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Recycled Concrete Aggregates: A Review

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Abstract: This paper discusses the properties of RCA, the effects of RCA use on concrete material properties, and the large scale impact of RCA on structural members. The review study yielded the following findings in regards to concrete material properties: (1) replacing NA in concrete with RCA decreases the compressive strength, but yields comparable splitting tensile strength; (2) the modulus of rupture for RCA concrete was slightly less than that of conventional concrete, likely due to the weakened the interfacial transition zone from residual mortar; and (3) the modulus of elasticity is also lower than expected, caused by the more ductile aggregate. As far as the structural performance is concerned, beams with RCA did experience greater midspan deflections under a service load and smaller cracking moments. However, structural beams did not seem to be as affected by RCA content as materials tests. Most of all, the ultimate moment was moderately affected by RCA content. All in all, it is confirmed that the use of RCA is likely a viable option for structural use.

Keywords: recycled concrete aggregate, water absorption, residual mortar, aggregate properties, concrete material properties, structural performance.

1. Introduction

After demolition of old roads and buildings, the removed concrete is often considered worthless and disposed of as demolition waste. By collecting the used concrete and breaking it up, recycled concrete aggregate (RCA) is created (Fig. 1). This paper focuses on coarse RCA which is the coarse aggregate from the original concrete that is created after the mortar is separated from the rock which is reused. The use of RCA in new construction applications is still a relatively new technique. Buck (1977) cites the beginning of RCA use to the end of World War II, when there was excessive demolition of buildings and roads and a high need to both get rid of the waste material and rebuild Europe. After the immediate need to recycle concrete, the use of RCA tapered off. In the 1970s, the United States began to reintroduce the use of RCA in non-structural uses, such as fill material, foundations, and base course material (Buck 1977). Since this time, some research has been conducted regarding how viable RCA is as an option to replace unused natural aggregate (NA) in structural concrete.

One of the main reasons to use RCA in structural concrete is to make construction more “green” and environmentally friendly. Some major environmental issues associated with construction, as stated by Oikonomou (2005), are that construction “takes 50 % of raw materials from nature, consumes 40 % of total energy, [and] creates 50 % of total waste.” The use of RCA on a large scale may help to reduce the effects of the construction on these factors by reusing waste materials and preventing more NA from being harvested.

2. Aggregate Properties

This section discusses the properties of RCA as compared to NAs. An understanding of how the aggregate changes after already being used in concrete can improve the ability to describe why RCA may perform differently when used in new concrete than NA. The main aggregate properties that are presented are the density, porosity, and water absorption of the aggregate, the shape and gradation of the aggregate, and the aggregate resistance to crushing and abrasion.

2.1 Density, Porosity, and Water Absorption

Residual adhered mortar on aggregate is a main factor affecting the properties of density, porosity, and water absorption of RCA. The density of RCA is generally lower than NA density, due to the adhered mortar that is less dense than the underlying rock. The variation in density is dependent on the specific aggregate in question. A study by Limbachiya et al. (2000) showed that the relative density of RCA (in the saturated surface dry state) is approximately 7–9 % lower than that of NA. Sagoe-Crentsil et al. (2001) reported bulk densities of 2,394 and 2,890 kg/m^3 for RCA

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Fig. 1 Recycled concrete aggregates (RCA).

and NA, respectively, approximately a 17 % difference. The adhered mortar can be lightweight compared to aggregate of the same volume, which causes the decrease in density.

Porosity and water absorption are related aggregate characteristics, also attributed to residual mortar. NA generally has low water absorption due to low porosity, but the adhered mortar on RCA has greater porosity which allows the aggregate to hold more water in its pores than NA. Shayan and Xu (2003) found water absorption values of 0.5–1 % for NA and 4–4.7 % for RCA in the saturated surface dry condition, up to a 4.2 % difference. Other studies showed differences where RCA absorption was 5.6 and 4.9–5.2 % compared to NA absorption of 1.0 and 2.5 % (Sagoe-Crentsil et al. 2001; Limbachiya et al. 2000).

The aggregate characteristics of density, porosity, and water absorption are a primary focus in determining the proper concrete mix. These characteristics should be known to limit absorption capacity of aggregates to no more than 5 % for structural concrete, and thus the proportion of RCA is often limited in concrete mixes (Exteberria et al. 2007), as is discussed later in this paper. Table 1 summarizes acceptance criteria for RCAs used worldwide.

2.2 Shape and Gradation

The shape of the aggregate pieces is influential on the workability of the concrete. Exteberria et al. (2007) warned that the method of producing RCA and the type of crusher that is used in this process is influential in the shape of RCA produced. NA is generally an angular shape with smooth sides. Sagoe-Crentsil et al. (2001) initially described the plant-produced RCA as grainy in texture and later discussed that the RCA has a more rounded, spherical shape which seemed to improve workability. The residual mortar on RCA can smooth out the hard edges of the original aggregate. This allows the new mortar to flow better around the aggregate. The effects of the aggregate shape on workability and strength parameters of concrete are discussed further later in this paper.

Standards for concrete aggregate define a range within which the gradation of aggregate must lie in order to be acceptable aggregate for structural concrete. Both Sagoe-Crentsil et al. (2001) and Shayan and Xu (2003) found that the gradation curves of RCA were within this specified range. This indicates that RCA should have acceptable gradation by applicable standards without adjustments being made.

2.3 Crushing and L.A. Abrasion

Crushing and Los Angeles (L.A.) abrasion tests are measures of the durability of aggregate material on its own. There is a general trend that RCA has higher values for crushing and L.A. abrasion than NA, meaning when the aggregate is contained and crushed or impacted by steel balls in the L.A. abrasion test RCA has more fine particles break off of than NA. Crushing tests resulted in values of 23.1 % for RCA vs. 15.7 % for basalt (a NA) and 24 % for RCA vs. 13 % for basalt in two separate studies (Sagoe-Crentsil et al. 2001; Shayan and Xu 2003). L.A. abrasion values for RCA versus NA were found in two studies as 32 vs. 11 % and 26.4–42.7 vs. 22.9 % (Shayan and Xu 2003; Tavakoli and Soroushian 1996). This is a reasonable result for these tests, in that the RCA has residual mortar that can break off easily at the interfacial transition zone (ITZ), which is the typically weak area of concrete. It is logical that, when subjected to loading, the residual mortar on RCA would break off, while NA does not have a similar coating to lose.

The behavior of RCA in crushing and abrasion tests demonstrates the weakness of the adhered mortar. Since this layer is most likely to break off of the aggregate itself, it is predicted that the adhered mortar layer may also create a weak connection within concrete.

3. RCA Concrete Material Properties

Since the recycled aggregate has different properties than NA, it behaves differently in concrete mixes and causes the finished concrete to perform unlike conventional concrete. This section describes the variation between the properties of RCA concrete compared to conventional NA concrete.

3.1 Compressive Strength

Compressive strength of RCA concrete can be influenced by the properties and amount of recycled aggregate. Several factors can influence the compressive strength in RCA concrete, including the water/cement (w/c) ratio, the percentage of coarse aggregate replaced with RCA, and the amount of adhered mortar on the RCA. Most research recommended that, without changes to the mix involving adjustments to the w/c ratio, up to 25 or 30 % of coarse aggregate can be replaced with RCA before the ceiling strength is compromised. In a study by Limbachiya et al. (2000), concrete specimens made with up to 30 % RCA had equal compressive strengths for w/c ratios greater than 0.25 as seen in Fig. 2, which shows trends for compressive strengths for three RCA fractions as they vary with w/c ratio. The data for 30 % RCA follows that of 0 % RCA for almost every w/c ratio tested, while the 100 % RCA data lie at

Table 1 Acceptance criteria regarding recycled concrete aggregates.

Country or standard	Recycled aggregate type	Oven-dry density criterion (kg/m^3)	Absorption ratio of aggregate criterion (%)
Australia (AS1141.6.2) (AS 1996)	*Class 1A*	≥2,100	≤6
	Class 1B	≥1,800	≤8
Germany (DIN 4226-100) (DIN 2002)	*Type 1*	≥2,000	≤10
	Type 2	≥2,000	≤15
	Type 3	≥1,800	≤20
	Type 4	≥1,500	No limit
Hong Kong (Works Bureau of Hong Kong 2002)	–	≥2,000	≤10
Japan (JIS A 5021, 5022 and 5023) (JIS 2011, 2012a, b)	Coarse—*Class H*	≥2,500	≤3
	Fine—*Class H*	≥2,500	≤3.5
	Coarse—*Class M*	≥2,300	≤5
	Fine—*Class M*	≥2,200	≤7
	Coarse—*Class L*	No limit	≤7
	Fine—*Class L*	No limit	≤13
Korea (KS F 2573) (KS 2002)	Coarse	≥2,500	≤3
	Fine	≥2,200	≤5
RILEM (1994)	*Type 1*	≥1,500	≤20
	Type 2	≥2,000	≤10
	Type 3	≥2,500	≤3
Spain (EHE 2000)	–	≥2,000	≤5

Australia (AS 1996): *Class 1A* well graded RCA with no more than 0.5 % brick content; *Class 1B* Class 1A RCA blended with no more than 30 % crushed brick.

Germany (DIN 2002): *Type 1* concrete chippings + crusher sand; *Type 2* construction chippings + crusher sand; *Type 3* masonry chippings + crusher sand; *Type 4* mixed chippings + crusher sand.

Japan (JIS 2011): *Class H* no limitations are put on the type and segment for concrete and structures with a nominal strength of 45 MPa or less; *Class M* members not subjected to drying or freezing-and-thawing action, such as piles, underground beam, and concrete filled steel tubes; *Class L* backfill concrete, blinding concrete, and concrete filled in steel tubes.

RILEM (1994): *Type 1* aggregates from masonry rubble, *Type 2* aggregates from concrete rubble; *Type 3* mixture of natural (min 80 %) and recycled (max 20 %) aggregate.

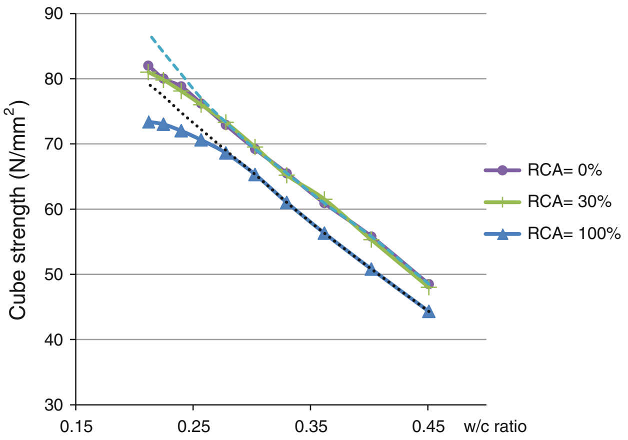

Fig. 2 Concrete compressive strength versus water-to-cement ratio for RCA contents of 0–100 % (plotted using data from Limbachiya et al. 2000).

compressive strength values below that of 0 or 30 % RCA by about 5 N/mm^2. At the lowest w/c ratios, the compressive strengths for mixes with RCA become more dissimilar to conventional concrete.

Exteberria et al. (2007) found similar behavior with tests using 25 % RCA that performed as well as conventional concrete with the same w/c ratio. This study tested concrete made with 0, 25, 50, and 100 % RCA concrete mixes and concluded that up to 25 % could be replaced without significant change in compressive strength or a different w/c ratio; however, to obtain the same strength with 50–100 % RCA, w/c ratio needed to be 4–10 % lower, and without this alteration, the compressive strength for 100 % RCA mixes was reduced by 20–25 % (Exteberria et al. 2007). Recent tests by Kang et al. (2012) also showed that the compressive strength was reduced by about 25 % for the same mix but with 50 % RCA, and reduced by up to 18 % for 15–30 % RCA mixes (Table 2).

Table 2 RCA material tests (by Kang et al. 2012).

Concrete	f'_c (MPa)	Reduction in f'_c (%)	f_{ct} (MPa)	Reduction in f_{ct} (%)	f_r (MPa)	Reduction in f_r (%)
RCA 0 %	38.6	–	3.3	–	10.2	–
RCA 15 %	32.7	15	3	9	9.7	5
RCA 30 %	31.7	18	2.7	18	9.0	12
RCA 50 %	29.0	25	2.7	18	8.9	13

f'_c compressive strength; f_{ct} splitting tensile strength; f_r modulus of rupture.

Yang et al. (2008) attributed a reduction in compressive strength for RCA concrete to the increased water absorption of the aggregate and found that at relatively low water absorption (relatively low RCA fraction) concrete had equivalent compressive strengths while higher RCA fractions and absorption compressive strengths were 60–80 % of that of conventional control concrete, but that the compressive strength improved with age. Since the aggregate can store more water, this water can be released into the new mortar over time to continue to feed the cement for longer time, which improves strength.

The degree of strength reduction in RCA concrete does vary with each source aggregate. Froudinstou-Yannas (1977) also found that some mixes replacing 100 % of coarse aggregate with RCA had about 76 % of the compressive strength of conventional concrete, while mixes using different w/c ratios had as low as 4 % reduction in compressive strength. Furthermore, a report by Tavakoli and Soroushian (1996) studied compressive strength of concretes made with two different sources for RCA side-by-side. It is found that while RCA usually reduces concrete compressive strength due to higher water absorption of the aggregate and the weak residual mortar layer. It is possible to produce concrete that is stronger than a conventional concrete if the source concrete is stronger than that at which the RCA concrete is intended to perform. It would be recommended that when using RCA for structural concrete applications, strength tests be performed to ensure what strength of concrete the RCA is capable of producing and verify what RCA fraction is acceptable or if there are changes in the w/c ratio needed in order to produce concrete of the desired strength.

3.2 Splitting Tensile Strength

Splitting tensile strength is less affected by RCA content than compressive strength. Several past and recent tests (e.g., Kang et al. 2012) show that the splitting tensile strength of RCA concrete is comparable to conventional concrete. In some cases, RCA concrete performed superior to NA concrete with regards to tension. According to Exteberria et al. (2007), the improvement is due to the increased absorption of the mortar attached to the recycled aggregate and the effective ITZ, which indicates a good bond between aggregate and the mortar matrix. While this residual mortar creates a weakened spot for compressive failure to occur, limited quantities improve the tensile capacity by creating a smoother transition between mortar and aggregate.

Unlike with compressive strength, high-strength concrete mixes with low w/c ratios show even greater improvement in splitting tensile strength. Figure 3, from Tavakoli and Soroushian (1996), shows the tensile strengths for RCA concrete mixes made from two aggregate sources as compared to NA mixes. In Fig. 3, the samples with lower w/c ratios have more improved tensile strength than the higher w/c ratios when aggregate size and dry mixing time do not have a distinct influence. Most RCA concrete samples in the figure at the lower w/c ratio have showed the improved tensile strength. Overall, the confidence interval of the measured RCA tensile strength is greater than the measured NA tensile strength.

Similarly, Yang et al. (2008) relate improved tensile performance of RCA concrete to high strength source aggregate which has lower water absorption and w/c ratios. This mirrors the effect of high strength source concrete on compressive strength. Figure 4 shows that samples made with high strength concrete (grade I) have greater normalized tensile strengths than samples made with lower strength source concrete (grade III). Also, it shows that the generalized relationship to predict tensile strength (f_t) from compressive strength (f'_c) where ($f_t/\sqrt{f'_c} = 0.53$) is conservative for all samples made from grade I concrete, but not all grade III samples reached the predicted value (Yang et al. 2008). This indicates that using RCA from higher strength source aggregate may be as beneficial in improving tensile strength as it is for improving compressive performance.

3.3 Modulus of Rupture and Elasticity

The modulus of rupture, a measure of flexural strength, and the modulus of elasticity (also known as Young's modulus), a measure of concrete stiffness, are often predicted from compressive strength, but these relationships do not represent RCA concrete as well as NA concrete. This section examines each modulus and how RCA affects these characteristics of concrete.

The modulus of rupture is not well represented by the standard relationship with compressive strength. Tavakoli and Soroushian (1996) described that the modulus of rupture tests of RCA concrete gave more varied results. The RCA concrete performed better in terms of the modulus of rupture than conventional concrete at the higher water-cement ratio, but it performed worse at the lower water-cement ratio. Since the current model relating compressive and flexural strengths is inadequate, there should be more research on the impact of RCA on concrete flexural strength so that a new, more representative, relationship can be developed. Yang et al. (2008) examined how

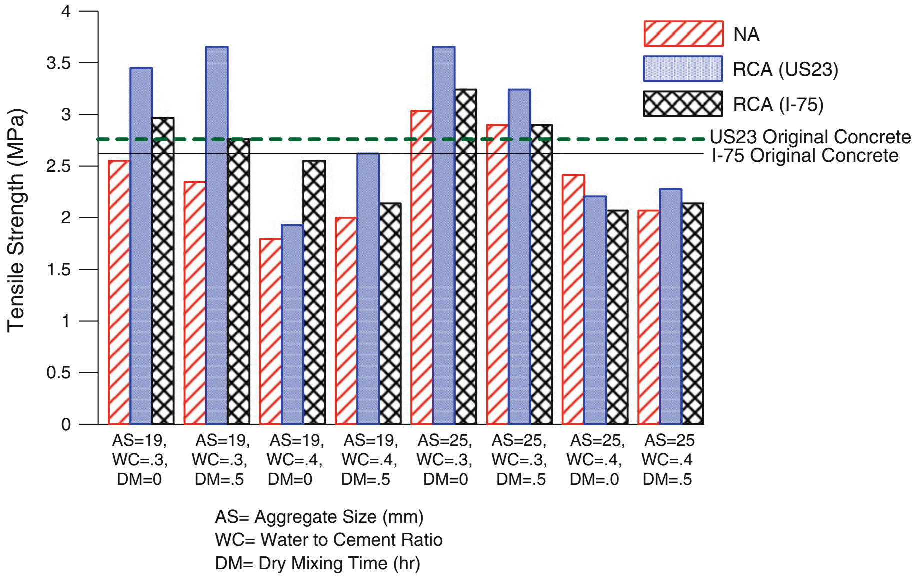

Fig. 3 Splitting tensile strength for RCA and NA concrete with varied aggregate size, w/c ratio, and dry mix time (plotted using the data from Tavakoli and Soroushian 1996).

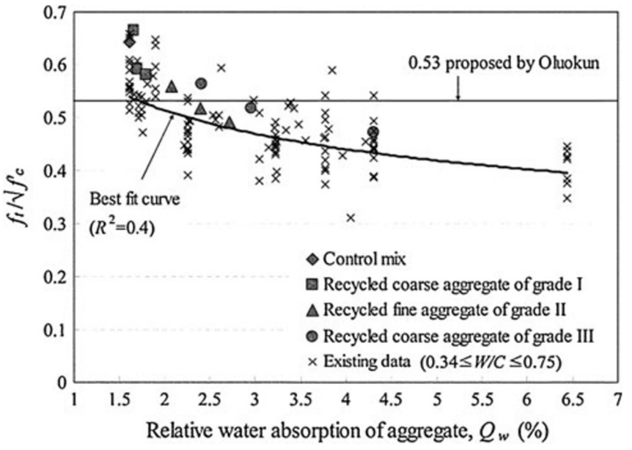

Fig. 4 Normalized splitting tensile strength versus aggregate water absorption for RCA concrete (adapted from Yang et al. 2008).

water absorption of RCA and the strength of RCA source concrete influence how well compressive strength predicts modulus of rupture. This paper concluded that RCA concrete made with RCA from high strength source concrete with low water absorption perform like conventional concrete, while low strength source RCA with high water absorption yields a modulus of rupture less than predicted, likely due to the weak residual mortar layer (Yang et al. 2008). Since both compressive and tensile strengths generally decrease under the same conditions that cause reduced flexural strength, this conclusion is reasonable. While in flexure the top of the specimen experiences compression while the lower portion experiences tension. If either the compressive or tensile capacity of the specimen is compromised, the flexural strength will also be affected. Tensile strength was also greater than the predicted value for concrete with RCA from a high strength source with low water absorption. Since concrete is weaker in tension than in compression, it is reasonable that modulus of rupture would follow a similar pattern to tensile strength, the weaker chord resistance. Recent tests by Kang et al. (2012) proved that the modulus of rupture is moderately affected by the replacement of RCA. For the RCA replacement ratio of 15–50 %, the modulus of rupture was reduced by only 13 % at most (Table 2).

The main factor affecting the RCA concrete modulus of elasticity is the modulus of elasticity for the aggregate itself. Improvement of tensile strength with the addition of RCA would usually be associated with an improved elasticity; however, because the "recycled aggregates are more prone to deformation than raw aggregates," the weakness of the aggregate reduces the Young's modulus for concrete when RCA is used (Exteberria et al. 2007). Generally, Young's modulus for RCA concrete was lower than that of conventional concrete, but there is significant variation between studies as to how much the modulus is reduced. For example, a study by Froudinstou-Yannas (1977) found that the modulus of elasticity for RCA concrete was as low as 60 % of that of NA concrete, whereas a study by Maruyama et al. (2004) found a reduction of only 20 %. The most likely cause for this variation is the different properties of the aggregate used in each study. This would further prove the theory that the modulus of elasticity is controlled by the aggregate properties (e.g., aggregate elasticity) rather than the properties of the concrete as a whole (e.g., compressive or flexural strength). Similar to modulus of rupture, the effect of RCA on Young's modulus of concrete requires further research to develop a relationship that can be used to better predict the behavior.

In the following section, given that the properties of RCA concrete are known, structural performance of RCA concrete beams is assessed.

4. Structural Performance of RCA Beams

Knowing about how the different properties of aggregate affect concrete material behavior is vital to understanding how the concrete will perform in structural members. It

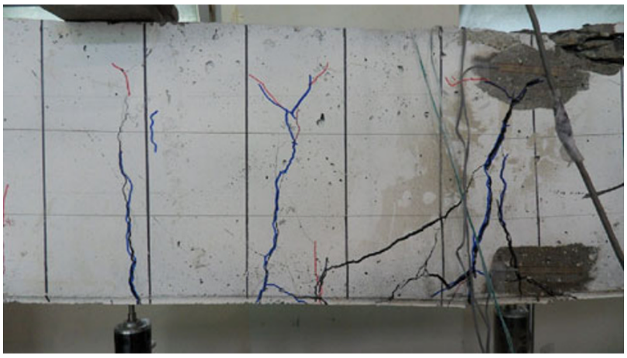

Fig. 5 Flexural failure of RCA beam (tested by Kang et al. 2012).

cannot be determined if RCA concrete is a structurally viable material without realizing how the changes in concrete properties from RCA addition will influence overall performance on the large scale. This section examines the behavior of large-scale RCA concrete beams in flexure and how it compares to that of conventional concrete beams.

4.1 Midspan Deflection Under Service Load

Based on service load deflection, RCA reinforced concrete beams perform less well than conventional concrete beams. However, the change in aggregate does not have enough influence on deflection to discourage RCA use in concrete beams. In a study by Fathifazl et al. (2009), it was found that, under a load of 40 % of failure load, midspan deflection was greater for RCA beams than for NA beams, but that predicted deflections from the ACI 318-11 (2011), Eurocode 2 (2004), and the moment curvature method are still greater than the observed deflections. Maruyama et al. (2004) and Sato et al. (2007) also confirm that midspan deflections of beams are larger with RCA than NA based concrete; while Sato et al. (2007) went a step further to note that this effect is consistent regardless of RCA type and source concrete or the wet or dry curing condition of the beam.

A likely cause for increased deflections in RCA concrete beams is the reduced modulus of elasticity of the RCA concrete (Maruyama et al. 2004). The low Young's modulus indicates that the material is easier to deform; thus, a lower load may cause greater deformation in an RCA concrete beam than in a conventional concrete beam. The most important thing to consider, however, is if the increase in deformation is enough to rule out RCA concrete as a viable structural material. Since the standard predictions of

Table 3 Criteria of RCA replacement ratio for production of structural concrete.

<table>
<tr><th></th><th>Exposure class[a] or aggregate</th><th colspan="2">Type 1[b] (%)</th><th colspan="2">Type 2[b] (%)</th></tr>
<tr><td rowspan="5">DAfStb (1998)—Germany</td><td>X0 [coarse]</td><td colspan="2">≤45</td><td colspan="2">≤35</td></tr>
<tr><td>XC1 to XC4 [coarse]</td><td colspan="2">≤45</td><td colspan="2">≤35</td></tr>
<tr><td>XF1 and XF3 [coarse]</td><td colspan="2">≤35</td><td colspan="2">≤25</td></tr>
<tr><td>XA1 [coarse]</td><td colspan="2">≤25</td><td colspan="2">≤25</td></tr>
<tr><td>[Fine]</td><td colspan="4">Not allowed</td></tr>
<tr><th></th><th></th><th>Type 1[c]</th><th colspan="2">Type 2[c]</th><th>Type 3[c]</th></tr>
<tr><td rowspan="2">RILEM (1994)</td><td>Coarse (≥4 mm)</td><td>≤100 %</td><td colspan="2">≤100 %</td><td>≤20 %</td></tr>
<tr><td>Fine (<4 mm)</td><td colspan="4">Not allowed</td></tr>
<tr><td rowspan="2">NEN 5950:1995 (VBT 1995)—Netherlands (NEN 5950:1995 nl 1995)</td><td>Coarse</td><td colspan="4">≤20 %</td></tr>
<tr><td>Fine</td><td colspan="4">≤20 %</td></tr>
<tr><td rowspan="2">CRIC (2004)—Belgium</td><td>Coarse</td><td colspan="4">≤100 %</td></tr>
<tr><td>Fine</td><td colspan="4">Allowed with restriction</td></tr>
<tr><td rowspan="2">DS 481 (1998)—Denmark</td><td>Coarse</td><td colspan="4">≤100 %</td></tr>
<tr><td>Fine</td><td colspan="4">≤20 %</td></tr>
<tr><td rowspan="2">BS EN 12620:2002+A1 (BS 2002)—UK</td><td>Coarse</td><td colspan="4">≤20 %</td></tr>
<tr><td>Fine</td><td colspan="4">Not allowed</td></tr>
</table>

[a] According to EN 1992-1-1:2004: E (Eurocode 2 2004) or DIN EN 206-1 (DIN 2001) and DIN 1045-2 (DIN 2008); X0: No risk of corrosion or attack, very dry; XC1 to XC4: carbonation, dry to permanently wet; XF1 and XF3: freeze/thaw attack, moderate to high water saturation; XA1: chemical attack, slightly aggressive.

[b] *Type 1* concrete chippings + crusher sand, *Type 2* construction chippings + crusher sand.

[c] RILEM: *Type 1* aggregates from masonry rubble, *Type 2* aggregates from concrete rubble; *Type 3* mixture of natural (min 80 %) and recycled (max 20 %) aggregate.

midspan deflections are still more severe than deflections produced by the use of RCA, there is no reason to deny RCA use in regards to deflection.

4.2 Crack Width and Spacing

Maruyama et al. (2004) also found that RCA beams had greater crack width and smaller crack spacing, but noted that the variation of these parameters between RCA and NA concrete was small from an engineering perspective and that RCA beam crack width was still well below the applicable standards. A third study by Sato et al. (2007) had similar relationships, but also studied the effect on the curing conditions, where dry curing had smaller crack spacing than wet curing, still with no significant effect. It can be concluded that RCA can increase crack width and reduce crack spacing, but that current standards can still be used to predict these parameters. An explanation for this behavior stems from the addition of a second ITZ region in RCA concrete. This region is a weak point in the concrete where cracking is most likely to occur. With both the ITZ from the residual mortar and the ITZ from the new mortar meeting the RCA, this ITZ can become larger and yield closer, wider cracking. Since the effect of RCA on these parameters is still small, RCA is not a hindrance to structural concrete members with respect to crack spacing and width.

4.3 Ultimate and Cracking Moments

Ultimate moments of reinforced concrete beams tended to be unaffected by the use of RCA, as long as steel yielding occurs prior to concrete crushing. This was true even if RCA beams had larger upward shifts of the neutral axis after cracking compared to the NA beams (Fig. 5). As described earlier, only the concrete strength is reduced for RCA concrete. If the concrete strengths were the same between the RCA and NA beams, the difference in moment strength turned out to be very small (Kang et al. 2012). Furthermore, the difference was even negligible if ratio of the volume of RCA to the volume of NA would be limited to about 3/7 (Kang et al. 2012). The criteria of RCA replacement ratio for the production of structural concrete set forth by various countries are summarized in Table 3.

Sato et al. (2007) also concludes that as long as the steel yielding occurs the ultimate moments of RCA and NA reinforced concrete beams are practically the same and that "the ultimate moment can be predicted using Japanese codes irrespective of the type of original aggregate and original concrete." Knowing that RCA from more than one source performed the same provides confidence that the behavior is consistent for all RCA concrete and that there is no special consideration to be made if the aggregate is of a lower quality or from a weaker source concrete. The conclusion that ultimate moment is unchanged by RCA use is verified in other studies as well. One study by Maruyama et al. (2004) found that all experimental ultimate moments were 10–20 % greater than predicted, and Fathifazl et al. (2009) also shows measure ultimate moments greater than predicted values by several methods, as seen in Fig. 6, where beam IDs beginning with "E" and "C" represent RCA and NA concretes, respectively. With evidence that beams with RCA have equivalent ultimate moments and that various predictors of this moment are still applicable, there is no reason that RCA cannot be used with respect to ultimate moments.

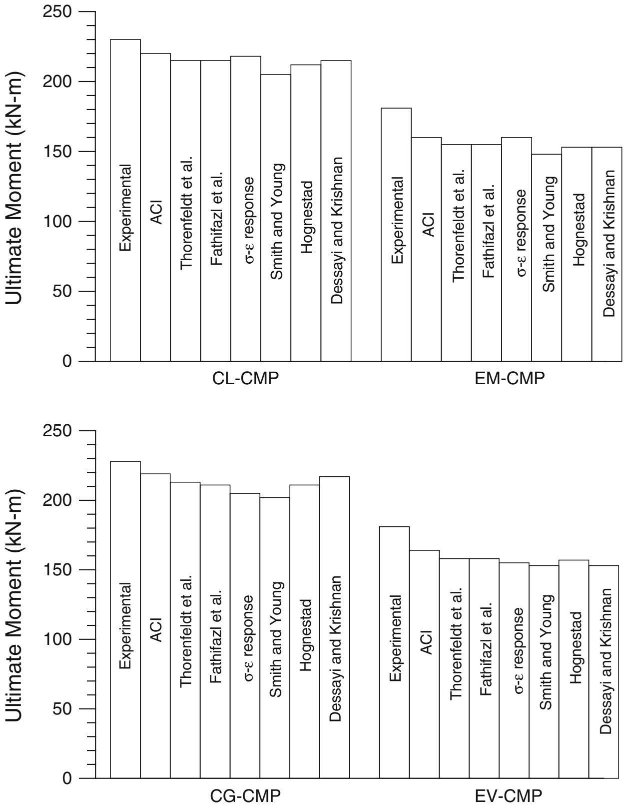

Fig. 6 Comparison of experimental and predicted ultimate moments (plotted using data from Fathifazl et al. 2009).

Cracking moments are more impacted by RCA than ultimate moments, since the strength properties of the concrete itself have more influence on cracking. Fathifazl et al. (2009) found that RCA concrete cracking moments were lower than with NA and compared the experimental cracking moment from visual inspection to what is predicted based on both the modulus of rupture and the splitting tensile strength. While either prediction was still applicable to RCA concrete beams, the cracking moment predicted from splitting tensile strength was closer to the observed cracking moment, within 20 % of predicted for all but one test (Fathifazl et al. 2009). Since the changed concrete properties with RCA use lower cracking moment and some strength parameters are better predictors, more research should be done to determine if, generally, concrete made with RCA is still acceptable for structural use with regards to cracking moment. Cracking moments for RCA concrete beams being only slightly lower than those of conventional concrete beams from an engineering perspective would indicate that the harm of RCA is limited, but the change in effectiveness of the predictors with RCA use could be a concern, possibly requiring an amendment to the current standards.

5. Conclusion

This paper has discussed properties of RCA, the effects of RCA use on concrete material properties, and the large scale impact of RCA on structural members. Aggregate properties are most affected by the residual adhered mortar on RCA. Because of this, RCA is less dense, more porous, and has a higher water absorption capacity than NA. While RCA and NA have similar gradation, RCA particles are more rounded in shape and have more fines broken off in L.A. abrasion and crushing tests. Replacing NA in concrete with RCA decreases the compressive strength, but yields equivalent or superior splitting tensile strength. The modulus of rupture for RCA concrete was less that of conventional concrete, likely due to the weakened interfacial transition zone from residual mortar. The modulus of elasticity is also lower than expected, caused by the more ductile aggregate. Full scale beams did not seem to be as affected by RCA content as small scale materials tests. Beams with RCA did experience greater midspan deflections under a service load, but the deflections were still much less than the codified maximums. Crack spacing was closer and crack widths were greater, but these variations were not different enough from conventional concrete to warrant concern. Ultimate moment, still controlled by steel yielding was unaffected by RCA content. Lastly, cracking moments were reduced in beams with RCA. While cracking moment was still predictable by relationships to splitting tensile strength and modulus of rupture, the relationship to modulus of rupture seemed less representative for RCA beams.

Overall, even though RCA can be lower quality aggregate and have a negative influence on concrete material properties, the large scale testing showed that, when looking at a complete structural member, RCA can still be used to create a structural concrete. Since the performance of RCA concrete beams is still within standard specifications, it is likely a viable option for structural use. Since the qualities of RCA are still highly varied among different sources, there is room for more testing to make sure the conclusions that have been drawn in this paper are applicable in the broad sense of RCA concrete, regardless of the RCA source.

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References

ACI Committee 318. (2011). *Building code requirements for structural concrete (ACI 318-11) and commentary*. Farmington Hills, MI: American Concrete Institute.

AS. (1996). *Particle density and water absorption of aggregates (AS 1141.6.2-1996)*. Sydney: Australian Standard.

BS EN 12620:2002+A1. (2002). *Aggregates for concrete*. British-Adopted European Standard.

Buck, A. D. (1977). Recycled concrete as a source of aggregate. *ACI Journal, 74*, 212–219.

CRIC. (2004). *TRA 550—Toepassingsreglement beton, versie 2.1* (in Dutch).

DAfStb. (1998). *Deutscher ausschuss für elsenbeton*. Germany: German Committee for Reinforced Concrete (in German).

DIN. (2001). *Concrete—Part 1: Specification, performance, production and conformity (DIN EN 206-1)*. Berlin: Deutsches Institut für Normung.

DIN. (2002). *Aggregates for mortar and concrete—Part 100: Recycled aggregates (DIN 4226-100)*. Berlin: Deutsches Institut für Normung.

DIN. (2008). *Concrete, reinforced and prestressed concrete structures—Part 2: Concrete—Specification, properties, production and conformity—Application rules for DIN EN 206-1 (DIN 1045-2:2008)*. Berlin: Deutsches Institut für Normung.

DS 481. (1998). *Concrete—Materials*. Draft 3rd version (in Danish).

EHE. (2000). *Instrucción de hormigón structural*. Madrid: Ministerio de Fomento (in Spanish).

Eurocode 2. (2004). *Design of concrete structures—Part 1-1: General rules and rules for buildings (EN 1992-1-1)*. European Standard, European Committee for Standardization, Ref. No. EN 1992-1-1:2004: E.

Exteberria, M., Vásquez, E., & Marí, A. R. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research, 37*, 735–742.

Fathifazl, G., Razaqpur, A. G., Igsor, O. B., Abbas, A., Fournier, B., & Foo, S. (2009). Flexural performance of steel-reinforced recycled concrete beams. *ACI Structural Journal, 106*(6), 858–867.

Froudinstou-Yannas, S. (1977). Waste concrete as aggregate for new concrete. *ACI Journal, 74*, 373–376.

JIS. (2011). *Recycled aggregate for concrete-class H (JIS A 5021:2011)*. Tokyo: Japan Concrete Institute (in Japanese).

JIS. (2012a). *Recycled concrete using recycled aggregate class M (JIS A 5022:2012)*. Tokyo: Japan Concrete Institute (in Japanese).

JIS. (2012b). *Recycled concrete using recycled aggregate class L (JIS A 5023:2012)*. Japan Concrete Institute: Japan Concrete Institute (in Japanese).

Kang, T. H.-K., Kim, W., Kwak, Y.-K., & Hong, S.-G. (2012). The choice of recycled concrete aggregates for flexural members. In *Proceedings of 18th international association for bridge and structural engineering congress on innovative infrastructures*, Seoul, Korea.

KS. (2002). *Recycled aggregates for concrete*. Korean Standards Association, Korea (in Korean).

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregate in high-strength concrete. *Materials and Structures, 33*, 574–580.

Maruyama, I., Sogo, M., Sogabe, T., Sato, R., & Kawai, K. (2004). Flexural properties of reinforced recycled beams. In *Proceedings of international RILEM conference on the use of recycled materials in buildings and structures, 1*, 525–535.

NEN 5950:1995 nl. (1995). *Voorschriften beton technologie (VBT 1995)—Eisen, vervaardiging en keuring*. Nederlands Normalisatie Instituut, 01-09-1995, Netherlands (in Dutch).

Oikonomou, N. (2005). Recycled concrete aggregates. *Cement & Concrete Composites, 27*, 315–318.

RILEM. (1994). Specifications for concrete with recycled aggregates. *Materials and Structures, 27*, 557–559.

Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research, 31*, 701–712.

Sato, R., Maruyama, I., Sogabe, T., & Sogo, M. (2007). Flexural behavior of reinforced recycled concrete beams. *Journal of Advanced Concrete Technology, 5*(1), 43–61.

Shayan, A., & Xu, A. (2003). Performance and properties of structural concrete made with recycled concrete aggregate. *ACI Materials Journal, 100*(5), 371–380.

Tavakoli, M., & Soroushian, P. (1996). Strengths of aggregate concrete made using field-demolished concrete as aggregate. *ACI Materials Journal, 93*(2), 182–190.

Works Bureau of Hong Kong. (2002). *Specifications facilitating the use of recycled aggregates*. WBTC No.12/2002.

Yang, K.-H., Chung, H.-S., & Ashour, A. F. (2008). Influence of type and replacement level of recycled aggregates on concrete properties. *ACI Materials Journal, 105*(3), 289–296.