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Recycled aggregates in concrete: a performance-related approach

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The relative proportions of the three main constituents within recycled aggregates (unbound stone, crushed concrete and crushed brick) can vary widely and it is generally assumed that, as a result, the performance of concrete containing recycled aggregates can vary significantly. Thus, in order to ensure satisfactory concrete performance, specifications are strict on the composition of recycled aggregates that may be used. However, research has shown that it is possible in many circumstances to use recycled aggregates satisfactorily that do not meet the current specifications in BS 8500-2. A proposed approach, which may encourage wider use of recycled aggregates and promote sustainability, is to base the selection of recycled aggregates on performance-related characteristics that relate the properties of recycled aggregates to concrete performance across the whole range of recycled aggregate quality, independent of constituents and source. To develop this performance-related approach, concrete mixes were cast and tested using combinations of unbound stone, crushed concretes and crushed bricks. From the results, three classes of recycled aggregates have been derived based on Los Angeles coefficient, aggregate absorption, density and drying shrinkage of the combined coarse aggregate. The concept is that the highest quality recycled aggregates will be suitable for high-performance applications, meeting the relevant standards and specifications, while the two lower classes will be more appropriate for lower performance applications. Given this approach, material that is currently not fully specified for use in BS 8500 may be classified and considered for relevant applications. This should remove the main technical barrier that is preventing the uptake of recycled aggregates in concrete, and lead to greater confidence in specifying and using recycled aggregates.

Introduction

The annual production of construction, demolition and excavation waste (CDEW) in the UK amounts to approximately 110 million tonnes, accounting for over 60% of the UK's total waste. Rather than send CDEW to landfill, increased sustainability concerns should give rise to the use of these materials as a resource; at present only about half of all CDEW is used as recycled aggregate (RA).

BS 8500-2:2006 (BSI, 2006) defines RA as aggregate resulting from the processing of inorganic material previously used in construction, for example crushed concrete, masonry, or brick. Within this family of materials, RA that is made predominantly from crushed concrete is called recycled concrete aggregate (RCA). The performance characteristics of RCA have been extensively investigated (Dhir and Paine, 2004; Dhir *et al.*, 1999; Sagoe-Crentsil *et al.*, 2001; Topçu and Sengel, 2004; Xiao *et al.*, 2006) and it is specified in BS 8500-2:2006 for use in concrete up to the strength class of C40/50 and exposure classes X0, XC1-4, DC1 and XF1.

Recycled aggregate that does not meet the requirements for RCA may have a wide range of composition, for example: (*a*) a mixture of 94% crushed concrete and 6% crushed brick, and (*b*) 100% crushed brick, are both considered to be RA. Concerns expressed in BS 8500-2:2006 mean that it is not possible to permit its use for a given type of concrete without the need for additional provisions in the specification, based on the composition of the proposed RA. With these restrictions in place, ready-mixed concrete suppliers have informed the British Standards Institution that it is not viable to stock RA (BS 8500-2:2002 (BSI, 2002)). The problem is exacerbated when it is considered that many

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RAs contain over 80% of unbound stone, but this may not be used in concrete because of masonry contents in the order of, say, 10% by mass.

The present paper describes a study carried out to develop an alternative route for specifying RA for use in concrete, which overcomes concerns regarding potential variability through reference to the properties of the aggregate, as opposed to the composition.

The need for a performance-related approach

Recycled aggregate consists, mainly, of unbound stone (Ru), crushed concrete (Rc), and crushed brick (Rb), although, small percentages of asphalt, glass, lightweight materials and plaster may also be present. The relative proportions of these three main materials within RA can vary widely and, as a result, the performance of concrete containing RA can also vary significantly. BS 8500-2:2006 (BSI, 2006) has addressed this problem by only fully specifying RCA, material containing $\text{Rc} \geqslant 83{\cdot}5\%$ by mass and $\text{Rb} \leqslant 5\%$ by mass. This means that under current specifications, a large quantity of RA is in effect not permitted for use in concrete, even though research has shown that it is possible in many circumstances to use RA containing lower proportions of Rc and higher proportions of Rb satisfactorily (Dhir and Paine, 2003; Dhir *et al.*, 2005; Hansen, 1992; Khalaf and Devenny, 2004; Levy and Helene, 2004; Zakaira and Cabrera, 2006).

Because of the concerns that Rb may vary widely in its properties, it is understandable that specifiers of RA do not wish to increase the allowable quantity of Rb that may be used in concrete on an ad hoc basis. What is more important is the effect of a given RA on the performance of concrete. This is not necessarily dependent on the composition; therefore, a more logical approach will be to relate limits on allowable RA to performance-based properties (i.e. strength), or for practicality, to performance-related characteristics (e.g. Los Angeles (LA) coefficient). This will relate RA quality to concrete performance across the whole range of potential RA quality, independent of composition and source. The belief is that good-quality RA (conforming to, say, class A) will be suitable for high-performance applications, meeting the relevant standards and specifications, whereas lower classes will be more appropriate for lower value applications. Given this approach, material that would currently be classified as RA under BS 8500-2 (and therefore not specified for use) can be classified and considered for relevant applications. This should lead to greater confidence in specifying and using RA and thereby help to remove the main barrier that is preventing the uptake of RA in concrete.

To investigate the potential of this approach, an examination of previous research on the effect of the individual characteristics of RA on the performance of concrete was carried out, followed by a laboratory-based research programme using RA created with varying proportions of Ru, Rc and Rb contents. The RA materials thus constituted were used in concrete mixes tested for engineering, permeation and durability properties. The performance in concrete was then correlated with the most appropriate performance-related characteristics of the aggregate; chosen on the basis of

(*a*) requirements for RA in BS 8500-2:2006 (BSI, 2006)

(*b*) the likelihood of the property being specified for end uses in the UK for aggregates conforming to the series of European standards on aggregates (PD 6682-9:2003 (BSI, 2003))

(*c*) known relationships between the aggregate characteristics and concrete performance.

The addition of other possible constituents in RA was considered to be beyond the scope of this project. Indeed, RA usually has very low lightweight contents (less than 1% by mass), glass most often ends up in the fine aggregate fraction and plaster is not a concern provided sulfate contents are controlled (Dhir and Paine, 2004). Asphalt was not considered because it is not usually present in RA produced by mobile crushing plants dealing with demolition waste. However, the increased use of excavation waste to produce RA at established washing plants could make this a potential area for further study, although current maximum asphalt contents of 5–10% in BS 8500-2:2006 are still likely to apply.

Constituents of RA and their effect on concrete properties

It is recognised that the definition RA covers a range of materials with widely varying characteristics and performance levels, and in 2008 an amendment was made to BS EN 12620 (BSI, 2008) to include a classification for RAs based on constituents (Table 1). A method for classifying the constituent parts of coarse RA is given in prEN 933-11:2006 (CEN, 2006). Since the asphalt content is limited to a maximum of 10% by mass, this classification essentially limits RA for use in concrete to material consisting of Rc, Rb and Ru. Previous research on the effect of these constituents on the properties of concrete is described below as a brief literature review.

Crushed concrete (Rc)

The effect of Rc on the performance of concrete has been extensively described and investigated. Indeed, RA consisting predominately of Rc is categorised as RCA and it is fully specified for use in concrete by BS 8500-2:2006 (BSI, 2006).

The use of Rc in concrete with strength ranging from

Table 1. Categories based on the main constituents of coarse RA in BS EN 12620:2008

Category	Constituent	Content: % by mass
Rc_{90}	Rc	$\geqslant 90$
Rc_{70}		$\geqslant 70$
Rc_{Declared}		< 70
Rc_{NR}		No requirement
Rcu_{90}	Rc + Ru	$\geqslant 90$
Rcu_{70}		$\geqslant 70$
Rcu_{50}		$\geqslant 50$
Rcu_{Declared}		< 50
Rcu_{NR}		No requirement
Rb_{10-}	Rb	$\leqslant 10$
Rb_{30-}		$\leqslant 30$
Rb_{50-}		$\leqslant 50$
Rb_{Declared}		> 50
Rb_{NR}		No requirement

C8/10 to C35/45 has shown that the initial concrete source has little effect on the quality of the resulting Rc and that for all classes of concrete, 30% replacement of natural aggregate with coarse Rc has little effect on its performance, either in terms of fresh properties, strength and deformation characteristics or durability (permeation, carbonation, abrasion and freeze–thaw). At higher replacement levels, equal performance to natural aggregate concrete can be achieved at equivalent 28-day strength, but this requires some reduction in water-to-cement (w/c) ratio (Dhir *et al.*, 1999).

A thorough analysis of 528 test results from 38 studies throughout the world has concluded that for concrete containing high proportions of Rc as coarse aggregate, relationships could be applied between compressive strength and other engineering properties (flexural strength, tensile strength and static modulus of elasticity) in the same way as for natural aggregate concretes in current structural standards (Xiao *et al.*, 2006).

Research to investigate the use of Rc in high-strength concrete of 50–80 N/mm^2 (Dhir and Paine, 2004) has shown that use of 30% Rc had no effect on the ceiling strength of concrete and that strengths greater than 80 N/mm^2 could be achieved. Furthermore, high-strength concrete containing Rc had similar engineering and durability performance to natural aggregate concrete of the same strength.

While fine Rc may be used in very low quantities, it has been observed that it causes difficulties with the stability of the mix and the strength of the resulting concrete (Dhir *et al.*, 1999), and that it is also difficult to store and handle this material. For these reasons BS 8500-2:2002 does not permit use of fine RCA in concrete.

As a result of the large body of research on the use of Rc in concrete, RCA (unlike RA) is specified for use in concrete up to strength class of C40/50 and exposure classes X0, XC1-4, DC1 and XF1 in BS 8500-2:2006. Indeed, it is recognised that the simplest route for using RCA in concrete is through designated concrete as advocated by Dhir *et al.* (1999) where the producer alone is responsible for ensuring and demonstrating that the concrete has achieved the specified strength. Thus, the producer determines the appropriate mix proportions, and consequently, any concerns that the use of RCA may adversely affect the concrete strength are addressed directly.

Crushed brick (Rb)

Recycled aggregate, as defined by BS 8500-2:2006, may have an Rb content between 0 and 100% by mass, and RAs with high Rb contents are common at recycling centres where a concerted effort has been made to separate out concrete to produce RCA. At centres where there is less sorting of CDEW, which is typical of mobile crushing plants, the Rb content of RA tends to be lower (less than 30%).

The effect of Rb on the performance of concrete has not been investigated to the same extent as that of Rc, but from the available literature the following generalisations may be given.

(*a*) As Rb is generally more porous and weaker than Rc and Ru, the use of RA with high Rb content tends to give lower concrete strength for a given w/c ratio (Khalaf and Devenny, 2004).

(*b*) The tensile and flexural strength of concrete containing Rb is generally proportional to the lower cube strength in the corresponding cases (Dhir and Paine, 2003).

(*c*) Concrete containing Rb has a lower static modulus of elasticity than equivalent natural aggregate concretes of the same strength (Hansen, 1992).

(*d*) Carbonation of concrete (for concretes of equal compressive strength) has been reported to decrease as the Rb content increases (Levy and Helene, 2004). It has been suggested that this is due to the higher cement content required to achieve a given strength when RA contains Rb. Thus, the additional alkalinity acts to protect against carbonation.

(*e*) The use of Rb is likely to be low risk with respect to damaging alkali–silica reaction (ASR), and there is no correlation between the alkali release content of Rb and ASR expansion (Dhir *et al.*, 2005).

(*f*) Air-entrained concrete with a significant Rb content gives good freeze–thaw scaling resistance (56-day scaling $< 0{\cdot}5$ kg/m^2) when tested in accordance with Swedish standards criteria (Dhir and Paine, 2003).

Unbound stone (Ru)

Recycled aggregate often contains a significant proportion of unbound stone (Ru), which may result from recovered unbound aggregate, or aggregate from crushed concrete where the surrounding paste has been removed. In practical terms, it is not always possible to tell the difference. As far as the authors are aware, there has been no research carried out to investigate the effect of Ru on the properties and use of RA, possibly because there are few reasons to suspect that these constituents will behave any differently to an equivalent natural aggregate.

Although RCA is considered a superior aggregate to RA in BS 8500-2:2006, it is reasonable to presume that an RA containing large quantities of Ru will be superior to one containing a large proportion of Rc.

Research programme

Materials

Tests were carried out using 34 RAs, created by selective combining of unbound stone (RU-N), two crushed concrete aggregates (RC-35 and RC-60) and three crushed brick aggregates (RB-1, RB-2 and RB-3) in various proportions. Physical, chemical and mechanical properties of these six constituents are given in Table 2.

For the purposes of the present work, a natural river gravel was used as the unbound stone (RU-N), reflecting an assumption that unbound aggregates within RA have similar properties to natural aggregates. However, it is appreciated that, whereas natural gravel is uncrushed, it is likely that Ru in RA will be crushed at least partially.

The two types of Rc used (RC-35 and RC-60) were cast specifically for this project (using the same natural gravel (RU-N)) and were crushed at 28 days when they had achieved design strengths of 35 N/mm^2 and 60 N/mm^2, respectively.

The three brick types were chosen, following tests on a number of UK bricks (Dhir and Paine, 2007), to reflect the range available in terms of strength, water absorption and sulfate content.

Mix proportions

Concrete mixes were proportioned for w/c ratios of 0·61 and 0·84 to achieve a cube strength range of 15–40 N/mm^2, in which RA is most likely to be specified when using CEM I and UK-sourced materials. An example of mix proportions is given in Table 3. Mixes containing only Ru were natural aggregate concrete, whereas mixes containing Ru and Rc may be described as RCA concretes. In this paper, the combination of aggregates has been referred to as RA; however, it should be noted that a combination of, for example, 70% Ru and 30% Rc, is in effect the equivalent of using 30% RCA as replacement for natural aggregate.

While mixes were proportioned for equal w/c ratio, the water content was adjusted to reflect the more angular shape of RA when compared with natural gravel – in the same way as natural crushed rock aggregates are used with higher water content in practice. The rationale behind this was to overcome occasional problems with consistence and finishability that had been observed when using RA concretes during previous research (Dhir *et al.*, 1999; Dhir and Paine, 2003).

Concrete properties

Cube strength

As shown in earlier studies, there was little difference in behaviour between concrete containing RC-35 and RC-60 aggregates, showing that the strength of the origin concrete has little effect on the performance of RA when used in new concrete mixes. Figure 1 shows the effect of Rc content on the 28-day cube strength. In general, there was a reduction in cube strength as the Rc content increased, but up to around 20–30% Rc content the measured strengths were all within the limits for repeatability of the test, as defined in BS 12390-3:2009 (BSI, 2009), and therefore may be regarded as identical. This confirms earlier studies in

Table 2. Properties and characteristics of RA constituents used in the test programme

	Ru	Rc		Rb		
	RU-N	RC-35	RC-60	RB-1	RB-2	RB-3
Density: kg/m^3						
SSD	2550	2385	2390	2300	2120	1940
Loose bulk	1485	1360	1250	1020	–	–
Water absorption: %	1·2	5·5	4·8	8·0	17·2	28·0
Acid-soluble sulfates: %	0·1	0·5	0·5	0·0	1·9	0·4
Acid-soluble chlorides: %	0·01	0·06	0·08	0·00	0·00	0·00
Water-soluble chlorides: %	0·00	0·00	0·00	0·00	0·00	0·00
Los Angeles coefficient, LA*	22	35	29	48	60	51
Micro-Deval coefficient, M_{DE}*	16	34	29	37	42	41
Drying shrinkage: %	0·050	0·065	0·060	0·040	0·125	0·115

* 14–10 mm only.

Table 3. Example mix proportions showing RU-N and mixes containing increasing quantities of RB-2 (w/c = 0·61)

Ru: %	Rb: %	Rc: %	Mix proportions: kg/m^3								
			Water	Cement (CEM I)	Sand (0/4)	Ru		Rb		Rc	
						4/10	10/20	4/10	10/20	4/10	10/20
100	0	0	180	295	734	389	779	0	0	0	0
80	6	14	182	298	720	305	611	23	46	53	106
80	14	6	182	298	717	304	608	53	106	23	46
80	20	0	182	298	710	301	602	75	150	0	0
0	30	70	190	311	663	0	0	105	211	246	492
60	40	0	184	301	686	218	436	145	290	0	0
0	70	30	190	311	647	0	0	240	480	103	206
0	100	0	190	311	614	0	0	325	651	0	0

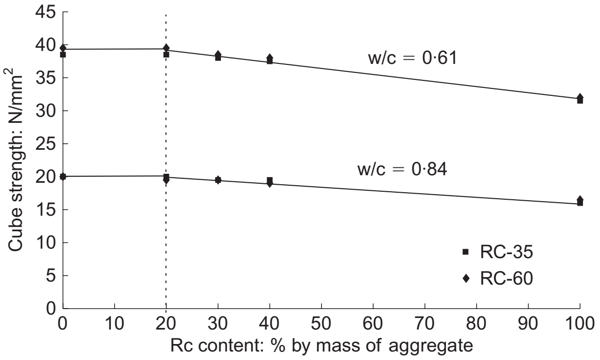

Figure 1. Effect of crushed concrete (Rc) content (by mass) on cube strength of concrete

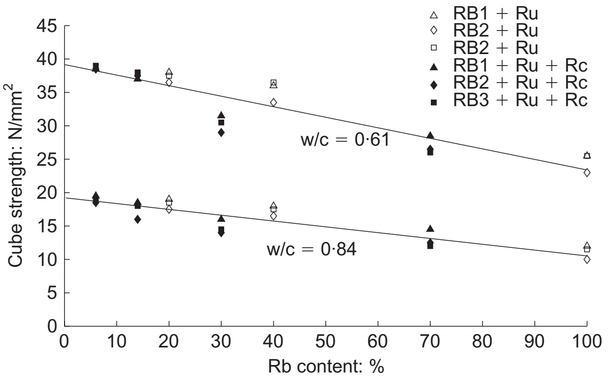

Figure 2. Effect of crushed brick (Rb) content (by mass) on cube strength of concrete

which it has been shown that up to a practical limit, Rc may be used without adversely affecting concrete performance, and the results seem to verify the current rule for use of RCA in designated concretes in BS 8500-2:2006 which proposes a maximum mass fraction of 20% of coarse aggregate. For practical engineering purposes it can be assumed that the reduction in strength with increasing Rc content beyond a mass fraction of 20% of coarse aggregate follows a linear trend.

The use of Rb reduced the cube strength to a greater extent than that of the Rc. Concretes containing 100% Rb had strengths approximately 40% lower than that of the natural aggregate concrete at the same w/c ratio, and approximately 25% lower than that of an equivalent concrete containing 100% Rc. Figure 2 shows the effect of the Rb content within the RAs on cube strength.

Since use of Rb and/or Rc (greater than 20% mass fraction) as coarse aggregate in concrete led to lower 28-day cube strength than use of the equivalent natural aggregate concrete it would be necessary in practice to reduce the w/c ratio to achieve equal cube strength. This is well established from earlier work using RCA (Dhir *et al.*, 1999). However, it should be noted that, from a practical point of view, this may prove unsustainable beyond a certain level of reduction in w/c ratio, owing to the requirement for higher cement contents and/or the need for increased dosages of admixture to offset lower water contents.

Consequently, an important requirement for use of RA in concrete is that it should not lead to large changes in the w/c ratio. Thus, as a starting point, and for the purposes of the current research, a maximum w/c ratio correction factor of 0·9 may be applied, which is equivalent to the maximum correction that was required for RCA in earlier work that demonstrated the applicability of this technique in producing equivalent performance in terms of strength and durability for both natural aggregate and RCA concrete (Dhir *et al.*, 1999).

Figure 3 shows the w/c ratio to strength relationship for RU-N aggregate concrete, and the relationship (dotted line) that would be given by a nominal concrete attaining the same strength at a w/c ratio that was a factor of 0·9 lower than that of the RU-N concrete. Based on these two curves, it can be determined that to meet the criteria for a maximum w/c correction factor of 0·9, RA concretes made at the two w/c ratios tested in this work, 0·61 and 0·84, should have strengths no lower than 32·4 N/mm^2 and 15·1 N/mm^2 respectively at 28 days.

From these strength requirements it can be determined which of the 34 types of RA tested in this work

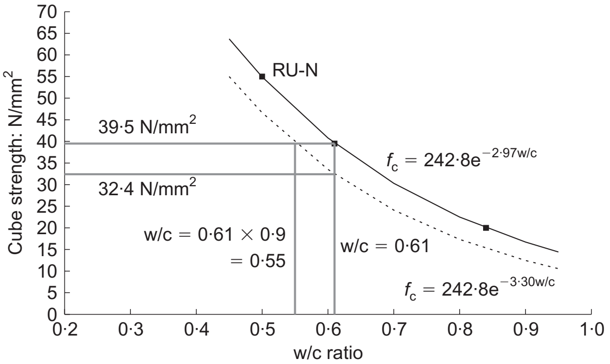

Figure 3. Relationship between w/c ratio and cube strength for RU-N concrete

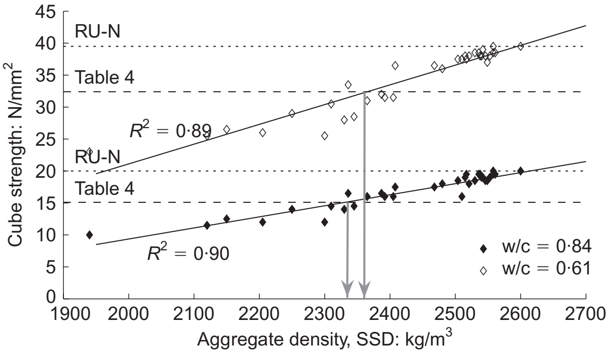

Figure 5. Relationship between density of coarse aggregate and cube strength of concrete

meet the above criteria and, more importantly, whether those RAs that meet the criteria may be predicted by their aggregate characteristics. For example, Figure 4 shows the relationship between the cube strength of all the concretes made in the current study and the LA coefficient of the aggregate (an indirect measure of aggregate strength) that was used in making that concrete. In general terms, it can be seen that aggregates with a low LA coefficient produced concretes with higher strengths at a given w/c ratio, and that the relationship between concrete strength and LA coefficient can be approximated as linear. Based on the linear relationships (at each w/c ratio), it can be determined that provided the LA coefficient of an aggregate was less than 40%, then the cube strength of concrete made with this aggregate was greater than or equal to 32·4 N/mm^2 at w/c ratio of 0·61, and greater than or equal to 15·1 N/mm^2 at w/c ratio of 0·84. In other words, RA meeting the LA$_{40}$ category in BS EN 12620:2008 (BSI, 2008) would require a w/c correction factor of between 0·9 and 1·0 to achieve equivalent strength to that of a natural aggregate concrete.

Alternatively, since Xiao *et al.* (2006) have suggested density as a more useful determiner of the effect of RA on compressive strength, because it is easy to measure, Figure 5 shows the relationships between aggregate density (SSD) and cube strength. Based on the same requirement it can be seen that, for the aggregates tested in this research, provided the density of combined aggregate was greater than 2375 kg/m^3 then the cube strength of concrete made with these aggregates was greater than or equal to 32·4 N/mm^2 at w/c ratio of 0·61, and greater than or equal to 15·1 N/mm^2 at w/c ratio of 0·84. Note that a value of 2375 kg/m^3 equates to the typical density of RCA.

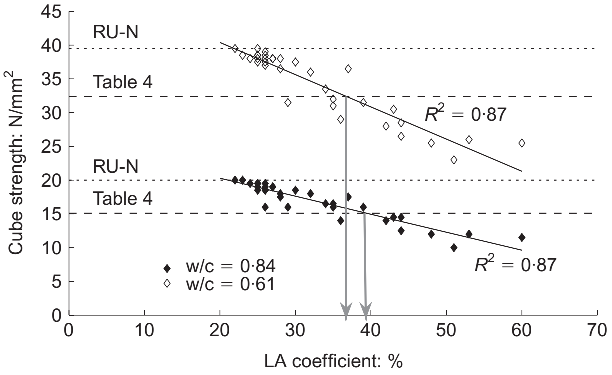

Figure 4. Relationship between LA coefficient of coarse aggregate and cube strength of concrete

Other properties

A similar set of criteria can be applied to many other properties of concretes that, for a given cement and mix constituents, show correlation with the w/c ratio (Dhir *et al.*, 2006). Relationships between w/c ratio and static modulus of elasticity, initial surface absorption (ISA), carbonation and rapid chloride permeability are shown in Figure 6 for concretes made with the RU-N aggregate used in this study. Furthermore, in all cases, a theoretical line showing the maximum allowable value for these properties based on a maximum w/c ratio correction of 0·9 is shown. In the case of carbonation, ISA and elastic modulus this is based on a linear relationship, and in the case of rapid chloride permeability by an exponential relationship. To meet the criteria for a w/c correction factor of 0·9, it can be determined that concrete at a w/c ratio of 0·61 and 0·84 should meet the values shown in Table 4.

Static modulus of elasticity. Static modulus of elasticity was measured in accordance with BS 1881-121:1998 (BSI, 1998) at 28 days. Because aggregate density has a known influence on the elastic modulus of coarse aggregate, and consequently on the elastic modulus of concrete (Zhou *et al.*, 1995) this was chosen as the most appropriate performance-related characteristic for comparing data. Figure 7 shows the relationships between aggregate density (SSD) and the resulting elastic modulus of concrete for all concretes tested. Because of the significantly lower elastic modulus of RA compared with RU-N, the results show that it is not possible for RA concretes to meet the values of 21·1 kN/mm^2 (at w/c ratio of 0·61) and 17·8 kN/mm^2 (at w/c ratio of 0·84), and that the aggregate density to meet these criteria should be

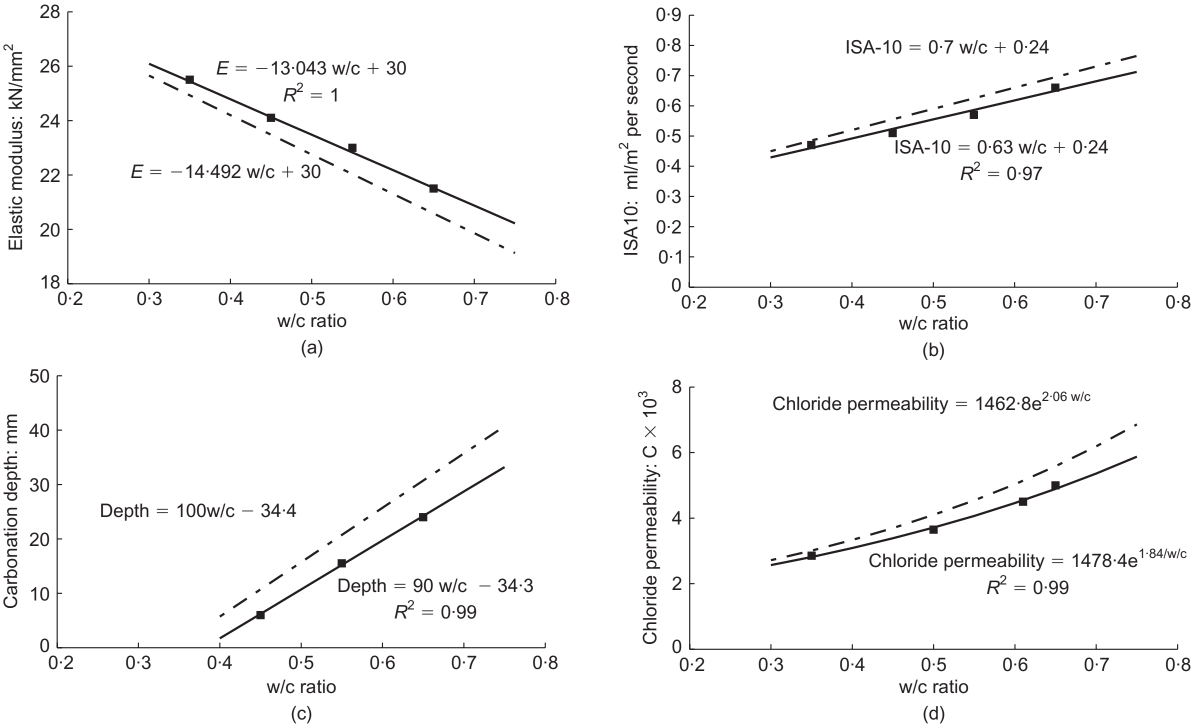

Figure 6. Relationship between w/c ratio and (a) elastic modulus; (b) ISA-10; (c) carbonation; (d) rapid chloride permeability, for RU-N concrete

Table 4. Recycled aggregate concrete performance requirements at w/c ratios of 0·61 and 0·84, to ensure that equivalent performance to RU-N concrete can be achieved with w/c ratio corrections of less than 0·9

Concrete requirement	Test method	w/c = 0·61	w/c = 0·84
Cube strength: N/mm^2	BS EN 12390-3:2009	32·4	15·1
Elastic modulus: kN/mm^2	BS 1881-121:1998	21·1	17·8
ISA-10: ml/m^2 per second	BS 1881-208:1996	0·66	0·82
Carbonation depth: mm	prCEN/TS 1230:2008	27·0	50·0
Rapid chloride permeability: C	ASTM C 1202-05	5150	8250

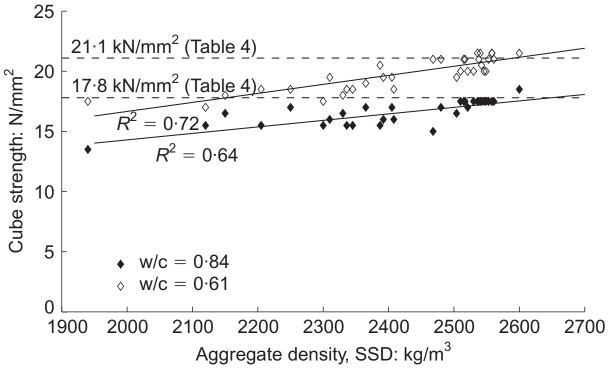

Figure 7. Relationship between density of coarse aggregate and static modulus of elasticity of concrete

greater than 2600 kg/m^3. The implications of this are discussed later.

Initial surface absorption. ISA tests were carried out in accordance with BS 1881-208:1996 (BSI, 1996) on selected specimens. Since, the ISA of concrete is known to be closely correlated with the water absorption of the coarse aggregates (Dhir *et al.*, 2006), this was determined to be the most appropriate performance-related characteristic. Figure 8 shows a non-linear relationship between the water absorption of the aggregate and the ISA of the resulting concrete. In general it can be supposed that provided the water absorption of the aggregate was less than 3·5% then the ISA-10 value at a w/c ratio of 0·61 was less than the value of 0·68 ml/m^2 per second given in Table 4.

Carbonation. Carbonation rate was measured using an accelerated method developed at the University of Dundee consisting of prismatic specimens exposed to 4% CO_2 in a chamber at 20°C and 55% relative humidity (RH) (Dhir *et al.*, 1985) and which is the basis for the method described in prCEN/TS 12390:2008 (CEN, 2008). Results are shown in

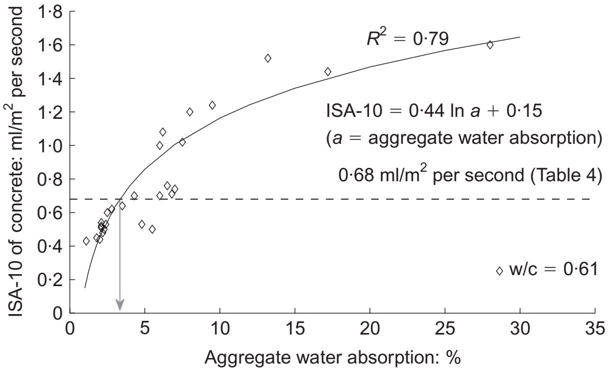

Figure 8. Effect of water absorption of coarse aggregate on the initial surface absorption of concrete after 10 min

Figure 9. In all cases, the use of RA containing Rc or Rb gave better performance with respect to carbonation than concrete containing only Ru. Similar results have been observed elsewhere (Dhir *et al.*, 1999; Levy and Helene, 2004), and the improvement in performance is probably related to

(*a*) the higher cement content in the RA concrete, to compensate for shape differences
(*b*) residual cement surrounding the Rc constituents of RA.

As a result of these factors the hydrated lime content of RA concrete is higher than that of natural aggregate concrete, and results in a reduction in the rate of carbonation per millimetre depth, to such an extent that it counteracts any apparent increase in permeability (as demonstrated by the higher ISA values). Since the use of RA in concrete tends to increase the resistance to carbonation (at equal w/c ratio), there is no reason to limit the use of RA in carbonation (XC) environments. However, given the limited data it is probably right to be cautious at very high Rb contents.

Chloride ingress. Chloride ingress was measured using the ASTM C 1202-05 (ASTM, 2005) method. This is a quick measurement of this property, suitable for comparative purposes, that is widely used throughout the world and has been included in performance-based specifications (Bentz, 2007). Since earlier work has demonstrated that water absorption can be used as an indicative measure of the ability for chlorides to ingress into concrete (Basheer *et al.*, 2001), the most appropriate performance-related aggregate characteristic was considered to be water absorption. Figure 10 shows the relationship between these two properties. In order to meet the limit on chloride permeability of concrete of 5150 C at a w/c ratio of 0·61, as given in Table 4, it can be seen that the water absorption of the coarse aggregate from which that concrete is made should not exceed 6%. This is substantially higher than the maximum water absorption of 3·5% to meet the ISA requirement, which will therefore control the performance.

Drying shrinkage. Drying shrinkage is an important property of concrete in which potential users of RA have shown concern (Collins, 2003) due to its effect on the long-term stiffness of concrete and the effects of any potential cracking, due to internal or external restraint, on a loss in durability. Unlike the four properties described previously, drying shrinkage shows no clear correlation with w/c ratio for a given cement and mix constituents. Although the drying shrinkage of concrete is not widely specified, limits on the drying shrinkage of aggregate (based on testing concrete) are given in BS EN 12620:2008 (BSI, 2008).

Tests to measure the drying shrinkage of RA concrete, using the method (although not the mix proportions) described in BS EN 1367-4:1988 (BSI, 1988)

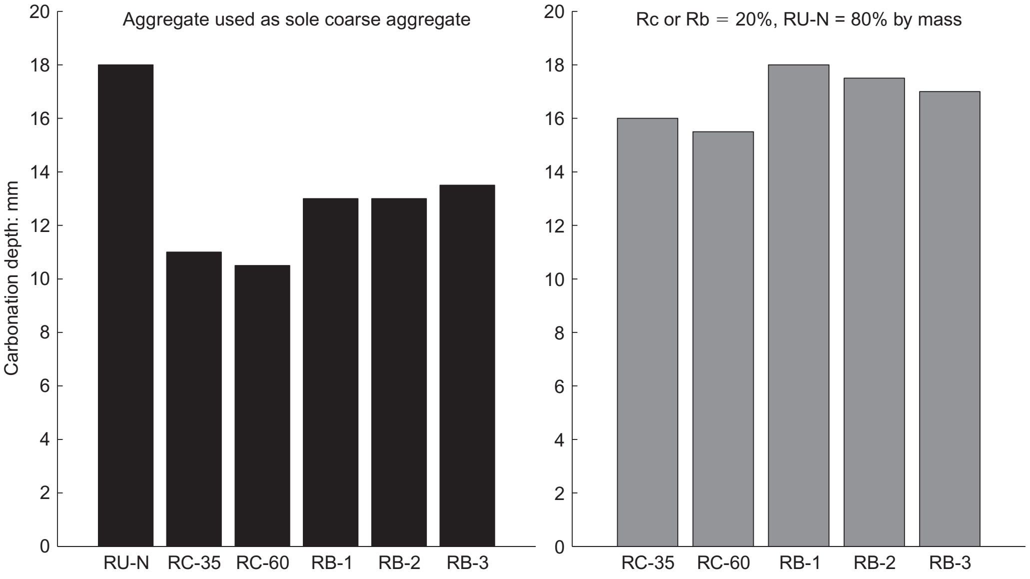

Figure 9. Effect of coarse aggregate type on carbonation depth of concrete after 12 weeks' exposure to accelerated environment

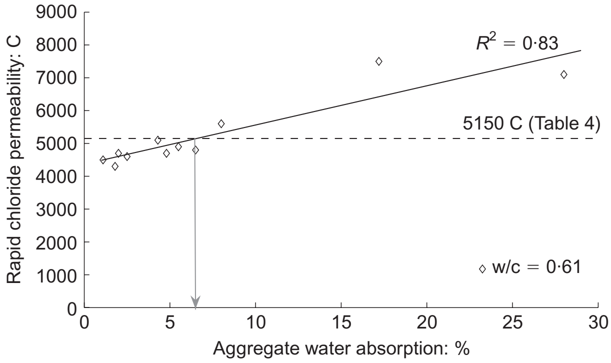

Figure 10. Relationship between water absorption of coarse aggregate and rapid chloride permeability of concrete

were carried out for selected mixes. Drying shrinkage tended to increase with both Rb and Rc content although there was considerable scatter, generally relating to the significant difference in the drying shrinkage value of RB-1 in comparison to RB-2 and RB-3 (Table 2). Given the variability in results and the fact that BS EN 12620:2008 (BSI, 2008) already contains a requirement that aggregates must have a drying shrinkage value less than 0·075%, there were seen to be no grounds for setting additional requirements for RA.

Discussion and recommendations

Analysis of the results has described requirements for RA in terms of:

(*a*) LA coefficient, ⩽ 40
(*b*) particle density, ⩾ 2600 kg/m^3
(*c*) water absorption, ⩽ 3·5%
(*d*) drying shrinkage value, ⩽ 0·075%

and shown that provided the limits for these properties are met then concrete made using these aggregates will have similar performance to that of natural aggregate concrete, to the extent that equivalent performance can be achieved by a small (10% or less) adjustment to the w/c ratio.

However, there are some important issues with regard to many of the values obtained. For example, it was shown that appropriate elastic modulus could only be achieved using RU-N, and not by using RA. In practice, however, aggregates that give a lower elastic modulus than that of RU-N (natural gravel) concrete are widely used in construction. Indeed Eurocode 2 (BS EN 1992-1-1:2004 (BSI, 2004)) permits the use of limestone and sandstone to give elastic moduli of concrete 10% and 30% lower than that of natural gravel concrete. Therefore the application of such tight limits on RA appears to be inappropriate.

Furthermore, it was shown that in order to achieve equivalent compressive strength, the minimum density of combined aggregate should be 2375 kg/m^3 (much lower than the value of 2600 kg/m^3 to achieve equivalent elastic modulus). An aggregate density of 2375 kg/m^3 equates, based on Figure 7, to an elastic modulus of concrete between 10% and 15% lower than that of the RU-N concrete. This falls well within the range expected of lower performing sandstone and limestone aggregates. Consequently, it is perhaps appropriate to control the density of RA based on achieving equal cube strength, and permit the elastic moduli of RA concrete to be up to 15% lower than that of the equivalent natural aggregate concrete, even after allowing for a w/c ratio correction.

In order to control both ISA and chloride permeability, a maximum water absorption of 3·5% for the aggregates was determined. However, this would in effect prevent many natural aggregates that have a long history of successful use from being used (Dhir *et al.*, 2006). It is therefore possible that a less stringent maximum water absorption should be applied. For example, a value of 4·5% by mass may be more reasonable, allowing ISA-10 values at a w/c ratio of 0·61 to reach 0·8 ml/m^2 per second. This acknowledges that a value of 0·8 ml/m^2 per second is not unreasonably high for concrete at a w/c ratio of 0·61, because while ISA tests on normally proportioned CEM I concretes (as in this work) give some indication of the degree of resistance of concrete to ingress of deleterious substances, it is more common in practice to use additions, water-reducing admixtures and particle packing techniques to reduce the ISA of concrete.

On the other hand, aggregates with a water absorption value up to 4·5% will tend, based on the linear relationship in Figure 10, to give a maximum chloride permeability of 4800 C. This can be regarded as high, since ASTM C 1202-05 (ASTM, 2005) states that concrete with moderate chloride ingress resistance should have a rapid chloride permeability value of less than 4000 C. Therefore, there is some concern here as to whether adequate chloride permeability could really be achieved with these aggregates at lower w/c ratios. Of course, in practice such high resistance to chloride ingress would be achieved using blended cements and combinations and the modest research there has been in this area suggests that this is valid for recycled aggregate concretes (Ann *et al.*, 2008; Kou *et al.*, 2008). Furthermore, for the RU-N aggregates used in this project, a value of less than 4000 C could only be achieved with CEM I as the cement using a w/c ratio of less than 0·5, and not with the high w/c ratio (0·61) and low cement contents (295–310 kg/m^3) used in this project. However, it is the authors' opinion that further research is still required to confirm the ability of RA concrete to achieve suitable resistance to chloride ingress when used in conjunction with CEM II and CEM III cements, and until such time, the use of RA in concrete for chloride environments should be treated with caution.

Consequently, the limits on RA properties in order to produce RA concrete with similar performance to that of natural aggregate concrete (w/c correction factor ⩾ 0·9) can be given as those shown in the centre data column of Table 5. Of course, higher or lower relative concrete performance can be given by imposing more or less strict requirements on w/c ratio correction (for example 0·95 or 0·8, respectively). The relevant limits for these corrections are also shown in Table 5, and the three limits given could be proposed as three classes of RA: A, B and C.

It should be noted that the selection of aggregate characteristics chosen for determining these classes is compatible with BSI considerations for the likely aggregate properties to be specified for end uses in the UK (PD 6682-9:2003 (BSI, 2003)) and furthermore are similar to those used in the Japanese standard JIS A 5021:2005 (JSA, 2005). Indeed, the requirements for RA in JIS A 5021:2005 are similar to those for the proposed class B, with limits on an oven-dry density of greater than 2500 kg/m^3, water absorption less than 3·0%, and a LA coefficient of less than 35%.

Based on the results, Table 6 provides a tentative list of environments in which it can be assumed that these three classes of RA could be used. For example, it can be suggested that RA meeting class A is suitable for a range of exposure conditions, including use in concrete exposed to carbonation (up to XC-4), sulfate conditions (up to D-2) and other aggressive agents. Based on earlier work, this class of RA will also have good resistance to freeze–thaw conditions (up to XF-4) provided suitable air-entrainment is used (Dhir and Paine, 2003). In addition, it is tentatively suggested that due to the low water absorption value, RA meeting class A will be suitable for use in the least aggressive chloride (XD and XS) environments because performance is similar to that of natural aggregate.

Recycled aggregate meeting class B would be suitable for use in fewer exposure conditions, but could be used in concrete exposed to carbonation (XC-4), moderate sulfate conditions (DC-2), other aggressive agents (provided appropriate cements are used) and moderate freeze–thaw conditions (XF-2) (Dhir and Paine, 2003). However, as discussed, they probably should not, as yet, be used in chloride environments until further research has proven their suitability.

Recycled aggregate meeting class C has very low requirements and therefore would only be suitable for use in concrete exposed to moderate levels of carbonation (XC-2) and sulfates (DC-1).

Where the concrete will be designed such that drying out never occurs, for example mass concrete surfaced with air-entrained concrete, and structural elements symmetrically and heavily reinforced and not exposed to the weather, as described in BS EN 12620:2008 (BSI, 2008), users can make a judgement as to whether the drying shrinkage requirement given in Tables 5 and 6 is necessary.

Conclusions

(*a*) Results showed that although the use of Rc and/or Rb in concrete led in the most part to lower concrete performance than equivalent concrete mixes prepared with natural aggregates at the same w/c ratio, the loss in performance could be correlated to appropriate properties of the aggregate (LA coefficient, aggregate absorption, density and drying shrinkage). It was also possible to separate the combinations of aggregate into classes that would perform to a given requirement provided suitable practical considerations were taken into account, for example slight adjustments to the w/c ratio, as recommended elsewhere (Dhir *et al.*, 1999).

(*b*) Observation of the results obtained in this study against the known performance of some natural aggregates, such as sandstones and limestones, the use of which is permitted within the framework of Eurocode 2 and other CEN standards as stated in this paper, suggests that there is a strong case for considering the use of all aggregates on a performance-related basis. Indeed, as the results show, this will encourage greater use of all RAs.

(*c*) Arising from this study, and supported by previous studies undertaken by the authors, a three-part classification of RA for its use in concrete has been proposed based on performance-related properties. The proposed classification of RA should permit a wider use of RAs in higher-value applications than the current compositional limits in BS

Table 5. Recycled aggregate performance requirements in order to achieve concrete within a given w/c correction factor range of RU-N concrete

Aggregate characteristic	The w/c reduction factor to produce equivalent performing concrete to RU-N concrete		
	⩾ 0·95	⩾ 0·9	⩾ 0·8
Maximum LA coefficient	29	40	55
Minimum density, SSD: kg/m^3	2500	2375	2150
Maximum water absorption: %	3	4·5	n/a
Maximum drying shrinkage value: %	0·075	0·075	0·075

Table 6. Performance-related aggregate requirements for the three proposed classes of coarse RA and permissible forms of concrete based on exposure conditions

Class A	Minimum LA class		LA_{25}	
	Minimum density, SSD: kg/m^3		2500	
	Maximum water absorption: %		3	
	Max. drying shrinkage value:		0·075	
No risk of corrosion	XO			
Corrosion induced by carbonation	XC-1	XC-2	XC-3	XC-4
Corrosion induced by chlorides	XD-1	XD-2		
Corrosion induced by chlorides (sea water)	XS-1	XS-2		
Freeze–thaw attack	XF-1	XF-2	XF-3	XF-4
Sulfate attack	DC-1	DC-2		
Class B	Minimum LA class		LA_{40}	
	Minimum density, SSD: kg/m^3		2375	
	Maximum water absorption: %		4·5	
	Max. drying shrinkage value: %		0·075	
No risk of corrosion	XO			
Corrosion induced by carbonation	XC-1	XC-2	XC-3	XC-4
Freeze–thaw attack	XF-1	XF-2		
Sulfate attack	DC-1	DC-2		
Class C	Minimum LA class		LA_{55}	
	Minimum density, SSD: kg/m^3		2150	
	Maximum water absorption: %		No limit	
	Max. drying shrinkage value: %		0·075	
No risk of corrosion	XO			
Corrosion induced by carbonation	XC-1	XC-2		
Sulfate attack	DC-1			

8500-2:2006. This in turn should encourage the development of sustainable use of all CDEW.

(*d*) Given the ever-increasing importance of recycling CDEW, and the relevance of embracing a performance-based approach to the specification of concrete and its constituents, it is recommended that further work, similar to that reported here, be undertaken so that proposed classification for the RA can be further strengthened for its adoption in practice.

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