The effect of fine crushed concrete aggregate on the durability of structural concrete

DODDS Wayne[1,a*], GOODIER Chris[1,b], AUSTIN Simon[1,c],
CHRISTODOULOU Christian[2,d], DUNNE David[2,e] and CHAN Matthew[1]

[1]Centre for Innovative and Collaborative Construction Engineering, School of Civil and Building Engineering, Loughborough University, Leicestershire, UK, LE11 3TU

[2]AECOM, Colmore Plaza, 20 Colmore Circus Queensway, Birmingham, UK, B4 6AT

[a]W.J.Dodds@lboro.ac.uk, [b]C.I.Goodier@lboro.ac.uk, [c]S.A.Austin@lboro.ac.uk,
[d]Christian.Christodoulou@aecom.com, [e]David.Dunne@aecom.com

*corresponding author

Keywords: Crushed concrete aggregates, recycled concrete aggregates, durability, water absorption, chloride ingress

Abstract - The specification of crushed concrete aggregates (CCA) is increasing, particularly for low-grade applications, where quality is of less importance. In higher value applications, such as structural concrete, further research is required to understand the effect of CCAs on mechanical and durability performance. One disadvantage of using CCA is that the fine material (0-4mm) is often removed, which is not efficient. This research investigated the effect of fine CCA and its combination with coarse CCA in PC/GGBS structural concretes. The resistance to water and chloride ingress in terms of surface resistivity, sorptivity and rapid chloride migration were evaluated, together with compressive strength to determine compliance with characteristic and target mean strengths. From this limited study of CCA which forms a wider research project, the results indicate that a higher proportion of CCA, both fine and coarse, is detrimental to the resistance to water and chloride ingress, possibly due to the higher water absorption characteristics of the recycled material. The incorporation of GGBS however, significantly improves the durability performance, therefore making structural concrete with fine and coarse CCA a viable option.

Introduction

Recycled aggregates (RA) and crushed concrete aggregates (CCA) 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 were produced in the UK in 2013 and 2014 respectively, and the quantity has been predicted to continue to increase annually [1]. CCA can be utilised across a wide variety of applications, but it is primarily specified as low-grade unbound aggregates in general fill, capping layers and as drainage materials, as the quality of these aggregates are generally of less importance [2,3].

The majority of CCA sources produced in the UK are in compliance with the *Quality Protocol for the Production of Aggregates from Inert Waste* [4]; however for use in structural concrete they must also conform to the European standard for aggregates in concrete [5]. Utilising CCA in lower grade applications enables the fines content (0-4mm) to be incorporated which has its economic advantages. This also eliminates the need for aggregate screening and in turn helps to reduce any potential waste being produced. Recycled aggregate producers are continually 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 more limited due to a higher uncertainty regarding performance; this is currently not an issue within the UK construction industry however, as the potential supply of quality RA and CCA is fully utilised as unbound aggregates [6].

An opportunity may arise in the UK to incorporate CCA within structural concrete if a good quality source could be utilised on a regeneration project. 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%'* [7]. The UK standard allows CCA up to 20% by mass, in concrete up to strength class C40/50, except when the structure is likely to be exposed to chlorides [8,9]. The acceptable quantity of fine CCA is not prescribed in the UK standard: *'BS8500 does not preclude their use where it is demonstrated that, due to the source of material, significant quantities of deleterious materials are not present and their use has been specified or permitted'*. This is due to concerns over the quantity of gypsum plaster present in the source of fine CCA when a source is crushed, which can increase the sulfate content of the resultant concrete and in turn cause delayed hydration. The possible detrimental effect on strength is also a concern [10].

This therefore highlights an uncertainty when it comes to incorporating the fine proportion of the CCA which would ultimately become a waste product if it was screened out from coarse aggregates. Further research is required to understand the true effects of fine CCA on mechanical and durability properties, if a clearer specification for the combined use of fine and coarse CCA is to become a possibility in the future. 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 [11,12].

A review of existing research has highlighted that the compressive and tensile strength, and deformation characteristics of concrete can be affected by the inclusion of fine CCA. Suitable replacement levels of 30% and 60% have been reported [13,14]. The detrimental effect is more notable in higher strength concretes [15]. The relationships between engineering properties and compressive strength however have been found to be valid for the majority of existing design codes [16]. There is a higher uncertainty on the true effect of fine CCA on the durability performance of structural concrete as less published work is available. Evangelista and de Brito found that 30% fine CCA inclusion was feasible to produce durable structural concrete, contrary to the general belief that this quantity is not suitable for this type of application [17]. Larger quantities of fine CCA had a much more detrimental effect, causing the water absorption by immersion, water absorption by capillary action, and non-steady state chloride migration coefficient to rise by 46%, 70% and 34% respectively for total replacement of natural fines compared to control concretes. Supplementary cementitious materials (SCMs) were suggested as an alternative to overcome the detrimental effect of fine CCA; however this was not quantified. SCMs can improve the durability performance of CCA concrete, due to the reduced porosity of the cement matrix, improved quality of the interfacial transition zones of aggregates and improved chloride binding capacity [18-23]. Similar studies have assessed fine CCA by other test methods such as; ultrasonic pulse velocity (UPV), surface resistivity and water penetration under pressure, and all have come to a similar conclusion that fine CCA has a detrimental effect on durability performance; however no limiting values are recommended [13,24].

The rise in all transport properties tested has been attributed to the presence of the fine CCA producing more and longer capillaries by its own increased porosity [25]. Similar effects have been observed in durability studies on coarse CCA in structural concrete primarily due to the increased water absorption of the aggregates [26-30].

The majority of existing published work has focused primarily on the inclusion of fine CCA only, and the combined effect of fine and coarse CCA is still under-researched. The aim of this limited study therefore was to examine combinations of fine and coarse CCA content in structural concrete to determine its resistance to water and chloride ingress. Ground granulated blast furnace slag (GGBS) was also incorporated to replace Portland cement (PC) by 50% to quantify the potential beneficial effects on durability performance. The compressive strength was tested to determine compliance with the characteristic and target mean strength.

Methodology

A structural concrete was designed to achieve characteristic and target mean strengths of 43MPa and 57MPa respectively by the BRE mix design method [31]. PC (CEM I) and GGBS (50% - CEM III/A) concrete mixes were tested at a free water-binder ratio of 0.5. The free water-binder ratio and cement content of 390kg/m^3 were chosen to comply with the recommendations for XD3/XS3 exposure classes in Table A.4 of BS8500-1 [8] and account for the aggregate absorption. Fine CCA was incorporated at 20% and 40% to replace natural fine aggregate by mass, denoted as 'F20' and 'F40' respectively. Mixes with both fine and coarse CCA were also tested at 20% and 40% to determine the combined effect, denoted as 'F/C20' and 'F/C40' respectively. All CCA concretes were compared against a control batch made with 100% natural aggregates (rounded quartzite river gravel and sand). No additional cement or water was added to compensate for the inclusion of CCA. Table 1 details the test methods employed.

Table 1 - Test methods employed

Test	Justification
Compressive cube strength [32]	To determine compliance of mixes with characteristic and target mean strengths and to analyse the effect of fine and coarse CCA on compressive strength.
Surface resistivity [33]	To determine the effect of fine and coarse CCA on electrical resistivity of concrete, to provide an indication of its ability to resist chloride ion penetration.
Absorption by capillary action [34]	To determine the effect of fine and 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.
Rapid Chloride Migration [35]	To determine the effect of fine and 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.

Statistical analysis of the results was undertaken using t-tests to determine the effect on sample means when fine and coarse CCA were added. The probability of a significant detrimental effect was calculated based on a 10% decrease in performance when compared to the control batch for PC and GGBS concrete.

European standards state 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 [7]. Our CCA was from the demolition of a 1970's office building structure in Leicester, UK. Three randomly selected samples were sent for petrographic analysis [36,37] to determine the concrete composition and type (Figure 1). Randomly selected samples of fine and coarse CCA were tested for water absorption properties, and concrete cores from larger sections were taken to determine compressive strength [38-41].

CCA Composition

The water absorption for the fine and coarse CCA is shown in Table 2 and compared against that of the natural aggregates used in this study. The water absorption of CCA is higher for both 30 minute and 24 hour water absorption. A higher water content was added during mixing to account for the short-term water absorption of fine and coarse CCA in accordance with the BRE mix design method [31]. Water absorption of fine and coarse CCA has been reported elsewhere between 4.61% and 12.90%, dependent on the original source of concrete [26-30]. The results of compressive strength testing from cored specimens are shown in Table 3.

Table 2 - Water absorption properties of CCA and natural aggregates

	CCA		Natural aggregate	
	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
0-4mm (Fine)	8.55	8.79	0.42	0.53

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	

The key findings of the petrographic analysis were:

- The concrete is produced with partly-crushed gravel typical of East/South-East England (sandstone, limestone, quartzite and chert), quartz-dominated sand and ordinary Portland cement.
- No cement replacements or admixtures have been used.
- Estimated water-cement ratio, slump and 28 day strength are 0.58, 30-60mm and 38.5MPa respectively; the latter is similar to that of the equivalent in-situ characteristic strength.
- Estimated cement content is 325kg/m³, 13.8% 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 interfacial transition zones.
- Phenolphthalein indicator solution suggests maximum carbonation of 20-25mm.

Fig. 1 - Thin section of demolition concrete for petrographic analysis [42]

Analysis of Results

Compressive Strength

Tests were conducted on 100mm cube samples at 7, 28 and 56 days. The results show that the inclusion of fine CCA, and a combination of fine and coarse CCA, does have an increasingly detrimental effect on compressive strength at both 28 and 56 days for both PC and GGBS concrete (Figures 2 and 3 respectively). The target mean strength (57MPa) at 28 days was only achieved in the control concretes for PC and GGBS. In the majority of cases the characteristic strength (43MPa) at 28 days was easily achieved, except for the PC concrete made with 40% fine and coarse CCA. At 56 days the characteristic strength was met for all concrete mixes.

A left-tailed t-test was used to determine if the additions of CCA had a detrimental effect (10% decrease) on sample means, compared to the control concretes for both binder types. A high probability ($p>0.721$) was obtained for all concrete mixes at 28 days, indicating a detrimental effect greater than 10%, except for the 20% fine CCA in PC concrete mix which had a probability of $p<0.115$.

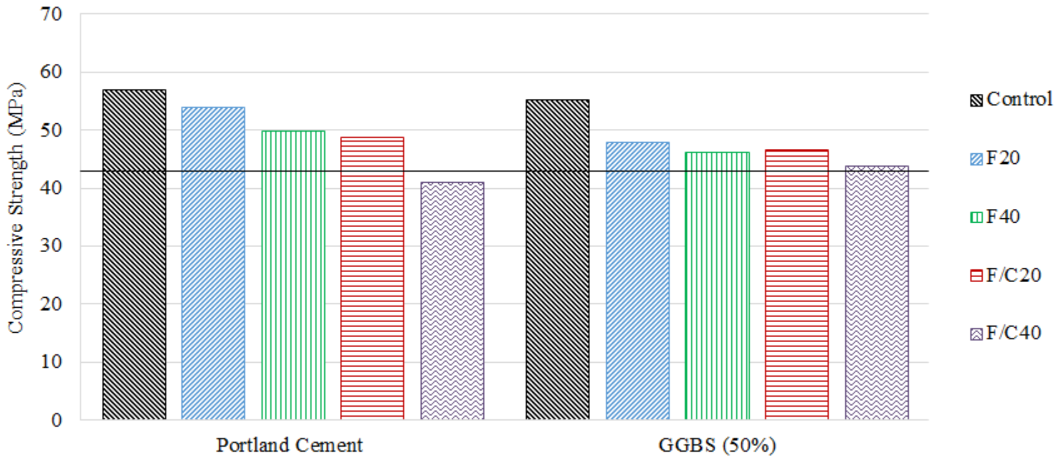

Fig. 2 - 28 day compressive cube strengths of PC and GGBS concretes

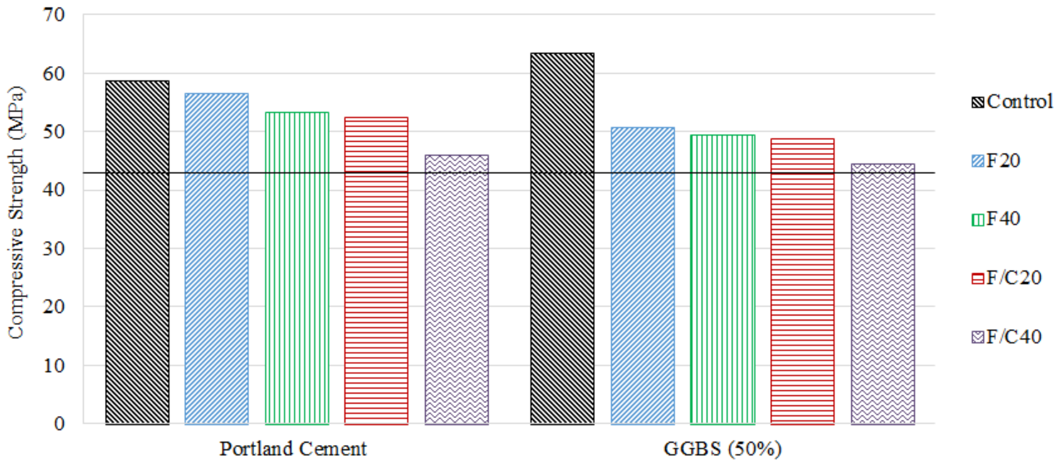

Fig. 3 - 56 day compressive cube strengths of PC and GGBS concretes

Surface Resistivity

The surface resistivity of cylindrical specimens (200mm x 100mm diameter) was measured at 28 days (Figure 4); it is a relatively quick method for assessing the microstructure and subsequent transport properties of different concretes [43]. The results are commonly interpreted following the recommendations in Table 4. A lower resistivity indicates a more porous concrete microstructure as it allows a higher current to pass between the probes at the surface.

Table 4 - Interpretation of four-point Wenner probe readings [33,44]

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 results show that the PC concrete has a lower surface resistivity than GGBS concrete, by a factor of 3 to 4. The addition of combined fine and coarse CCA had an increasingly detrimental effect on the surface resistivity of both concrete types; however the fine CCA content on its own seems to have had a beneficial effect on the surface resistivity of GGBS concrete. The results for the PC mixes indicate a ‘high to moderate’ chloride ion penetration/corrosion rate range, dependant on the quantity of CCA included. In contrast, the results for GGBS concrete indicate a ‘very low’ chloride ion penetration and ‘low’ corrosion rate.

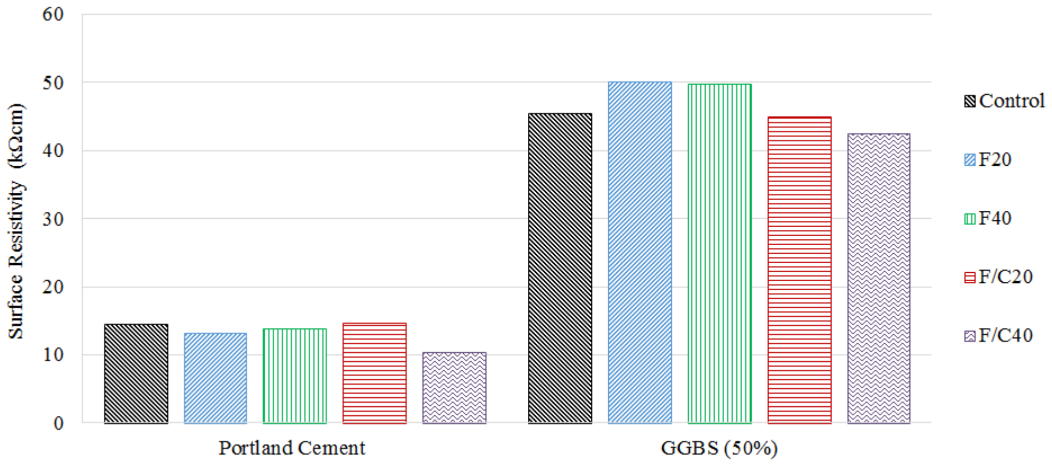

Fig. 4 - Concrete surface resistivity at 28 days of PC and GGBS concretes

Statistical analysis showed a particularly high probability ($p>0.584$) that the surface resistivity would not decrease by more than 10%, except for the PC concrete made with 40% fine and coarse CCA ($p<0.022$). GGBS concretes in particular had a much higher probability of no detrimental effect ($p>0.855$).

Absorption by Capillary Action

Kropp *et al* describe sorptivity as the *'transport of liquids into porous solids due to surface tension acting in capillaries'* [11]. 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 the side to ensure uni-directional ingress of water. Cumulative absorption was measured at 28 days for PC and GGBS concrete mixes (Figure 5a and 5b respectively) and the sorption coefficients were determined from the gradients at 12 minutes and 24 hours (Table 5).

For 20% fine CCA content, a relatively low probability was calculated for the 24 hour sorption coefficient to increase by more than 10% for both PC ($p<0.554$) and GGBS ($p<0.040$) concrete. All CCA contents above this have a higher probability of a detrimental effect, particularly for the PC concrete ($p>0.994$) compared to GGBS concrete ($p>0.492$). The inclusion of GGBS significantly reduced the detrimental effect of coarse and fine CCA on both the initial (12 mins) and final (24 hour) sorption coefficients.

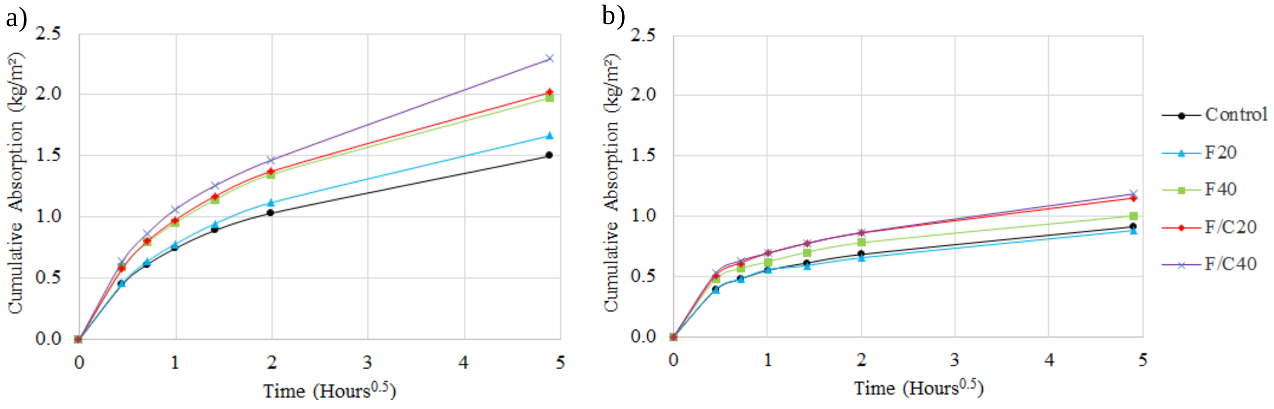

Fig. 5 - Cumulative absorption at 28 days for a) PC concrete, and b) GGBS concrete

Table 5 – 28 day sorption coefficients for all concretes tested

	PC					GGBS				
CCA Content	C	F20	F40	F/C20	F/C40	C	F20	F40	F/C20	F/C40
12 mins Sorption Coefficient $[kg/m^2.h^{0.5}]$	1.00	1.02	1.31	1.29	1.42	0.87	0.88	1.07	1.14	1.18
% change	-	2	31	29	42	-	1	23	31	36
24 hour Sorption Coefficient $[kg/m^2.h^{0.5}]$	0.31	0.34	0.40	0.41	0.47	0.19	0.18	0.20	0.24	0.24
% change	-	10	29	32	53	-	-5	5	26	26

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 an anode [45]. The non-steady state migration coefficients in Figure 6 have been calculated from average penetration depths.

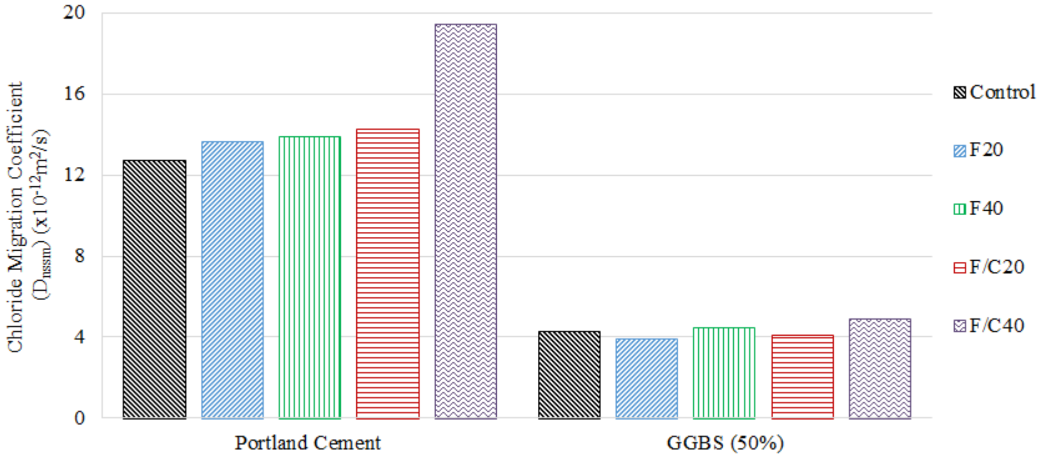

Fig. 6 - Rapid chloride migration at 28 days of PC and GGBS concretes

The results show that the inclusion of both coarse and fine CCA content had an increasingly detrimental effect on the migration coefficient of concrete. Statistical analysis showed a relatively high probability that the migration coefficient would not increase by more than 10% for all CCA contents, except for the higher content of F/C40. GGBS concrete ($p>0.653$) had a higher probability compared to PC concrete ($p>0.421$). Similar to the results of surface resistivity and absorption by capillary action, a small quantity of fine CCA appears to have a beneficial effect on durability performance in GGBS concrete. In all cases the GGBS had a significant beneficial effect at resisting chloride ion penetration compared to PC, by a factor of 3 to 4.

Discussion

Compressive Strength

The statistical analysis of the 28 day compressive strength results has reinforced the evidence that the inclusion of both fine and coarse CCA has an increasingly detrimental effect, except for the lower fines content in PC concrete (up to 20%), which confirms the common concern of fine CCA in the industry [10]. This finding is lower than other reported suitable replacement levels for fine CCA [13,14]; however this may be due to a more detrimental effect in higher strength concretes [15].

The target mean strength at 28 days was not always achieved, particularly for concretes with a higher CCA content (Figure 2). The mix design could be changed for the CCA concretes to include a higher cement and water content, in order to increase the compressive strength. This however would offset any sustainability savings achieved by utilising CCA, and therefore is unlikely to be adopted as an approach for designing structural concrete. Although the target mean strengths were not met for CCA concrete, the majority of mixes still achieved the characteristic strength at 28 days, except for the F/C40 PC concrete. At 56 days the characteristic strength was easily achieved for all mixes (Figure 3). These findings suggest that the BRE method of mix design is suitable for designing structural concrete with a fine CCA content up to 40%, and also a combined fine and coarse CCA content up to 20% [16].

The latent effect of GGBS was only observed in the control concrete at 56 days (Figure 3). This is possibly due to the fine CCA content causing a delay in the hydration process, as mentioned in BS8500 [8,9]. The lower rate of strength gain was similar to that of the PC concrete mixes.

Surface Resistivity

Figure 4 shows that an increase in the fine CCA content, and a combination of fine and coarse CCA content, generally reduced the surface resistivity of concrete. This is possibly due to the increased porosity of the CCA, which is a common explanation for the reduction of durability performance [25-30]. This finding is in agreement with other research that has tested the surface resistivity of PC concrete [13,24].

An exception to this occurred with both the 20% and 40% fine CCA GGBS concretes, which appear to have experienced a beneficial effect with approximately a 10% increase in surface resistivity. The inclusion of small quantities of fine CCA in this case may have reduced the porosity of GGBS concrete. As no literature has quantified the effect of fine CCA on the durability performance of GGBS concrete it is difficult to determine if this is a common trend for different types of fine CCA. 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 high/moderate range to very low (Table 4).

Absorption by Capillary Action

The sorption coefficients and statistical analysis indicate that both fine and coarse CCA have an increasingly detrimental effect on structural concrete (Figure 5a and 5b; Table 5), similar to the findings of Evangelista and de Brito for water absorption by capillary action [17]. This is most likely due to the increased porosity of the CCA itself [25-30]. Again, a small quantity of fine CCA (20%) appears to have had a beneficial effect on the sorption of GGBS concrete.

The inclusion of GGBS not only reduced the initial (12 minute) and 24 hour sorption coefficients, but also reduced the impact of both a fine and coarse CCA content (up to 40%). The highest influence on the 24 hour sorption coefficient was observed for the F/C40 concrete, a 53% and 26% increase for PC and GGBS concretes respectively. The initial sorption coefficient for F/C40 concrete was also reduced from 42% to 36% for PC and GGBS concretes respectively. This indicates that the GGBS content has reduced the radius, tortuosity and/or continuity of the capillaries, either by a reduced porosity of the cement matrix or an improved quality of interfacial transition zone between the cement paste and the surrounding aggregates [19-23]. The effect of GGBS is more dominant over a longer exposure period of 24 hours compared to 12 minutes, which is particularly beneficial to structural concrete likely to be exposed to cyclic ponding.

Rapid Chloride Migration

Figure 6 shows that an increase in the fine CCA, and a combination of fine and coarse CCA generally increased the rapid migration coefficient of concrete, primarily due to its own increased porosity [25-30]. This is in agreement with other published research [17]. The statistical analysis however has confirmed that the chloride ingress is unlikely to increase by more than 10%, except for the higher CCA content of F/C40 for PC and GGBS concrete. As observed with other durability test methods, a small quantity of fine CCA (20%) appears to have had a beneficial effect on the migration coefficient of GGBS concrete.

GGBS addition significantly improves resistance to chloride ion penetration compared to PC; by a factor of 3 to 4. There is also strong statistical evidence to suggest that the effect of fine and coarse CCA is more dominant in the PC concrete mixes compared to those with 50% GGBS.

Similar to the results of absorption by capillary action this is most likely due to a reduced porosity of the cement matrix or an improved quality of interfacial transition zones [19-23]. An improved chloride binding capacity may also contribute to a reduction in the rapid migration coefficient [18].

Conclusions

From this limited study of CCA which forms a wider research project, the results show that the inclusion of fine CCA, and the combined effect of coarse and fine CCA, does have a detrimental effect on the different transport mechanisms in concrete, and also the compressive strength.

The results of compressive strength testing showed that the target mean strength was not always achieved at 28 days, particularly for concretes with a higher CCA content; however the characteristic strength was still met for the majority of mixes. This indicates that the BRE method of mix design is generally suitable for designing concrete with a fine CCA content up to 40%, and also a combined fine and coarse CCA content of 20%. The latent hydraulic properties of GGBS were only observed for the control concrete at 56 days, which suggests that the fine CCA content causes a delay in the hydration process.

The tests conducted into the durability have highlighted that the inclusion of fine and coarse CCA can have an increasingly detrimental effect on water and chloride ingress, even for quantities as low as 20% fines. In the majority of cases the combined effect of fine and coarse CCA caused a higher detrimental effect than a fine CCA content alone. This suggests that coarse CCA is the primary contributor to a reduced resistance to water and chloride ingress. Further research is required to determine if the beneficial effect of small quantities of fine CCA observed in GGBS concrete is a regular phenomenon.

The inclusion of GGBS can significantly increase the durability performance, in some cases by a factor of 3 to 4 times, due to the reduced porosity of the cement matrix, improved interfacial transition zones and the increased chloride binding capacity of the material. These findings suggest that both fine and coarse CCA can be a viable option for new sustainable structural concrete, even if the structure is likely to be exposed to chloride environments during its service life, provided that a suitable level of GGBS is incorporated to compensate for any detrimental effects on mechanical or durability properties. This is a positive finding for the incorporation of CCA into a wider variety of higher-value applications as the fines content can also be purposely utilised.

Acknowledgements

The authors thank the Engineering and Physical Sciences Research Council (EPSRC) and Loughborough University’s Centre for Collaborative and Innovative Construction Engineering (CICE) for the funding of this research, and also AECOM for their support. The authors would also like to acknowledge DSM Demolition Group for helping to obtain the CCA source and Hanson Limited for the cementitious materials.

References

[1] National Federation of Demolition Contractors (NFDC), 2015. *Waste returns spreadsheet 2013 and 2014*, personal communication, 18th May 2015.

[2] Waste and Resources Action Programme (WRAP), 2009. *Delivering higher recycled content in construction projects* [pdf]. Accessed: 1st July 2016.

[3] Waste and Resources Action Programme (WRAP), 2003. *A strategy for construction, demolition and excavation waste as recycled aggregates* [pdf]. Accessed: 1st July 2016.

[4] Environment Agency and WRAP, 2013. *Quality protocol: Aggregates from inert waste* [pdf]. Accessed: 1st July 2016.

[5] British Standards Institution (BSI), 2013a. *BS EN 12620:2013, Aggregates for concrete*. London: BSI.

[6] Barritt, J, 2015. *An overview on recycling and waste in construction*. Proceedings of the ICE, Construction Materials, Volume 169, Issue 2, pp1-5.

[7] British Standards Institution (BSI), 2013b. *BS EN 206-1:2013, Concrete: Specification, performance, production and conformity*. London: BSI.

[8] British Standards Institution (BSI), 2015a. *BS 8500-1:2015+A1:2016, Concrete - Complementary British Standard to BS EN 206 – Part 1: Method of specifying and guidance for the specifier*. London: BSI.

[9] British Standards Institution (BSI), 2015b. *BS 8500-2:2015, Concrete – Complementary British Standard to BS EN 206 - Part 2: Specification for constituent materials and concrete*. London: BSI.

[10] Saffiuddin, M. Alengaram, U.J. Rahman, M.M. Salam, M.A. Jumaat, M.Z, 2013. *Use of recycled concrete aggregate*. Journal of Civil Engineering and Management, Volume 19, Issue 6, pp796-810.

[11] Kropp, J. Hilsdorf, H.K. Grube, H. Andrade, C. Nilsson, L. 1995. *Chapter 2: Transport mechanisms and definitions,* In: Kropp, J. Hilsdorf, H.K. *RILEM Report 12 - Performance criteria for concrete durability,* E&FN Spon.

[12] Ollivier, J. Massat, M. Parrott, L, 1995. *Chapter 4: Parameters influencing transport charcteristics,* In: Kropp, J. Hilsdorf, H.K. *RILEM Report 12 - Performance criteria for concrete durability,* E&FN Spon.

[13] Mardani-Aghabaglou, A. Tuyan, M. Ramyar, K, 2015. *Mechanical and durability performance of concrete incorporating fine recycled concrete and glass aggregates*. Materials and Structures, Volume 48, pp2629-2640.

[14] Evangelista, L. de Brito, J. 2007. *Mechanical behavior of concrete made with fine recycled concrete aggregates*. Cement and Concrete Composites, Volume 29, pp397-401.

[15] Khoshkenari, A.G. Shafigh, P. Moghimi, M. Mahmud, H.B, 2014. *The role of 0-2mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete*. Materials and Design, Volume 64, pp345-354.

[16] Collery, D. McKenna, P. Dunne, D. Paine, K, 2014. *Strength and deformation characteristics of concrete containing recycled aggregate fines*. In: Civil Engineering Research in Ireland (CERI 2014) conference, 2014-08-28 - 2014-08-29.

[17] Evangelista, L. de Brito, J. 2010. *Durability performance of concrete made with fine recycled concrete aggregates*. Cement and Concrete Composites, Volume 32, pp9-14.

[18] Bapat, J.D, 2013. *Mineral admixtures in cement and concrete,* CRC Press.

[19] Hwang, J.P. Shim, H.B. Lim, S. Ann, K.Y, 2013. *Enhancing the durability properties of concrete containing recycled aggregate by the use of pozzolanic materials*. KSCE Journal of Civil Engineering, Volume 17, Issue 1, pp155-163.

[20] Limbachiya, M. Meddah, M.S. Ouchagour, Y, 2012. *Use of recycled concrete aggregate in fly-ash concrete*. Construction and Building Materials, Volume 27, pp439-449.

[21] Somna, R. Jaturapitakkul, C. Amde, A.M, 2012. *Effect of ground fly ash and ground baggase ash on the durability of recycled aggregate concrete.* Cement and Concrete Composites, Volume 34, pp848-854.

[22] Berndt, M.L, 2009. *Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate*. Construction and Building Materials, Volume 23, pp2606-2613.

[23] Ann, K.Y. Moon, H.Y. Kim, Y.B. Ryou, J, 2008. *Durability of recycled aggregate concrete using pozzolanic materials*. Waste Management, Volume 28, pp993-999.

[24] Fan, C. Huang, R. Hwang, H. Chao, S, 2016. *Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes*. Construction and Building Materials, Volume 112, pp708-715.

[25] Wirquin, E. Hadjieva-Zaharieva, R. Buyle-Bodin, F, 2000. *Use of water absorption by concrete as a criterion of the durability of concrete – application to recycled aggregate concrete*. Materials and Structures, Volume 33, Issue 6, pp403-408.

[26] Lofty, A. Al-Fayez, M, 2015. *Performance evaluation of structural concrete using controlled quality coarse and fine recycled concrete aggregate*. Cement and Concrete Composites, Volume 61, pp36-43.

[27] Bravo, M. de Brito, J. Pontes, J. Evangelista, L, 2015. *Durability performance of concrete with recycled aggregates from construction and demolition waste plants*. Construction and Building Materials, Volume 77, pp357-369.

[28] Soares, D. de Brito, J. Ferreira, J. Pacheco, J, 2014. *Use of coarse recycled aggregates from precast concrete rejects: Mechanical and durability performance*. Construction and Building Materials, Volume 71, pp263-272.

[29] Pedro, D. de Brito, J. Evangelista, L, 2014. *Influence of the use of recycled concrete aggregates from different sources on structural concrete*. Construction and Building Materials, Volume 71, pp141-151.

[30] Kwan, W.H. Ramli, M. Kam, K.J. Sulieman, M.Z, 2012. *Influence of the amount of recycled coarse aggregate in concrete design and durability properties*. Construction and Building Materials, Volume 26, pp565-573.

[31] Building Research Establishment (BRE), 1997. *Design of normal concrete mixes: Second edition*. Watford, UK.

[32] British Standards Institution, 2009a. *BS EN 12390-3:2009, Testing hardened concrete. Part 3 – Compressive strength of test specimens*, London, BSI.

[33] American Association of State Highway and Transport Officials, 2015. *AASHTO T358-15, Standard test method for surface resistivity indication of concretes ability to resist chloride ion penetration*, Washington, USA.

[34] British Standards Institution (BSI), 2002. *BS EN 13057:2002, Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance of capillary absorption*. London: BSI.

[35] NordTest, 1999. *NT-Build 492, Chloride migration coefficient from non-steady state migration experiments*, NordTest Project No. 1388-98, Espoo, Finland.

[36] American Society for Testing and Materials (ASTM), 2014. *ASTM C856-14, Standard practice for petrographic examination of hardened concrete*. ASTM International, West Conshohocken, PA, USA.

[37] Concrete Society, 2010. *Concrete Society Technical Report 71: Concrete petrography*. The Concrete Society, Surrey, UK.

[38] British Standards Institution (BSI), 2013c. *BS EN 1097-6:2013, Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption*. London: BSI.

[39] British Standards Institution, 2010. *BS 6089:2010, Assessment of in-situ compressive strength in structures and precast concrete components – Complementary guidance to that given in BS EN 13791,* London, BSI.

[40] British Standards Institution, 2009b. *BS EN 12504-1:2009, Testing concrete in structures. Part 1: Cored specimens – Taking, examining and testing in compression,* London, BSI.

[41] British Standards Institution (BSI), 2007. *BS EN 13791:2007, Assessment of in-situ compressive strength in structures and precast concrete components*. London: BSI.

[42] Aston Services, 2015. *Petrography report: New Walk Centre, Leicester City Council Building, In-situ demolition waste RCA*. Report number LU/PA/101215, 10th December 2015.

[43] Angst, U.M. Elsener, B, 2014. *On the applicability of the Wenner method for resistivity measurements of concrete.* ACI Materials Journal, Volume 111, Issue No 6, pp661-672.

[44] Concrete Society, 2004. *Concrete Society Technical Report 60: Electrochemical tests for reinforcement corrosion.* Cromwell Press Ltd.

[45] Claisse, P. A, 2014. *Transport properties of concrete – Measurement and applications*. Woodhead Publishing.