<0.01/0.06
C	10.6	0.05/0.08	0.03/0.28

The compressive strength results of the cored specimens are shown in Table 8. The three sources of CCA provide a wide range of equivalent in-situ compressive strengths. Source A had the lowest compressive strength, followed by sources B and C respectively; therefore it may be expected that source A will have the largest detrimental effect on the resultant compressive strength of concrete. The key findings of the petrographic analysis are summarised in Table 9 (Aston Services, 2016).

Table 8 - Determination of equivalent in-situ characteristic strength from cored specimens

Source	Compressive strength of cored specimen [MPa]	Coefficient of Variation [%]	Correction Factor [$K_{is,cyl}$]	Corrected compressive strength [MPa]	Equivalent in-situ characteristic strength [$f_{ck,is}$] [MPa]
A	24.3	7.56	1.012	24.6	17.6
B	32.4	4.61	1.007	32.6	25.6
C	40.3	4.12	1.002	40.4	33.4

Table 9 - Key findings of petrographic analysis

Source	Key findings
A	– The concrete is produced with quartz dominated gravel typical of the Midlands and South East of England (average size 10mm – well graded), quartz sand and Portland cement. – No evidence of cement replacements or admixtures. – Estimated water-cement ratio, slump and 28 day strength are 0.51, 10-30mm and 40MPa respectively. – Estimated cement content is 365kg/m³, 15.2% of total weight of concrete. – There is no obvious segregation, excessive voids, honeycombing or visible microcracking. – Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs. – Phenolphthalein indicator solution suggests maximum carbonation from the surface is 7mm.
B	– The concrete is produced with river gravel with complex lithology typical of the Midlands (Quartz, Chert, Limestone, Ironstone – average size 12.5mm), quartz sand and Portland cement. – No evidence of cement replacements or admixtures. – Estimated water-cement ratio, slump and 28 day strength are 0.55, 0-10mm and 36MPa respectively. – Estimated cement content is 262kg/m³, 10.6% of total weight of concrete. – There is no obvious segregation, excessive voids or honeycombing. Some microcracking exists, however they are not considered significant. – Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs. – Phenolphthalein indicator solution suggests maximum carbonation from the surface is 5mm.
C	– The concrete is produced with quartz dominated river gravel typical of the Midlands (average size 12.5mm), quartz sand and Portland cement. – No evidence of cement replacements or admixtures. – Estimated water-cement ratio, slump and 28 day strength are 0.49, 0-10mm and 41MPa respectively. – Estimated cement content is 317kg/m³, 13.0% of total weight of concrete. – There is no obvious segregation, excessive voids or honeycombing. Some microcracking exists, however they are not considered significant. – Junctions between aggregates and enclosing binder are tightly sealed, indicative of good quality ITZs. – Phenolphthalein indicator solution suggests carbonation depth varies significantly. This is often typical of concrete that has been damp for long periods.

It should be noted that the values estimated in petrographic analysis are based upon point-counting of mix constituents across thin sections; care should be taken when interpreting this information.

Table 10 provides a summary of the characteristics of the coarse CCA sources. It can be seen that little correlation exists between the water absorption/particle density, equivalent in-situ strength and the petrography results. Little correlation also exists between the cement content, equivalent in-situ strength and estimated cement content (Tables 7 to 9). 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 compressive cube strength and durability performance 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.

Table 10 – Summary of coarse CCA characteristics

Source	24 hour water absorption [%]		SSD particle density [Mg/m³]		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

5 ANALYSIS OF RESULTS

5.1 COMPRESSIVE STRENGTH

Tests were conducted on 100mm cube samples at 28 and 91 days. The results confirm that the inclusion of coarse CCA has an increasingly detrimental effect on compressive strength at all ages for CEM I and CEM III/A concretes (Figures 1 and 2 respectively). The characteristic strength of 44MPa (indicated by the horizontal line) at 28 days was achieved by 24 of the 40 concrete mixes. Concretes with higher quantities of CCA and GGBS generally had lower strengths, with source B having the greatest detrimental effect, followed by sources C and A respectively. Concretes containing 100% coarse CCA only achieved the characteristic strength for mixes 0A, 36A and 0C. The characteristic strength was met for CEM III/A concretes (up to 50% replacement) produced with coarse CCA contents up to 60% for sources A and C. In comparison a reduced coarse CCA content of 30% could be used for the same binder type when source B is utilised.

The results at 91 days (Figure 2) show the latent hydraulic effect of GGBS with many of the CEM III/A concretes produced with higher quantities of GGBS having sufficient strength. At this later age, 37 of the 40 concretes achieved the characteristic strength of 44MPa. Only concretes 50B, 65B and 65C made with 100% coarse CCA content did not achieve the characteristic strength. These concretes have a confidence level of 0.997, 0.066 and 0.849 of achieving the characteristic strength respectively (when a human and batch reproducibility error above 10% is considered significant), which highlights that the 65B-100 concrete has the highest risk of non-compliance.

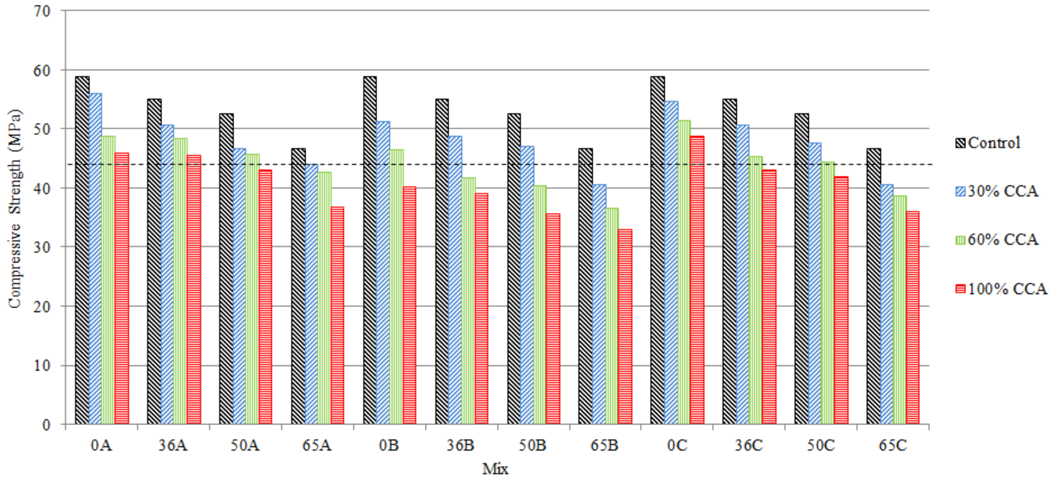

Figure 1 - Compressive cube strength at 28 days

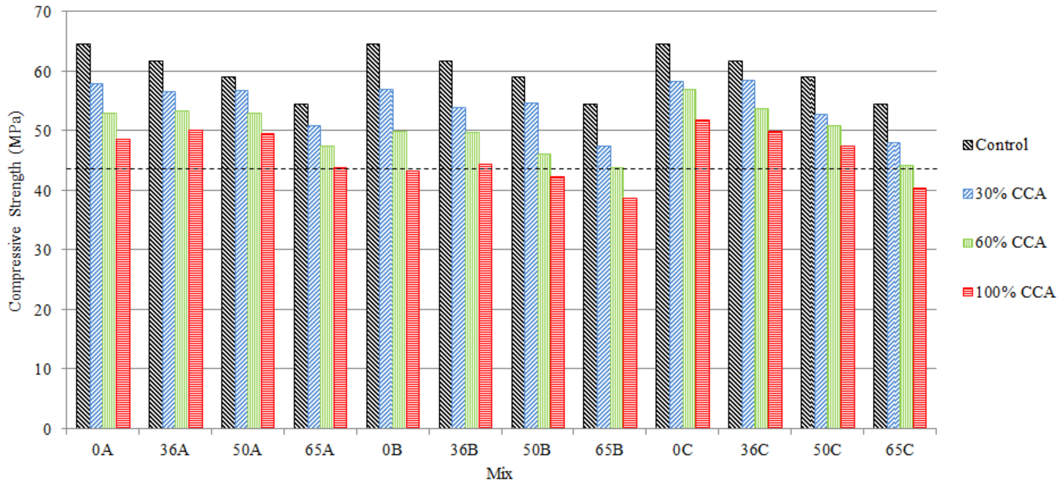

Figure 2 - Compressive cube strength at 91 days

5.2 SURFACE & BULK RESISTIVITY

The surface and bulk electrical resistivity of cylindrical specimens (200mm x 100mm diameter) was measured at 28, 56 and 91 days (Figures 3 to 6).

Figures 3 and 4 show that the surface and bulk resistivity reduced with increasing CCA content at 28 days. Similar trends were observed for concretes at 56 and 91 days, but are omitted for clarity. All CEM III/A concretes produced with up to 100% CCA content had a higher surface and bulk resistivity than the control CEM I concretes at all ages. At 28 days, 26 of the 40 concrete mixes were above 20kΩcm, which both interpretations acknowledge as being related to low corrosion rate/chloride ion penetration (AASHTO, 2015; Concrete Society, 2004). The concretes below this threshold consisted of all the CEM I concretes, 36B-60, 36A-100, 36B-100 and 36-C100. The surface resistivity continues to increase for the CEM III/A concretes above the 20kΩcm threshold with only the 36A-100 and 36B-100 batches not achieving this by 56 days. At 91 days only the CEM I concretes have surface resistivities lower than 20kΩcm. The data in Figures 3 and 4 highlights that source B predominantly was the worst performing source of coarse CCA, followed by sources A and C respectively.

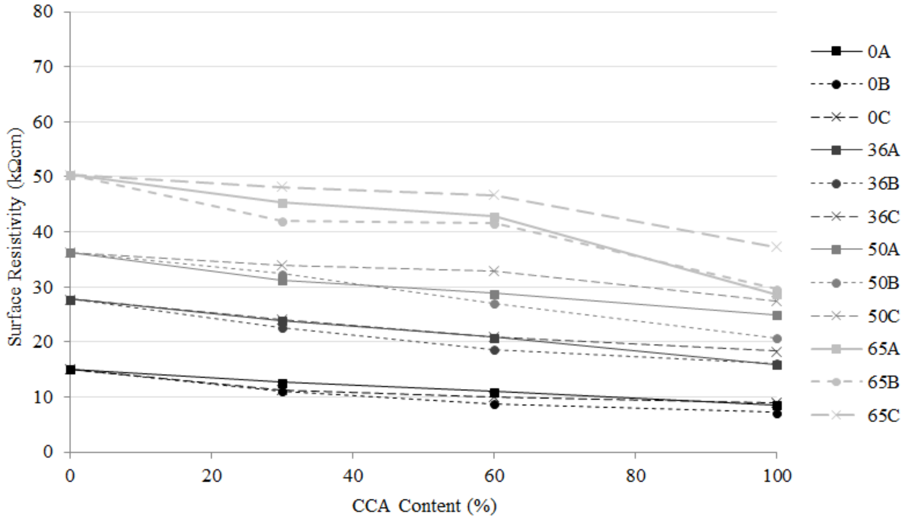

Figure 3 - Surface resistivity at 28 days

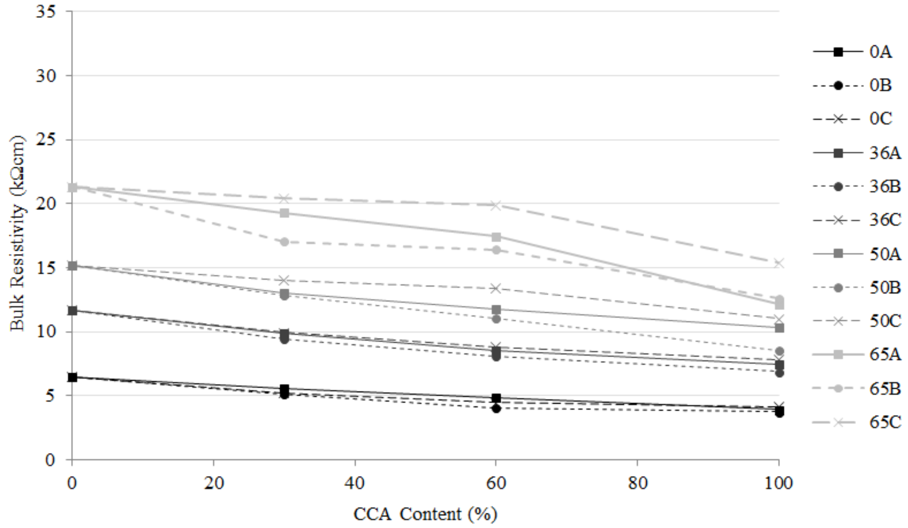

Figure 4 - Bulk resistivity at 28 days

A statistically significant detrimental effect in surface resistivity (indicated by a 10% decrease in sample means) was observed when CCA sources A and B were used in concretes produced with a GGBS content greater than 50% and a CCA content greater than 60%, when compared with a concrete produced with source C CCA ($P>0.758$). A low probability of a detrimental effect was observed for concretes 50C-30, 50C-60, 65A-30, 65C-30 and 65C-60 when compared against the respective control concrete for each binder type ($P<0.214$). No statistical analysis could be performed on the bulk resistivity results as only one reading was taken at each time interval.

Figures 5 and 6 show the beneficial latent hydraulic effects of GGBS in CEM III/A concretes as the surface and bulk resistivity continues to increase with time for concretes produced with coarse CCA from source B. Similar trends were observed for sources A and C, but are again omitted for clarity. Source B concretes produced with 65% GGBS content, along with 36B-0, 50B-0, 50B-30 and 50B-60 concretes at 91 days, achieved above 37kΩcm, which is acknowledged as being related to a very low chloride ion penetration (AASHTO, 2015).

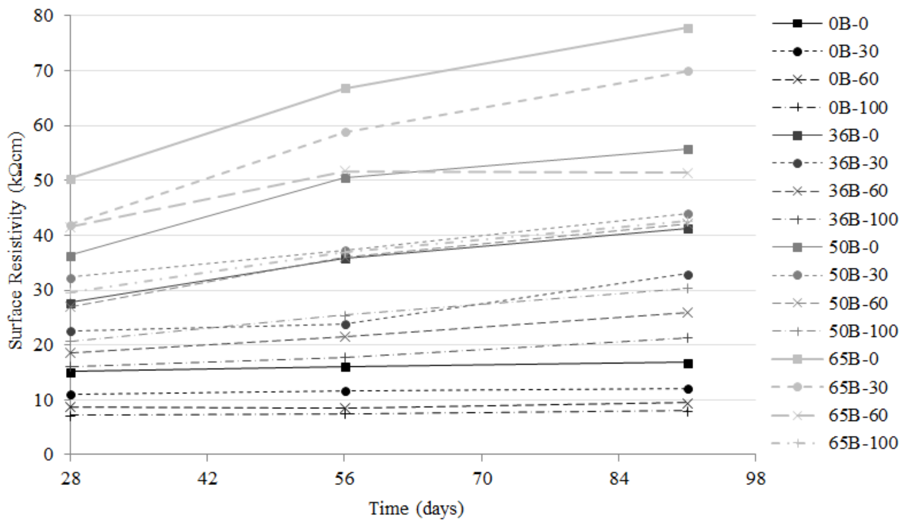

Figure 5 - Surface resistivity for source B concretes

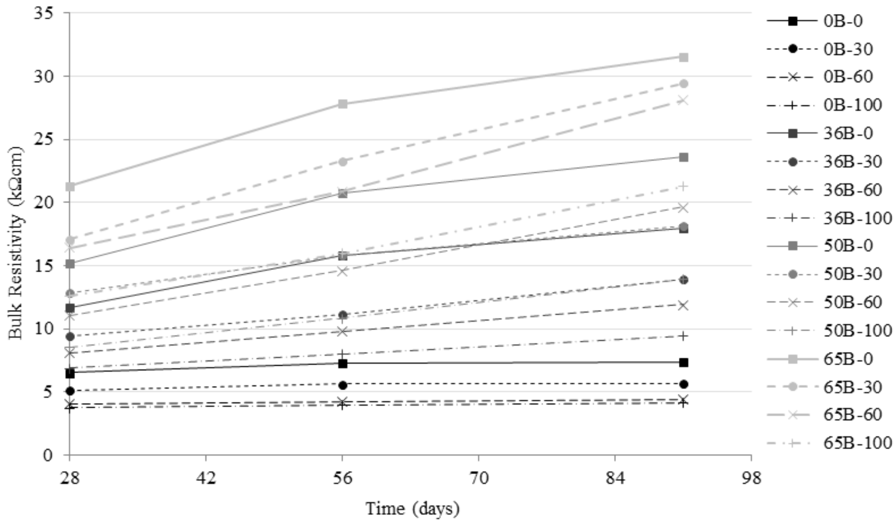

Figure 6 - Bulk resistivity for source B concretes

In addition to the individual trends observed in surface and bulk resistivity results with increasing CCA content and time, a strong correlation was observed between the two test methods as shown in Figure 7.

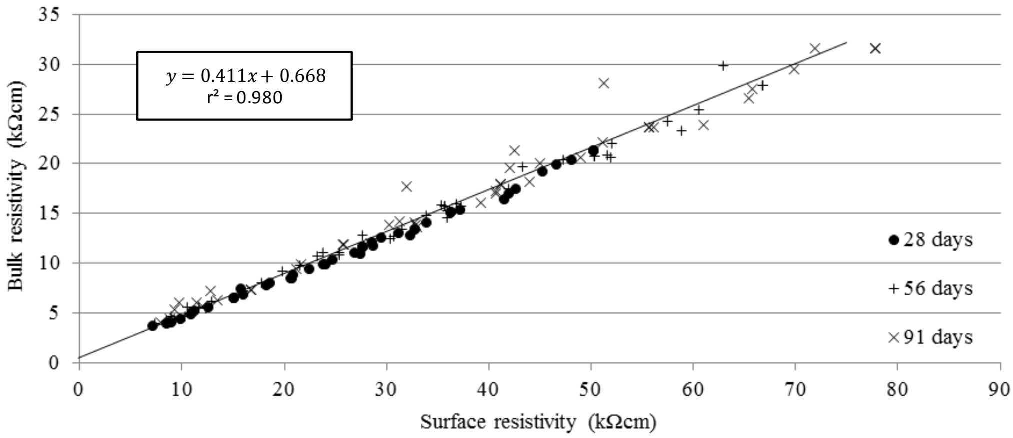

Figure 7 - Correlation between surface and bulk resistivity

5.3 ABSORPTION BY CAPILLARY ACTION

The 24 hour sorption coefficient of cylindrical specimens (60mm x 100mm diameter) was measured at 28, 56 and 91 days (Figures 8 to 10).

Figures 8 and 9 show that the 24 hour sorption coefficient generally increased with increasing coarse CCA content at 28 and 91 days. A similar trend was observed for concretes at 56 days. This trend was more evident at 91 days for all concrete types tested. At 28 and 91 days there was no clear trend of sorption coefficient with a particular source of coarse CCA; source A and B however had a detrimental effect on performance compared to source C CCA for CEM I concretes at 91 days (P>0.847). CEM III/A concretes produced with up to 100% CCA content had a lower 24 hour sorption coefficient than the control CEM I concretes at 91 days (P>0.936), except for the 50C-100 concrete, the probability of this concrete having a detrimental effect of 10% compared to the control CEM I concrete however was significantly low (P<0.021). At 28 days, the probability of CEM III/A concretes produced with up to 100% CCA content having a detrimental effect on the 24 hour sorption coefficient compared to the control CEM I concretes was significantly higher (0.938<P<0.999).

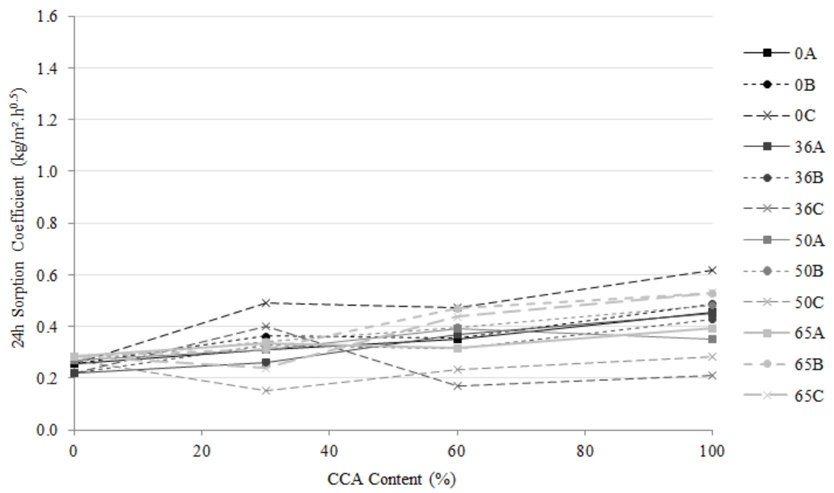

Figure 8 - 24hr Sorption coefficient at 28 days

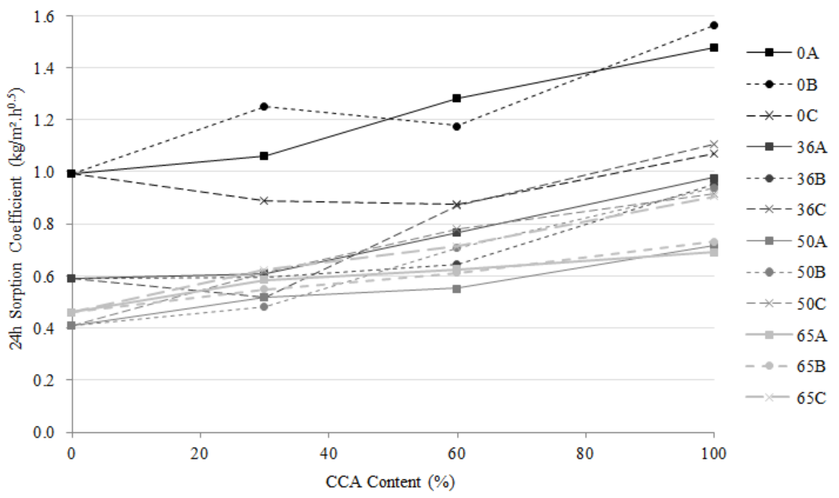

Figure 9 - 24hr Sorption coefficient at 91 days

Figure 10 shows that the sorption coefficient generally increases with time for concretes produced with coarse CCA from source B. Similar trends were observed for sources A and C. The beneficial latent hydraulic effects of GGBS in CEM III/A concretes can be observed as the sorption coefficient remains lower than CEM I concretes at 56 and 91 days. The CEM III/A concretes produced with higher quantities of coarse CCA content generally had higher sorption coefficients at all ages. At 56 and 91 days CEM III/A concretes produced with up to 100% coarse CCA from source B had lower sorption coefficients than the CEM I control concrete. Similar effects were observed for CCA sources A and C, except for the 36C-100 concrete.

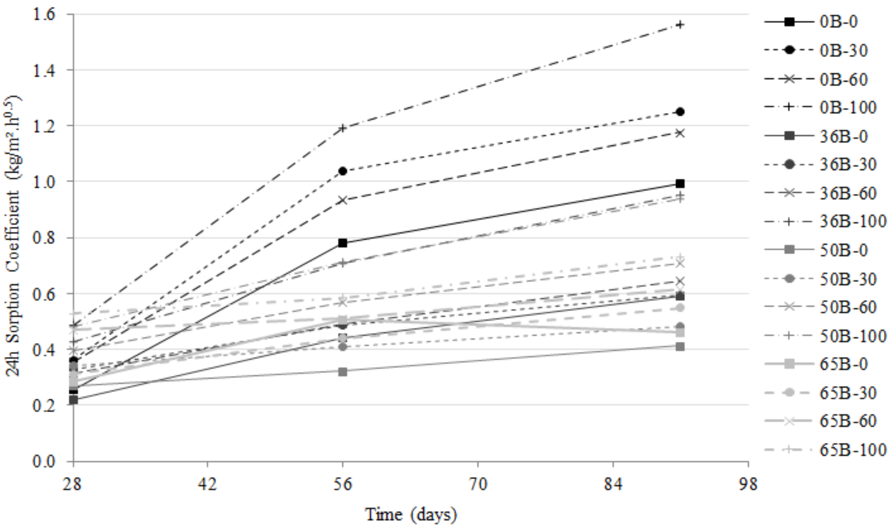

Figure 10 - 24hr Sorptivity coefficient for source B concretes

5.4 SEM ANALYSIS

Samples of CCA concrete for CEM I and CEM III/A binder types were randomly selected for SEM analysis. The samples were polished, coated with gold palladium and analysed in variable pressure (VP) mode with backscatter to produce high resolution, high magnification images. The areas between the coarse CCA and the new cement matrix were analysed to determine the quality of the ITZ (Figure 11).

The images show that there was no obvious increased porosity around the ITZ for CEM I concretes, compared to CEM III/A concretes. Instead the quality of ITZ for all concretes appeared to be dependent on the shape, size and arrangement of aggregates in a particular area. This effect can be observed in Figure 11c where the quality of ITZ is reduced in the area adjacent to the aggregate particle of the coarse CCA. In general, larger and more regular pores were observed in the new cement matrix for CEM I concrete (Figure 11a) compared to the CEM III/A concretes (Figures 11b, 11c and 11d). The pores generally reduced with size and frequency as the GGBS content increased. Larger and more regular pores were also observed in the old Portland cement matrix of the coarse CCA; whereas the pore size and distribution of the original aggregates was largely varied across samples and can be observed when comparing Figures 11c and 11d.

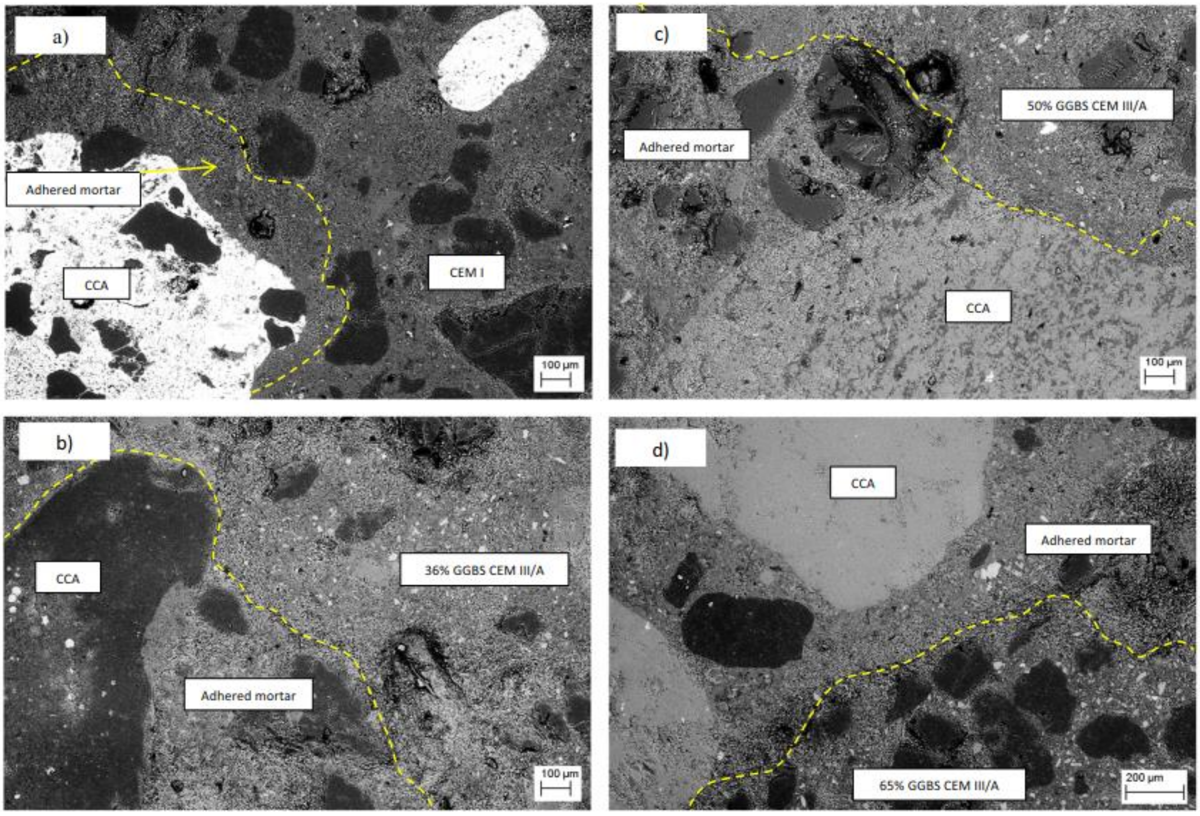

Figure 11 - SEM high resolution images for a) CEM I, b) 36% GGBS, c) 50% GGBS and d) 65% GGBS CCA concretes

6 DISCUSSION

The characteristic strength ($f_{c,cube}$) of 44MPa at 28 days was achieved by 24 of the 40 concrete mixes (Figure 1). CEM III/A concretes (up to 50% GGBS replacement level) produced with coarse CCA contents up to 60% for sources A and C, and 30% for source B, achieved the characteristic strength. In comparison 37 of the 40 concretes achieved the characteristic strength by 91 days (Figure 2), with only the 65B-100 concrete having a statistically high probability of non-compliance. Therefore if the characteristic strength at 28 days is of particular importance (as is usually the case in the construction industry) then it is recommended that the GGBS and coarse CCA content be restricted to 50% and 30% respectively. If a different approach is adopted whereby the long term 91 day compressive cube strength performance is assessed, then higher quantities of coarse CCA content can be utilised, producing a more sustainable structural concrete. In this case the coarse CCA content may be increased to 60% without significantly increasing the risk of not achieving the characteristic strength, which is higher than previously reported values of 25-50% (Bravo *et al*, 2015a; Padmini *et al*, 2009; Tabsh and Abdelfatah, 2009; Etxeberria *et al*, 2007). It is important to note that no superplastercisers were utilised in this study which could further contribute to an increase in compressive strength, and further research is required to quantify this effect.

The results of surface and bulk resistivity testing showed the beneficial latent hydraulic effects of GGBS as all CEM III/A concretes produced with up to 100% CCA content had a higher surface and bulk resistivity by a factor of 3 to 4 than the control CEM I concretes at all ages (Figures 3 to 6), which indicates a less porous microstructure related to a low corrosion rate/chloride ion penetration (AASHTO, 2015; Concrete Society, 2004). This finding is in agreement with other published research on the beneficial effects of SCMs (Faella *et al*, 2016; Singh and Singh, 2016; Goodier *et al*, 2015; Hwang *et al*, 2013; Kou and Poon, 2013; Limbachiya *et al*, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). At 91 days only the CEM I concretes had surface resistivities lower than 20kΩcm, which increases the risk of a reduced durability performance compared to CEM III/A concretes. A strong correlation was observed between surface and bulk resistivity (Figure 7), in agreement with other published research (Noort *et al*, 2016; Liu *et al*, 2015; Sengul, 2014; Ramezanianpour *et al*, 2011) which indicates that the surface resistivity readings can be used to assess the bulk microstructure of the concrete.

The beneficial latent hydraulic effect of GGBS was also observed in the test for absorption by capillary action, however was only evident at later ages (Figure 9). CEM III/A concretes produced with up to 100% CCA content had a lower 24 hour sorption coefficient by a factor 1.1 to 2.2 than the control CEM I concretes at 91 days, except for the 50C-100 concrete which was found to have a low probability of a significant detrimental effect in comparison ($P<0.021$).

The results of these durability tests have shown 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 concrete. The inclusion of coarse CCA generally reduced the surface and bulk resistivity and resulted in an increase in 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 (Bravo *et al*, 2015b; Lofty and Al-Fayez, 2015; Pedro *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Limbachiya *et al*, 2012). The magnitude of difference in the measured results between CEM I and CEM III/A concretes has shown that up to 100% coarse CCA, irrespective of the CCA sources adopted 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, which is higher than the previously reported values of 25-50% (Lofty and Al-Fayez, 2015; Soares *et al*, 2014; Zega *et al*, 2014; Kou and Poon; 2013; Limbachiya *et al*, 2012) and a positive finding for the wider implementation of coarse CCA to produce sustainable structural concrete (Dodds *et al*, 2017; Dodds *et al*, 2016). BS8500 provides guidance for cover depth and concrete mix design proportions based on the chosen binder type and expected environmental exposure conditions (BSI, 2015a,b). The guidance suggests that the cover depth 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 degredation regarding durability performance of CEM III/A CCA concretes is further reduced.

The SEM analysis of the microstructure of concrete, particularly the quality of ITZ between the new cement matrix and aggregates, revealed no additional voids due to the release of air from coarse CCA in this case (Figure 11). This result contradicts previously published work in this field (Leite and Monteiro, 2016; Tam *et al*, 2005), and further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes. Larger and a more regular pore structure was observed for the new and old cement matrices of CEM I concretes. The pore structure of the coarse CCA itself was largely varied throughout, which may cause some problems regarding variability in performance when higher quantities are incorporated.

Taking account of all the results together, source B CCA was found to be the worst performing aggregate, followed by sources A and C respectively. This however, was not the case for every individual test and concrete type, which again highlights some issues with the variability of performance for even the same source of CCA of known structural elements. The aggregate and concrete testing of CCA sources (Table 4) sought to characterise the CCA sources to be able to predict their effect on compressive cube strength and durability performance. It was found that little correlation existed between the results of water absorption/particle density, equivalent in-situ strength and petrography; however the information as a whole provided some indication that source B may perform worse than sources A and C due to a higher water absorption, higher estimated water-cement ratio, complex lithology and evidence of microcracking (Silva *et al*, 2014). It is recommended that sources of coarse CCA be tested in a similar manner before inclusion within structural concrete to be able to foresee any potential risks to mechanical and durability performance. In particular the results of water absorption, chemical analysis and petrographic analysis had a good correlation to potential performance.

7 CONCLUSIONS

In summary, the results show that the inclusion of coarse CCA generally has a detrimental effect on the microstructure and water ingress of structural concrete. The detrimental effects can be largely overcome through the use of GGBS to produce CEM III/A concretes, allowing higher proportions of coarse CCA to be utilised. Based upon the analysis of results, the following conclusions can be drawn:

1. It is recommended that the replacement of CEM I and NA with GGBS and coarse CCA be limited to 50% and 30% respectively in cases where compliance with the 28 day characteristic strength ($f_{c,cube}$) is of particular importance. If this criterion can be relaxed and the compressive cube strength of CEM III/A concretes tested at later ages for conformity, then higher quantities of coarse CCA may be incorporated up to 60% to produce a more sustainable structural concrete. Further research is required to determine the effect of superplastercisers on the acceleration of early strength gain and durability performance.

2. 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% NA in durability performance tests. If the cover depth of CEM III/A CCA concretes can be increased, similar to that of CEM I concretes, then the risk of potential durability performance issues can be further reduced. The quantity of coarse CCA should be limited to 60% however, to comply with conclusion one above.

3. The results of SEM analysis contradicted similar previously published work in this field. No additional voids around the ITZ were evident in the case of the three coarse CCA sources tested, suggesting that any observed detrimental effect may be due to other causes. It is recommended that further SEM work is required to confirm the effect of coarse CCA on the quality of the ITZ of different concretes, as this finding may not be a true representation of all coarse CCA sources.

4. It is recommended that when sources of coarse CCA are to be used, they are tested for water absorption, and chemically and petrographically analysed to determine the water

ingress, possible contamination and the original concrete composition. These test methods had a good correlation with the compressive cube strength and durability performance of coarse CCA sources adopted in this study.

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 CCA can be obtained. This is a positive outcome for the wider implementation of coarse CCA into structural concrete applications.

8 ACKNOWLEDGEMENTS

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APPENDIX F PAPER 5

Full Reference

Dodds, W. Christodoulou, C. Goodier, C. Austin, S. Dunne, D, 2017. *Durability performance of sustainable structural concrete: Effect of coarse crushed concrete aggregate on rapid chloride migration and accelerated corrosion*. Construction and Building Materials, Volume 155, pp511-521. DOI: 10.1016/j.conbuildmat.2017.08.073. ISSN: 0950-0618. https://dspace .lboro.ac.uk/2134/26920.

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.

Keywords – Crushed concrete aggregate (CCA), recycled concrete aggregate (RCA), chloride ion ingress, supplementary cementitious materials, corrosion, accelerated corrosion.

Paper type – Journal

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 (NFDC, 2016; DEFRA, 2015; WRAP, 2015). 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 (Barritt, 2015; Coelho and de Brito, 2013).

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 (BSI, 2015a,b; BSI, 2013a). 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 damaged reinforced concrete bridges was estimated at $8.29 billion annually in the USA alone (NACE International, 2012), 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 (Tuutti, 1982). 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 (Kropp *et al*, 1995).

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 (Glass *et al*, 2000; Kropp, 1995). The depassivation process results in the production of complex iron compounds which are soluble in the concrete pore solution (Dyer, 2014; Glass *et al*, 2007). 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 (Angst *et al*, 2011). The most common value published for free chloride content is 0.6% by mass of cement, with 0.4% being reported as the minimum (Alonso and Sanchez, 2009; Angst *et al*, 2009; Concrete Society, 2004; Kropp, 1995). Once the steel is exposed to the chlorides, the corrosion can then aggressively propagate as pitting occurs, producing further acidity from corrosion products (Glass *et al*, 2007; Bertlolini *et al*, 2004). Localised anodic areas exist at the location of the pits and the surrounding reinforcement becomes cathodic (Figures 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 0.3mm 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 (Concrete Society, 2010; Concrete Society, 2004; Raupach, 1996; BSI, 1992).

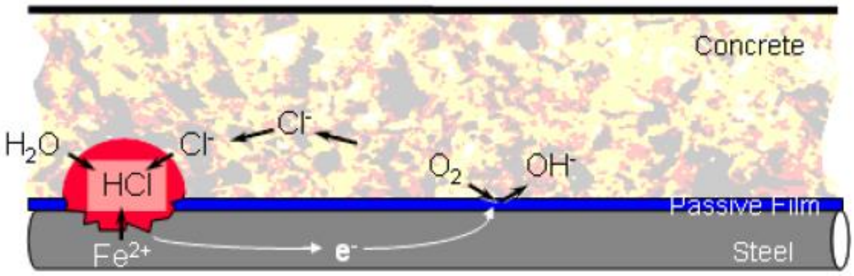

Figure 1 - Electrochemical process of chloride induced corrosion (Glass *et al*, 2006)

Figure 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 (Kropp *et al*, 1995). 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 (Glass and Buenfeld, 2000). 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) (Neville, 2011; Bertolini *et al*, 2004). 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 (Lollini *et al*, 2016; Dunne *et al*, 2015; Andrade and Bujak, 2013; Bapat, 2013; Reddy *et al*, 2002; Glass and Buenfeld, 2000; Dhir *et al*, 1997; Glass *et al*, 1997; Dhir *et al*, 1996). Microstructure analysis of GGBS has shown its ability to form higher quantities of Friedel's salt compared to CEM I concretes (Luo *et al*, 2003). 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 (Dyer, 2014).

Aggregates also play an important role in the transport of liquids as the water absorption properties and quality of the interfacial transition zone (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 natural aggregates (NA) 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 (Lofty and Al-Fayez, 2015; Bravo *et al*, 2015; Soares *et al*, 2014; Pedro *et al*, 2014; Kwan *et al*, 2012). 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 (Leite and Monteiro, 2016). However, Dodds *et al* (2017a) 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 (Claisse, 2014; Bertolini *et al*, 2004). 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 (ASTM, 2012; NordTest, 1999; Geiker *et al*, 1995).

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; 4/20mm), 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 (BSI, 2013a). 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 (BSI, 2015a; BSI, 2015b). 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 NA.

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 (Bravo *et al*, 2015; Lofty and Al-Fayez, 2015; Pedro *et al,* 2014; Soares *et al,* 2014; Zega *et al,* 2014; Limbachiya *et al,* 2012). 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 (Zega *et al*, 2014). Limbachiya et al (2000) established that a replacement level of up to 100% may not have a significant effect on the durability performance of high strength Portland cement (CEM I) concretes, provided the CCA source is obtained from high quality precast concrete sources. 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 (Dodds *et al*, 2017a,b; Dodds *et al*, 2016).

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 (Dodds *et al*, 2017a,b; Dodds *et al*, 2016; Faella *et al*, 2016; Saravanakumar and Dhinakaran, 2014; Bapat, 2013; Hwang *et al*, 2013; Kou and Poon, 2013; Lima *et al*, 2013; Kou and Poon, 2012; Somna *et al*, 2012; Berndt, 2009; Ann *et al*, 2008). 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 (Dodds *et al*, 2017b; Faella *et al*, 2016; Hwang *et al*, 2013; Kou and Poon, 2013; Lima et al, 2013; Kou and Poon, 2012; Somna *et al*, 2012; Berndt *et al*, 2009; Ann *et al*, 2008). Berndt (2009) 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 (NordTest, 1989). Zhao *et al* (2014) 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 44MPa and 58MPa respectively by the BRE mix design method (BRE, 1997). The concretes were produced in accordance with BS 1881-125 (BSI, 2013b) 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 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 (BSI, 2015a). Three sources of coarse CCA (4/20mm) 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%.

Table 1 - Mix design constituents for control batches

	Mix Design			
Constituents	CEM I	CEM III/A (36%)	CEM III/A (50%)	CEM III/A (65%)
Water-binder ratio	0.5	0.5	0.5	0.5
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

Six unreinforced and four reinforced concrete cylinders (200mm × 100mm diameter) were cast from each mix to undertake rapid chloride migration and accelerated corrosion testing in accordance with NT Build 492 and 356 (NordTest, 1999; NordTest, 1989). In the reinforced specimens, steel reinforcing bars (12mm in diameter) were cast centrally, with a 50mm 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 5V was applied, and the current was recorded daily. The test was terminated when a visible crack was observed (greater than 0.3mm), as this can be indicative of a failure of the protective concrete cover (Figure 3) (Concrete Society, 2010; Concrete Society, 2004; Raupach, 1996; BSI, 1992). Upon termination of the test, specimens were split axially along the crack plane and the minimum concrete cover measured (Figure 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.

Figure 3 - Typical cracking of 200mm × 100mm diameter reinforced concrete cylinder

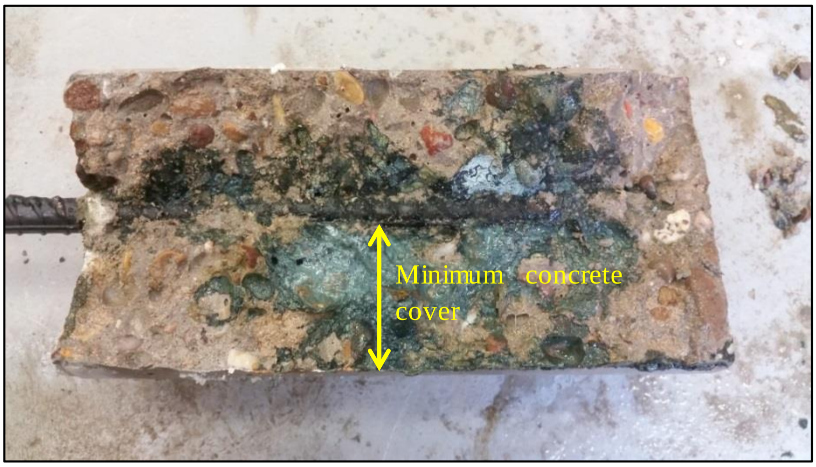

Figure 4 - Measurement of cover depth and development of 'green rust' precipitate

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 (Dodds *et al*, 2017a) for the CCA sources used in this research (Table 2).

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)

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 (BSI, 2013a; BSI, 2013c). 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 (Dodds *et al*, 2017a).

Table 3 – Summary of coarse CCA characteristics

Source	24 hour water absorption [%]		SSD particle density [Mg/m³]		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

5 ANALYSIS OF RESULTS

5.1 RAPID CHLORIDE MIGRATION

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

Figures 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 greater than 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 to 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 ($P<0.002$).

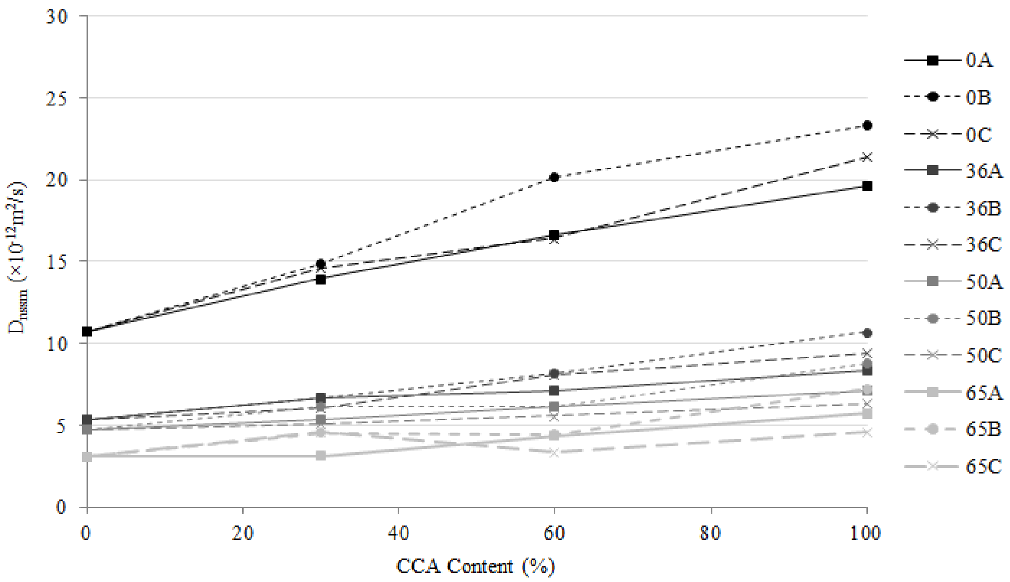

Figure 5 – Rapid chloride migration coefficient (D_{nssm}) at 28 days

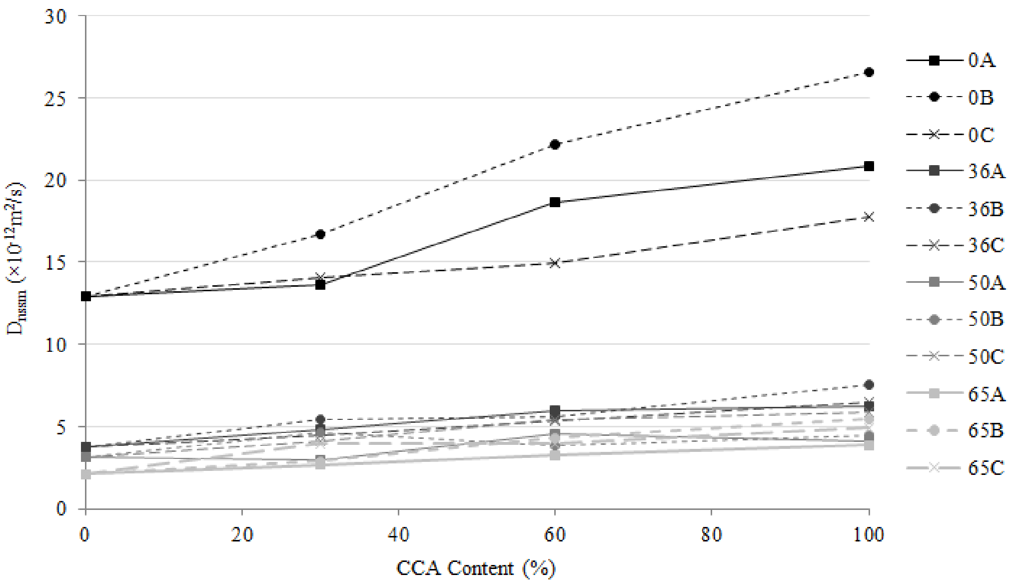

Figure 6 - Rapid chloride migration coefficient (D_{nssm}) at 91 days

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.

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

5.2 ACCELERATED TIME TO CORROSION INITIATION AND CRACKING

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

The results for CEM I concretes (Figures 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 the worst at both testing ages, followed by sources A and C, with both corrosion initiation and cracking occurring at earlier ages.

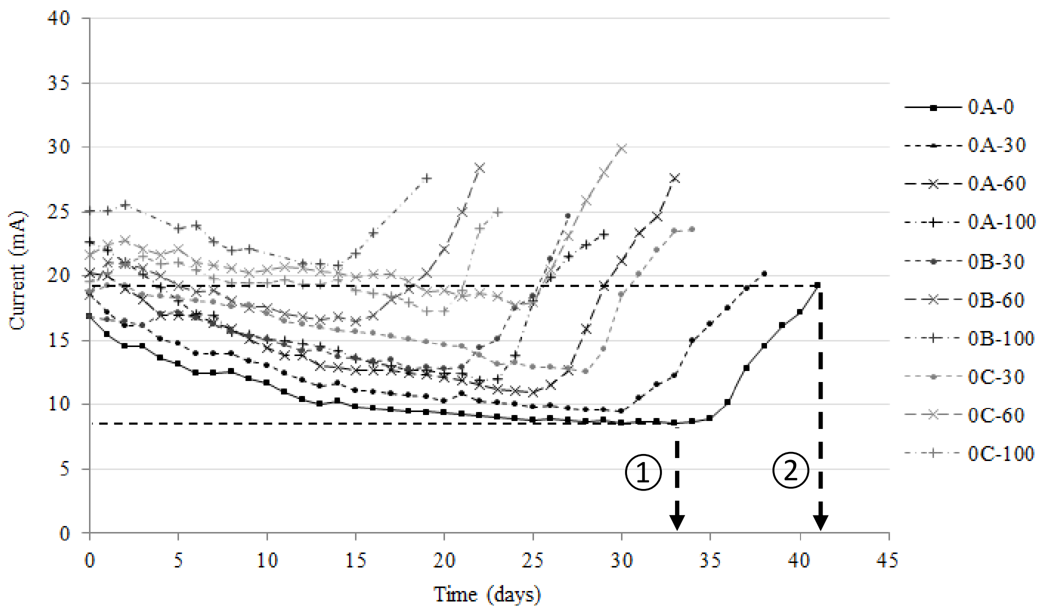

Figure 7 – Time to corrosion initiation and cracking (CEM I, 28 days)

The measured current (mA) for CEM I concretes at 91 days is generally higher (Figure 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 (Figures 9 to 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.

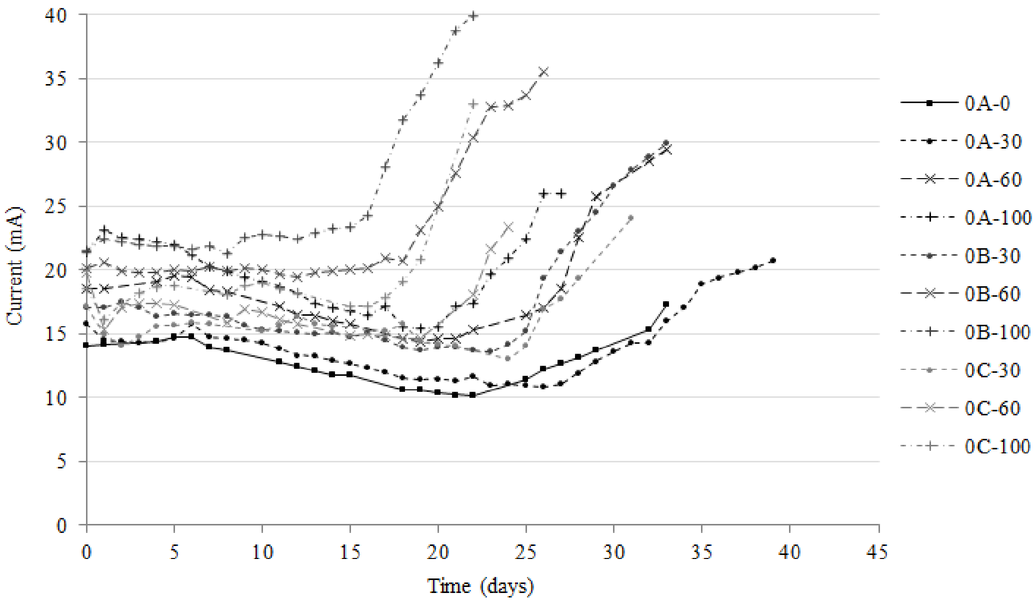

Figure 8 - Time to corrosion initiation and cracking (CEM I, 91 days)

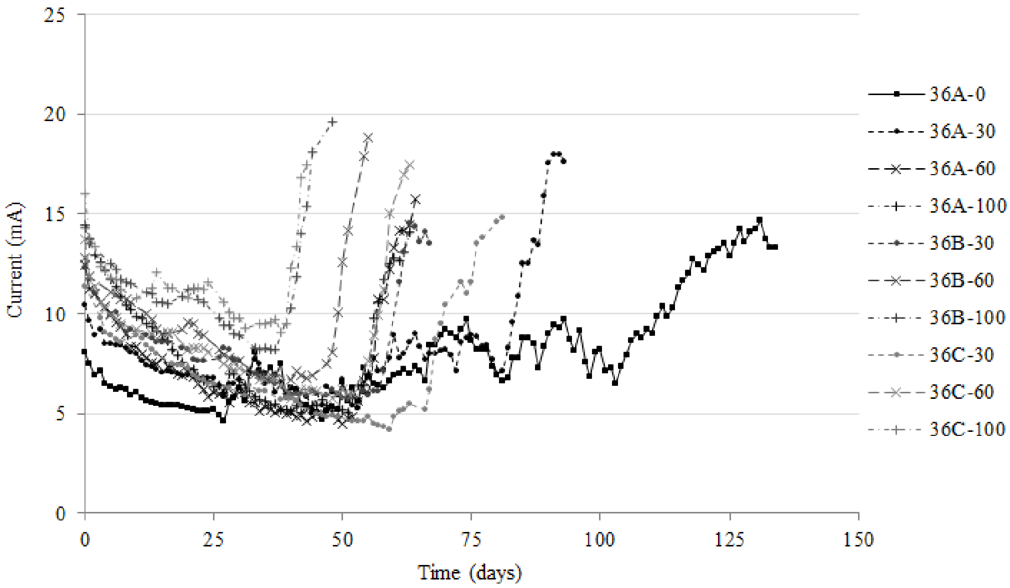

Figure 9 - Time to corrosion initiation and cracking (CEM III/A, 36% GGBS, 28 days)

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 (Figures 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.

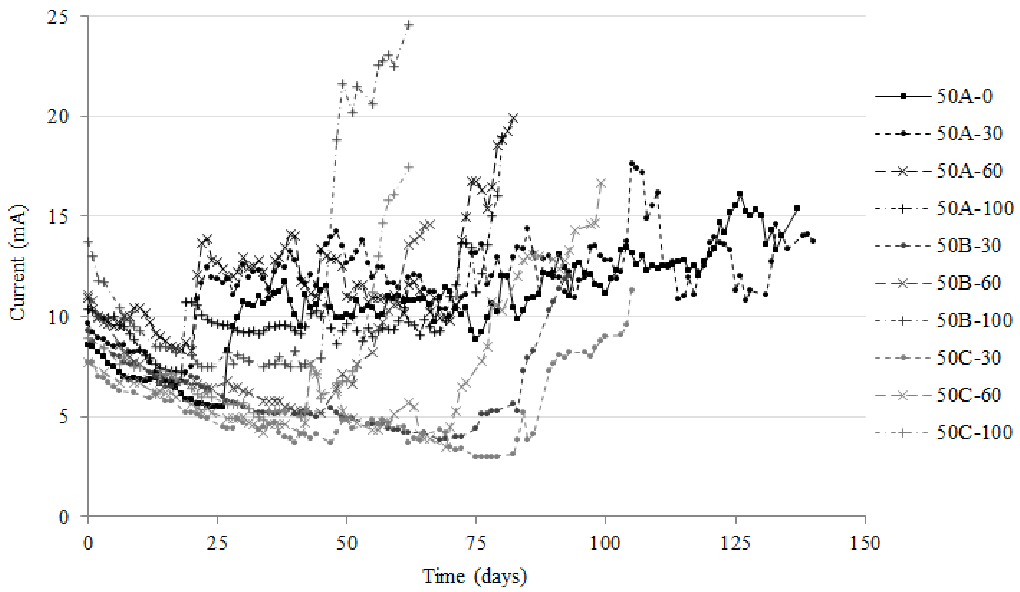

Figure 10 - Time to corrosion initiation and cracking (CEM III/A, 50% GGBS, 28 days)

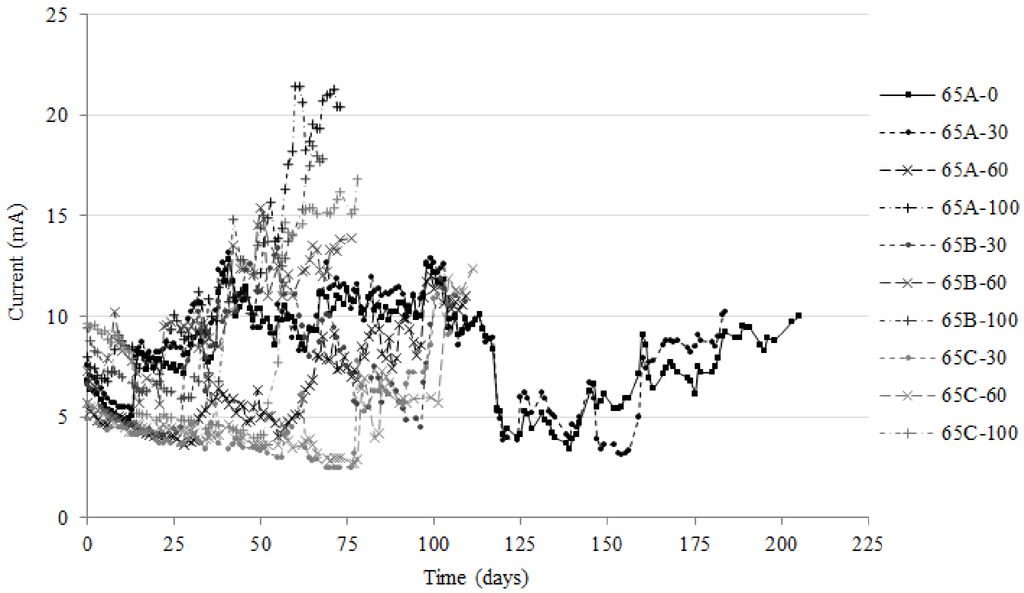

Figure 11 - Time to corrosion initiation and cracking (CEM III/A, 65% GGBS, 28 days)

Figure 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.

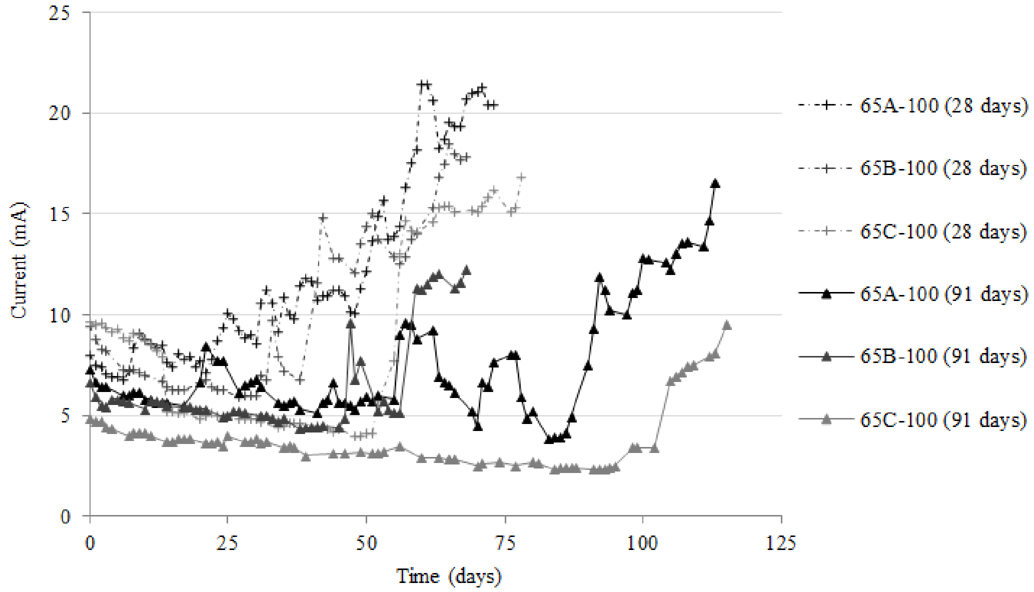

Figure 12 - Time to corrosion initiation and cracking (CEM III/A, 65% GGBS, 28 and 91 days)

Figure 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.

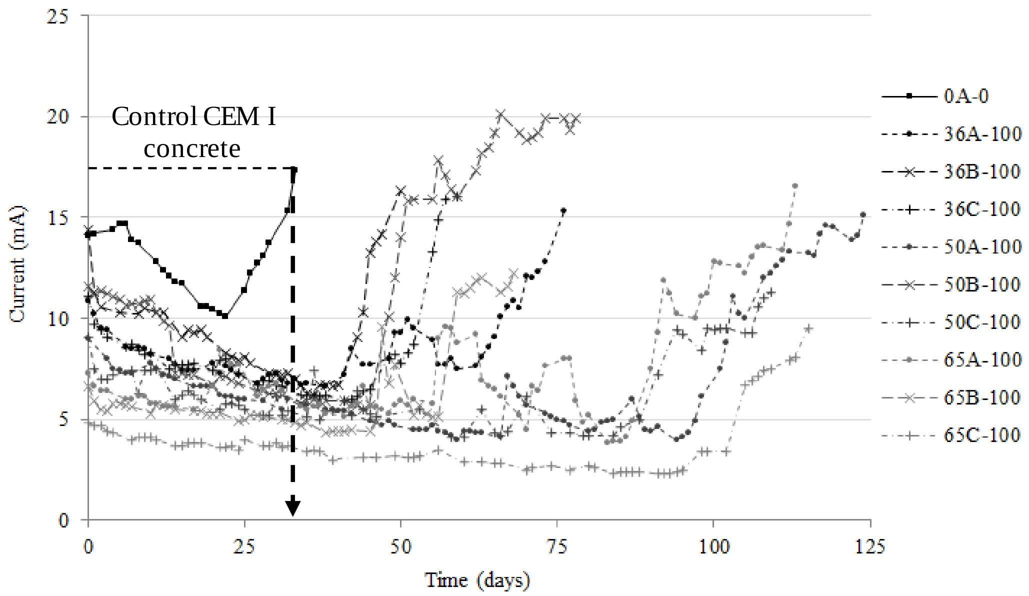

Figure 13 - Time to corrosion initiation and cracking (91 days)

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

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

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 (Figures 5 to 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) (Bravo *et al*, 2015; Lofty and Al-Fayez, 2015; Pedro *et al*, 2014; Soares *et al*, 2014; Zega *et al*, 2014; Zhao *et al*, 2014; Limbachiya *et al*, 2012). 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 to 6 with more than 36% GGBS (Figures 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 Figures 6 and 12 (Lollini *et al*, 2016; Dunne *et al*, 2015; Andrade and Bujak, 2013; Bapat, 2013; Reddy *et al*, 2002; Glass and Buenfeld, 2000; Dhir *et al*, 1997; Glass *et al*, 1997; Dhir *et al*, 1996), 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 (Dodds *et al*, 2017a,b; Dodds *et al*, 2016). 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 (BSI, 2015a; BSI, 2015b; BSI, 2013). Moreover, the BS8500 guidance on cover depth and concrete mix design proportions, which is based on the binder type and environmental exposure conditions (BSI, 2015a,b), 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* (2017a) 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

(Berndt, 2009). 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 (Figures 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 (Figure 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 (37.3mm and 41.8mm 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 (Figures 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 (>0.3mm) 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 (Glass and Buenfeld, 2000). 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 (Neville, 2011; Bertolini *et al*, 2004; Luo *et al*, 2003; Dhir *et al*, 1996).

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 (NordTest, 1989). 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 (Kropp *et al*, 1995; Tuutti, 1982). 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 acknoweldge 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 CCA source, 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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