Magazine of Concrete Research
Volume 67 Issue 1

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Magazine of Concrete Research, 2015, **67**(1), 1–12
http://dx.doi.org/10.1680/macr.14.00212
Paper 1400212
Received 07/07/2014; revised 04/11/2014; accepted 17/02/2015
Published online ahead of print xx/yy/zzzz

Evaluation of RCA concrete for the construction of Samwoh eco-green building

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This paper describes a study conducted to evaluate the use of concrete containing up to 100% recycled concrete aggregate (RCA) for the construction of a commercial building known as the Samwoh eco-green building in Singapore. The study is a continuation of research which established that concrete produced with RCA can achieve strength comparable to that of normal concrete produced with natural aggregate for structural applications by using a rational mix design approach. The present study was carried out to evaluate the effects of RCA on other engineering and durability properties of concrete, including compressive strength, flexural strength, tensile splitting strength, creep strain, water permeability, initial surface absorption, chloride ingress and sulphate resistance. With normal concrete serving as the basis for comparison, the experimental data showed that comparable compressive strength, flexural strength and tensile splitting strength were attainable for concrete containing up to 100% RCA. Although concrete with 100% RCA exhibited higher creep strain and initial surface absorption rate as well as lower resistance to water permeability, chloride ingress and external sulphate attack, the effects to the concrete performance are insignificant. On the whole, the research study suggests that RCA concrete can be designed to meet the specifications for structural applications, which led to the successful completion of the Samwoh eco-green building.

Notation

e depth of water penetration in concrete (m)
h hydraulic head (m)
K coefficient of permeability (m/s)
t_p time under pressure (s)
v fraction of the volume of concrete occupied by pores

Introduction

In response to the Singapore government's call for sustainable development, there is a need to divert construction and demolition waste (CDW) away from landfill as well as an exigency to source alternative materials to replace natural aggregates, which are mainly imported from neighbouring countries. A feasible solution is to produce structural concrete using recycled concrete aggregate (RCA) derived from CDW.

However, the use of RCA in concrete has been met with scepticism since it has long been confronted with an excessive volume of attached mortar and high porosity. Most studies in the literature have reported that compressive strength, flexural strength, tensile splitting strength and modulus of elasticity of RCA concrete decrease with an increase in replacement level of RCA (Casuccio *et al.*, 2008; Hansen and Bøegh, 1985; Ting, 2004). Furthermore, some reports on RCA concrete have also cited 5–50% increases in creep and 20–70% increases in shrinkage (Limbachiya *et al.*, 2000; Ravindrarajah and Tam, 1985). These features have restricted the use of high dosages of RCA in structural concrete applications.

Previous studies (Ho *et al.*, 2009, 2013 have shown that concrete made with RCA could be designed to produce comparable compressive strength and modulus of elasticity by adopting a rational mix design method in which natural coarse aggregate (NCA) was replaced with RCA (i.e. by mass of coarse aggregate) while keeping the water-to-cement (w/c) ratio constant with the addition of different dosages of water-reducing agent. This paper is a continuation of these studies, and describes laboratory tests carried out to determine the engineering and durability properties of concrete made with different replacement levels of RCA. The tests include measurements of compressive strength, flexural strength, tensile splitting strength, creep strain, initial surface absorption, water permeability and resistance to chloride and sulphate ingress.

Experimental programme

Materials

The RCA used in the study was acquired from a processing plant equipped with state-of-the-art equipment to process CDW into RCA. As shown in Figure 1, the processes include crushing and screening as well as removal of ferrous metals and foreign materials. Stringent and well-established quality control protocols are also undertaken to ensure that the RCA contains a minimal amount of foreign material, which is capped at about 6% (by mass of sample). This is much less than the total allowable limit of 16·5% specified by BS 8500-2 (BSI, 2006; Ho *et al.*, 2013). In order to remove as much of the attached mortar as possible, a two-stage crushing process was being introduced in the production plant. Only graded RCA within the range of 4–20 mm was accepted for the use in specimen preparation (SSC, 2008a). The qualities of the RCA, in terms of geometrical, mechanical and physical, thermal/weathering and chemical properties, were verified for compliance with the requirements of BS 8500-2 (BSI, 2006), SS EN 12620 (SSC, 2008a) and SS 31 (SSC, 1998).

The other materials used in the study also complied with the respective standards. CEM I 42·5N ordinary Portland cement, conforming to SS EN 197-1 (SSC, 2008b), was used in the investigation. Natural fine and coarse aggregates (concreting sand and granite respectively) were used for preparation of the concrete specimens. Both materials were tested and validated against the requirements stipulated in SS EN 12620 (SSC, 2008a) and SS 31 (SSC, 1998). The two types of admixtures selected for the study, namely a retarder and a water-reducing agent, were in compliance with SS 320 (SSC, 1987).

Concrete mix proportions

Based on a previous study conducted by Ho *et al.* (2013), a rational mix design method was adopted to address the high absorption properties of RCA. The key to this rational mix design method is the direct replacement of granite with RCA (i.e. by mass of coarse aggregate) while keeping both cement and water contents constant for a particular mix design. Due to the absorptive properties of RCA, the workability of RCA concrete can be addressed by adding water-reducing agent. As such, the property of fresh concrete can be reinstated back to the desired workability without affecting the integrity of the hardened concrete.

The 28 d compressive strength test results are shown in Figure 2 for different w/c ratios (0·35–0·67) and RCA replacement levels (0%, 20%, 40%, 60%, 80% and 100%). The concrete mixes with up to 40% RCA replacement level all showed higher compressive strength than the control mix (i.e. 0% RCA) for w/c $\geqslant$ 0·45. For w/c $<$ 0·45, a reduction in strength was observed when the RCA replacement level was more than 40%, albeit the drop was not

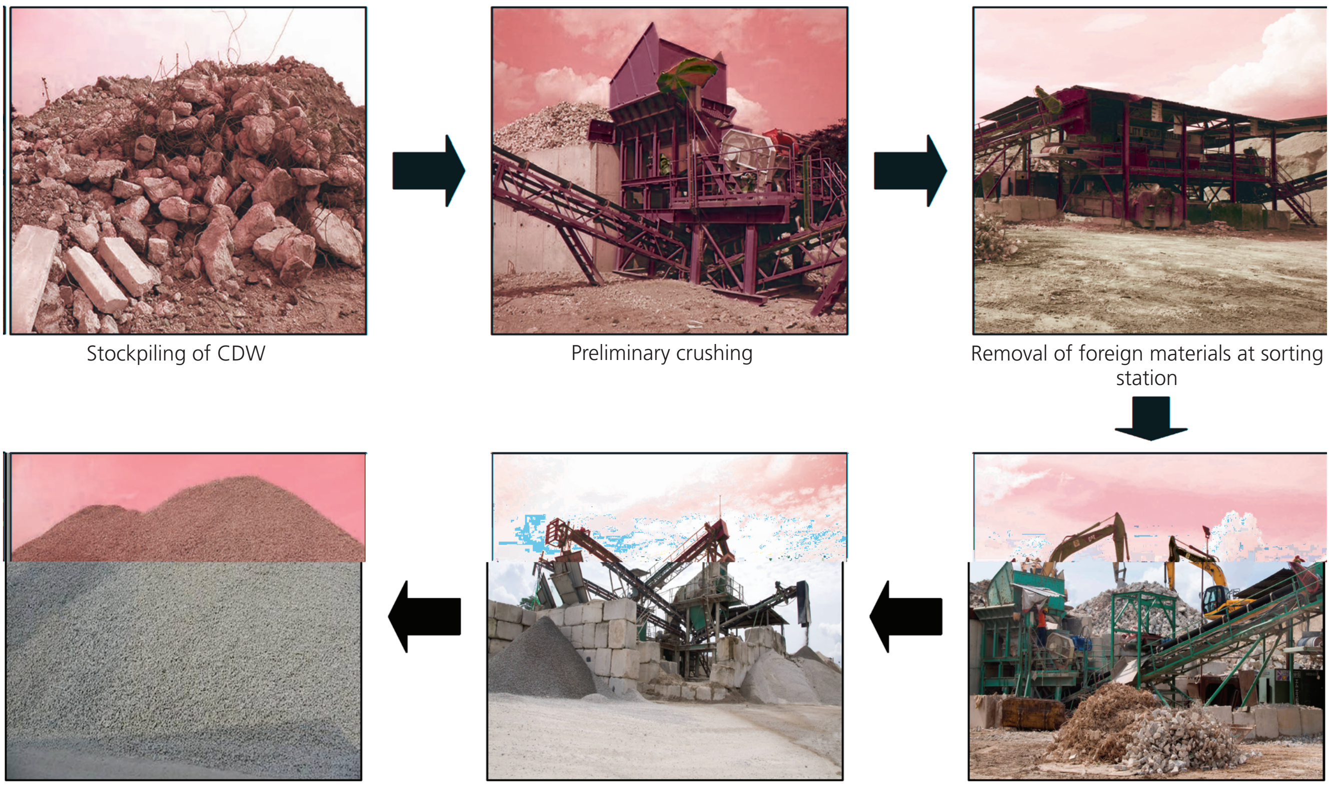


Figure 1. Processing of CDW into RCA

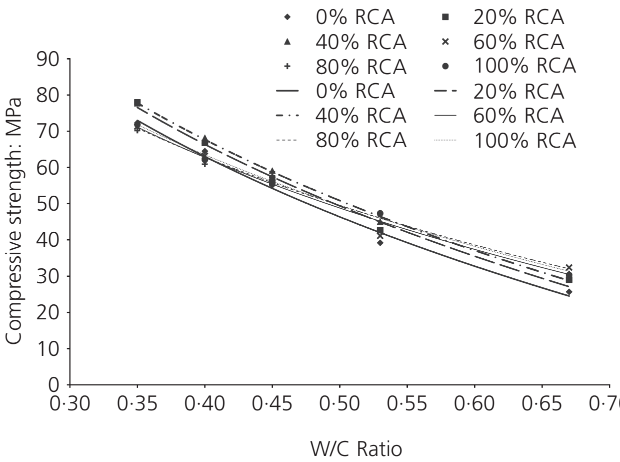


Figure 2. 28 d compressive strength of concrete containing different RCA contents at various w/c ratios

significant based on student's *t*-test at 5% significance level (Ho *et al.*, 2013). This phenomenon will be explained in detail in the next section.

The concrete design mix with a w/c ratio of 0·45 was thus selected for the next stage of the research study, an in-depth study of the engineering properties and durability characteristics of hardened concrete. Concrete mixes containing 0% RCA (M0), 30% RCA (M30), 50% RCA (M50) and 100% RCA (M100) were chosen for the in-depth study, with M0 serving as a basis for comparison.

Test programme for RCA concrete

Table 1 summarises the properties investigated conforming to standards and in-house test methods, the types, sizes and quantities of specimens prepared and their curing regimes. Table 2 describes the different curing regimes for the respective tests.

Property	Specimen size: mm	Specimen type	Number of specimens per mix	Curing regime (see Table 2)	Test method
Compressive strength	100	Cube	27	C1	BS EN 12390-3 (BSI, 2009a)
Flexural strength	100 × 100 × 500	Beam	9	C1	BS EN 12390-5 (BSI, 2009b)
Tensile splitting strength	∅150 × 300	Cylinder	9	C1	BS EN 12390-6 (BSI, 2000)
Creep	∅100 × 200	Cylinder	2	C2	In-house method with reference to ASTM C512-02 (ASTM, 2002)
Initial surface absorption	150	Cube	9	C3	BS 1881-208 (BSI, 1996)
Water permeability	150	Cube	9	C3	BS EN 12390-8 (BSI, 2009c)
Resistance to chloride ingress	∅100 × 50	Cut cylinder	6	C4	ASTM C1202-09 (ASTM, 2009a)
Resistance to sulphate attack	50×50 × 200	Prism	3	C2	In-house method with reference to ASTM C1012-09 (ASTM, 2009b)

Table 1. Tests on the properties of hardened concrete

	Curing regime
C1	Curing in water at 25 ± 3°C for 28 d; air-drying for 1 h before testing
C2	Curing in water at 25 ± 3°C for 28 d; carrying out initial measurement while specimen in saturated surface-dry condition
C3	Curing in water at 25 ± 3°C for 28 d; oven drying for 24 h; cooling to ambient temperature for 24 h before testing
C4	Curing in water at 25 ± 3°C for 24 d; air drying for 1 h before applying a layer of coating on the side surface of specimen; conditioning of specimen in accordance with ASTM C1202-09 before testing

Table 2. Description of different curing regimes

At present, there is no commercially available laboratory equipment for creep testing as described in ASTM C512-02 (ASTM, 2002). A specially designed creep testing equipment was thus developed and assembled to assess the influence of RCA on creep of concrete specimens (Figure 3). The equipment consists of a solid metal frame and hydraulic cylinder pumps driven by an air compressor. The main feature of the equipment is its capability to automatically detect and adjust to any drop in sustained stress when the concrete specimens deform. In turn, the required stress could be sustained throughout the measuring duration. Moreover, the equipment was able to provide simultaneous axial loading on six cylindrical specimens with different levels of pre-determined stresses. Nevertheless, the procedures for measurement were still in compliance with ASTM C512-02.

Results and discussion

Compressive strength

As shown in Figure 4, the concrete mixes with different RCA contents had comparable 3 d, 7 d and 28 d compressive strengths. This outcome validated the findings of Ho *et al.* (2013), with compressive strengths of RCA concrete tending to be comparable to the control mixes for w/c $\geqslant 0{\cdot}45$ (see Figure 2). This phenomenon could be attributed to two factors – the effective w/c ratio and the interfacial transition zone (ITZ). Indeed, there was a reduction in the effective w/c ratio of RCA concrete due to its absorptive nature. In general, the higher the replacement level, the lower the effective w/c ratio. On the other hand, there was only one ITZ for the control mix whereas RCA concrete has two ITZs – the interface between NCA and adhered mortar ('old ITZ') and the interface between adhered mortar and new mortar ('new ITZ').

Otsuki *et al.* (2003) explained that the 'new ITZ' governed the strength performance of concrete, noting that the new ITZ was weaker than the old ITZ. Furthermore, the cracks that occurred were not only confined to the surroundings of the old ITZ of RCA concrete but also appeared throughout the new mortar matrix. A similar distribution of cracks was observed in the control mix. Therefore, the old ITZ did not have much influence on the strength performance of concrete. Conversely, for mixes with w/c $< 0{\cdot}45$, the compressive strength of RCA concrete was slightly lower than that of control mix, although the reduction was not significant. This is largely due to the stronger new ITZ compared with the old ITZ; because of the dominance of the new ITZ, the old ITZ became a contributory factor for the strength performance of concrete. Neville (1995) also noted that the influence of the type of coarse aggregate on the strength of concrete varied in magnitude and depended on the w/c ratio of the mix. For w/c $< 0{\cdot}40$, concrete strength is affected by the properties of the aggregate rather than the strength of the mortar. With an increase in w/c ratio, the influence of aggregate falls off, presumably because the strength of the mortar itself becomes paramount. As the strength of mortar depends greatly on the mortar class, a lower effective w/c ratio should produce higher mortar strength and, consequently, the strength of concrete should be enhanced.

As noted earlier, a two-stage crushing procedure was used to produce RCA of the highest quality, with a minimal amount of adhered cement paste and better angularity. Moreover, the RCA used had a minimal foreign materials content (less than 6%) and this would also play an important role in RCA concrete achieving strength comparable to that of NCA concrete.

Strength in tension

A comparison of the flexural strength test results of M0, M30, M50 and M100 is presented in Figure 5. It is interesting to note that flexural strength showed an increasing trend with an increase in RCA replacement level, with M100 achieving the highest flexural strength of all the different concrete mixes. The flexural strength of the various concrete mixes was confined to a narrow range of 3·39–3·88 MPa. Based on statistical analysis, at a 95% level of confidence, there was no significant difference in flexural strength for M30 and M50 compared with M0, but M100 showed a significant difference in flexural strength compared with M0. Likewise, the tensile splitting strength test results for different RCA replacement levels were confined to a narrow range of 3·11–3·33 MPa, as shown in Figure 6. At a 95% confidence level, the splitting tensile strengths of M30, M50 and M100 did not show any significant difference when compared with the corresponding property of M0.

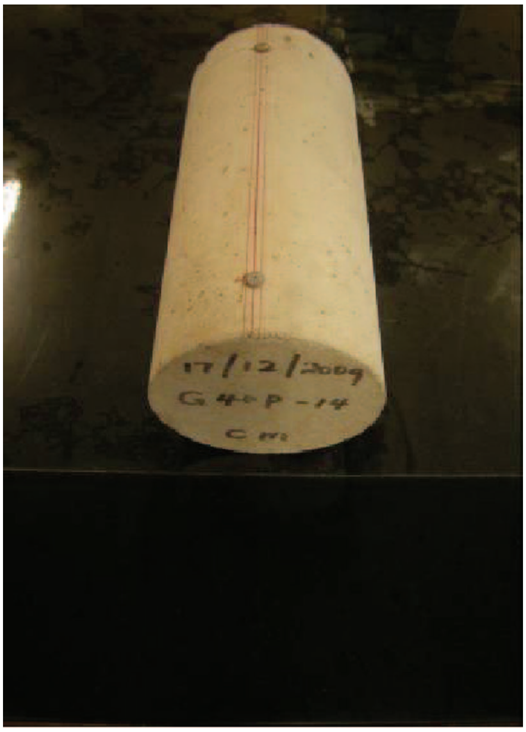
Based on the test results, concrete made with RCA produced higher or statistically comparable strength in tension with respect to concrete made with NCA. These findings appear to differ from some previous research works (Bairagi *et al.*, 1993; Park, 2001; Tabsh and Abdelfatah, 2009), but it is possible to provide some explanations for the contradictions.

Firstly, flexural strength is a direct function of the aggregate characteristics and is sensitive to the presence of coarse aggregate. The inclusion of coarse aggregate in concrete may not change the essential microstructure of the cement gel, but generally tends to convert a homogeneous matrix into a heterogeneous system. For low- and medium-strength concretes, the aggregate properties, especially shape and surface texture, have a greater impact on the strength in tension than the ultimate strength in compression (Neville, 1995). Since RCA is more angular in shape than NCA (Ho *et al.*, 2013), RCA has a tendency to provide better mechanical interlocking between itself and the mortar matrix.

Secondly, Kheder and Al-Windawi (2005) demonstrated that the tensile strength of RCA concrete was lower than that of its mortar matrix as the tensile bond strength of the ITZ was much lower than the tensile strength of the mortar matrix itself, particularly at high strength levels. The tensile strength of the mortar matrix thereby sets the upper limit for the tensile strength of RCA concrete. In fact, the existence of coarse aggregate in the concrete

Hydraulic system driven by air compressor

Metal frame for specimen loading



Attachment of locating discs on specimen

Taking measurement after loading with Demec gauge

Figure 3. Components and functioning of in-house creep testing equipment

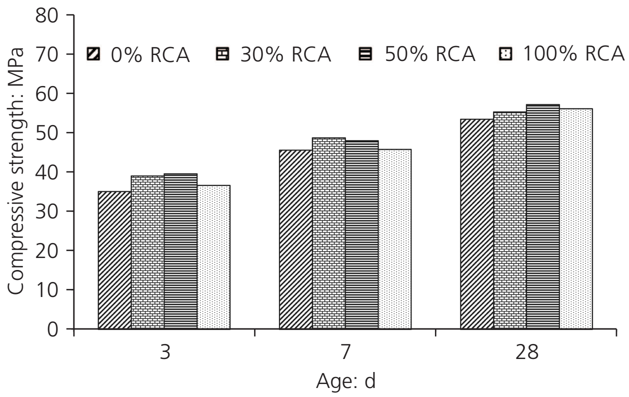


Figure 4. Compressive strength – average test results for concrete with different RCA replacement levels

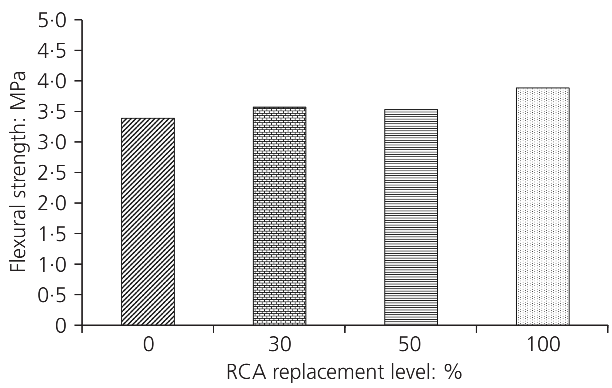


Figure 5. Flexural strength – average test results for concrete with different RCA replacement levels

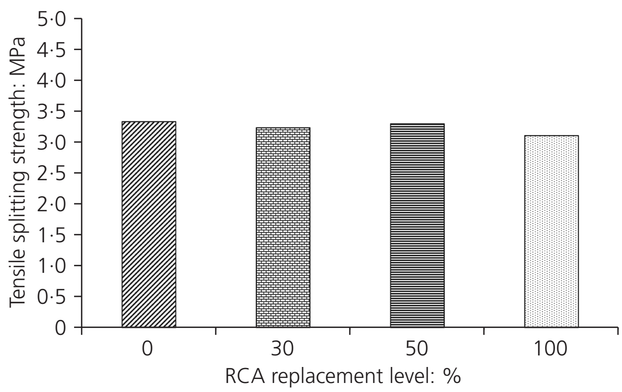


Figure 6. Tensile splitting strength – average test results for concrete with different RCA replacement levels

frame will prevent the concrete from reaching the ultimate tensile strength of the mortar matrix. This is probably due to the existence of very fine cracks at the ITZ, even prior to the application of load on concrete (Hsu *et al.*, 1963). This scenario may be attributed to the inevitable differences in mechanical properties of the coarse aggregate and the mortar matrix, coupled with different coefficients of thermal expansion and different responses to changes in moisture content (Mindess *et al.*, 2003; Neville, 1995). Nevertheless, the influence of the type of coarse aggregate on the strength of concrete varies in magnitude and depends on the w/c ratio of the mix. For w/c $> 0{\cdot}40$, the effects of the aggregate are likely to diminish and a concrete mix with a better mortar class will tend to attain a greater strength level (Neville, 1995). RCA concrete should thus attain better tensile strength than a control mix due to its enhanced mortar class as a result of the lower effective w/c ratio.

Evidence for the enhancement of mechanical interlocking between RCA particles and the mortar matrix can be obtained by observation of the fracture surfaces. Apart from the failure at the matrix itself, the fracture planes were primarily located at the ITZ and through coarse aggregates for M0 (Figure 7(a)). For the RCA concrete, the fracture planes were primarily through old mortar particles and coarse aggregates (Figure 7(b)). The interfaces between the old mortar and the new matrix generally remained intact, which implies good interfacial bonding.

Creep

Figure 8 shows that M0, M50 and M100 showed similar trends in the development of total deformation due to creep, although M50 and M100 showed higher creep that than M0, by about 8% and 15% respectively. After subjecting the specimens to sustained stresses for about 7 months, the average total deformation of two specimens of each concrete mix was in a narrow band of 2100–2600 microstrain.

As shown in Figure 9, specific creep increased with an increase in RCA replacement level. With respect to M0, the increase in specific creep was about 18% and 25% for M50 and M100 respectively. On the other hand, the creep coefficient values of

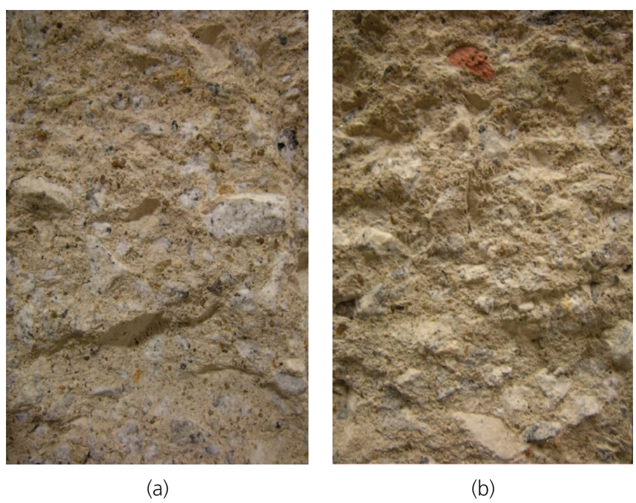


Figure 7. Spilt specimens for M0 (a) and M100 (b)

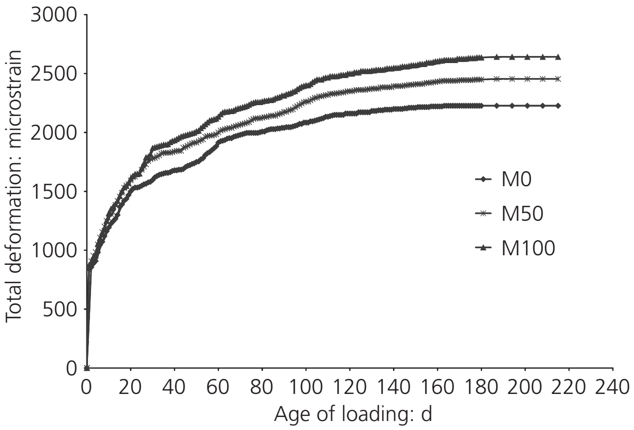


Figure 8. Average total deformation for M0, M50 and M100

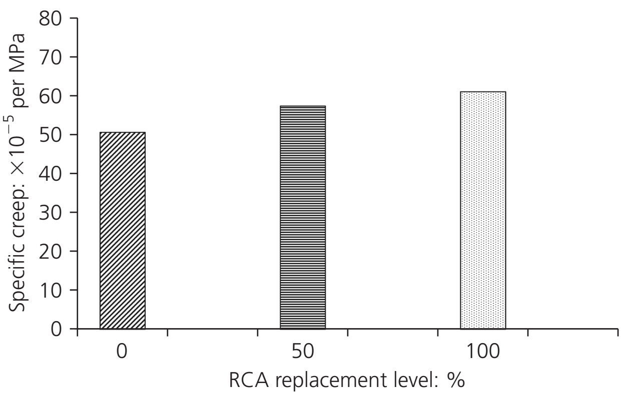


Figure 9. Specific creep for M0, M50 and M100 after 180 d of loading

M0, M50 and M100 were 1·27, 1·43 and 1·53 respectively (see Figure 10). Compared with M0, the creep coefficients of M50 and M100 were respectively about 13% and 21% higher. The increment in creep strain might be attributed to the lower

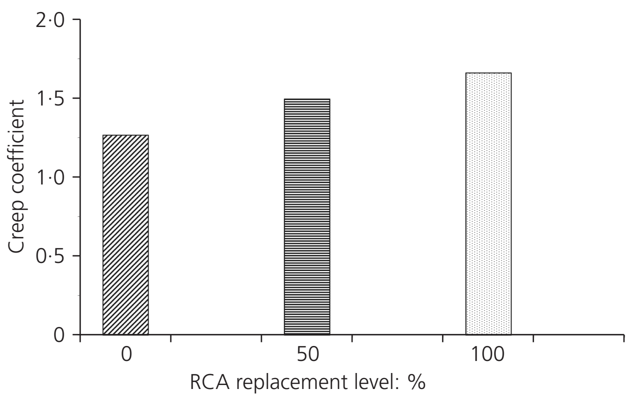


Figure 10. Creep coefficient for M0, M50 and M100 after 180 d of loading

restraining capacity of RCA particles and the presence of a creeping mortar component in RCA (Ravindrarajah and Tam, 1985). Moreover, the porosity of RCA plays a direct role in the transfer of moisture within concrete and this transfer produces conditions conducive to the development of drying creep (Neville, 1995).

Gómez-Soberón (2002), Limbachiya *et al.* (2004) and Domingo-Cabo *et al.* (2009) reported that concrete with up to 100% RCA replacement level experienced more than 50% higher creep when compared with a control mix. The difference in these results and those obtained in the current study could be attributed to a number of factors. Firstly, it has been found that the creep–stress relationship is non-linear for all values of stress, but is approximately linear in the stress range generally used (i.e. between 0·4 and 0·6 of the ultimate compressive strength) (Mindess *et al.*, 2003; Young *et al.*, 1998). With comparable strength development for M0, M50 and M100 (refer to Figure 2), the variations in creep strain for the control mix and RCA concrete should be within a confined range.

Furthermore, it is really the hydrated cement paste that undergoes creep, while the aggregate is usually not liable to creep under the stresses existing in the concrete. Creep is, therefore, a non-linear function of the volumetric content of cement paste in concrete (Neville, 1995). As the role of the aggregate in concrete is primarily that of restraint, an increase in aggregate content by volume of 65–75% can decrease creep by 10% (Neville, 1964). The direct replacement method adopted in this study tends to result in relatively higher volumes of aggregate content in RCA concrete than in the control mix and this might help to mitigate the adverse effect of low elastic modulus of RCA in the creep of concrete to a certain extent. Furthermore, at a constant w/c ratio, the variations in the volume of hydrated cement paste for different concrete mixes should fluctuate within a narrow range and hence the effect of hydrated cement paste in creep was consistent among the various concrete mixes. Unlike in many other studies, in order to achieve equivalent strength for both the control mix and RCA concrete, additional cement content was added to the RCA concrete and, as a result, the formation of larger volumes of hydrated cement paste may have caused higher creep deformation.

Initial surface absorption

As shown in Figure 11, the various concrete mixes showed a similar trend for the initial surface absorption test (ISAT) at stipulated intervals of 10 min (ISAT-10), 30 min (ISAT-30) and 60 min (ISAT-60). Mix M0 had the lowest ISAT values at the respective intervals. While all the RCA concrete mixes registered higher ISAT values than M0, the differences were less than 20%. Moreover, the ISAT values of M30 and M50 were almost identical except at the initial point, whereas there was an obvious increase in ISAT values when the RCA content was increased up to 100%. This phenomenon could be due to the residual mortar attached to the aggregate particles, which served as a potential

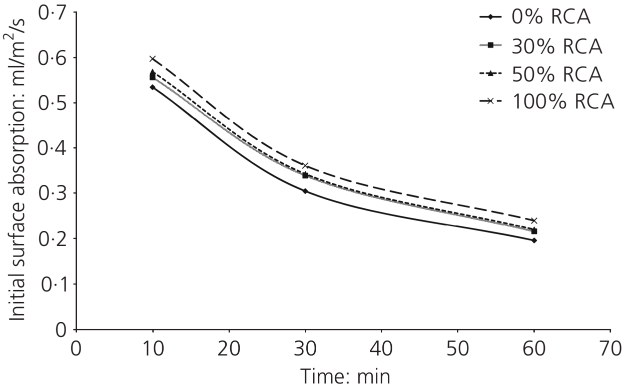


Figure 11. Initial surface absorption for concrete with different RCA replacement levels

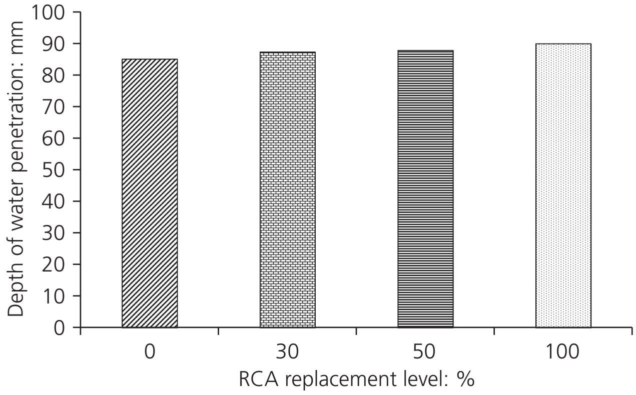


Figure 12. Depth of water penetration under pressure for concrete with different RCA replacement levels

conduit for moisture transport. The high ISAT-10 of M100 could also be associated with an increase in the effective path length for moisture movement and the effective areas over which flow can take place as the porosity of RCA concrete is higher than that of M0. As the tests continued, the absorption rates decayed for all concrete mixes containing different RCA contents since the capillary pores near the surface of the tested specimens became saturated with water. Furthermore, since the different concrete mixes underwent similar pre-conditioning treatments, the dilution of moisture gradient should be consistent with the increase in distance away from the surface.

Although an ISAT-10 value of 0·5 ml/(m^2/s) is usually considered to be high, which might be attributed to the fact that the specimens were oven dried at 105±5°C for 24 h and the surfaces were cooled down to ambient temperature prior to testing, Price and Bamforth (1993) reported that a value of 1·0 ml/(m^2/s) is approximately the upper limit of performance for typical natural aggregate concrete. The results obtained in this study would suggest that all the concrete mixes have a reasonably average quality surface and would provide satisfactory resistance to the ingress of harmful substances.

Water permeability

As shown in Figure 12, the depth of water penetration increased with increasing RCA content. Once again, the range of water penetration for the control mix and concrete with different RCA replacement levels was within a narrow scope of 85–90 mm. In addition, the difference in water penetration between M0 and M100 was only about 6%.

In an effort to correlate the direct measurement of water flowing through a concrete specimen to the coefficient of permeability, an expression was developed by Valenta (1969) to convert depth of water penetration into the coefficient of permeability, which is equivalent to that used in Darcy's law

$$K = \frac{e^2 v}{2ht_p} \quad (1)$$

Based on this equation, the relevant parameters were translated to the specified units and the volume of pores that may exist within the concrete was assumed to be 2% since this value was alleged to be the expected air content during the formulation of the concrete mix design. Together with the pertinent parameters for the computation of the coefficient of permeability, the values of K for the range of concrete mixes are given in Table 3. The results illustrate that K increased with an increase in RCA content, but the differences were capped at about 18%. Although the coefficient of permeability of M100 seemed to be the highest of all the concrete mixes, the difference can be regarded as insignificant since all values were the same order of magnitude (Neville, 1995).

Larger water penetration depths and coefficients of permeability were expected for RCA concrete than for M0 due to the porosity of attached mortar, which offers a shorter flow path for moisture to circumvent the aggregate particles. However, the incorporation of RCA did not seem to have immense detrimental effects on the permeability characteristics of concrete as the differences were minor. This phenomenon could be explained by the fact that w/c ratio is the single parameter that has the largest influence on durability. The w/c ratio has a dual role to play in concrete durability since a lower w/c ratio also increases concrete strength and hence improves resistance to cracking from internal stresses that may be generated by adverse reactions (Mindess *et al.*, 2003). In general terms, it is possible to say that the higher the strength of the concrete, the lower its permeability – a state of affairs to be expected because strength is a function of the relative volume of gel in the space available to it. Besides, permeability of concrete is not a simple function of its porosity but also depends on the size, distribution, shape, tortuosity and

Fraction of concrete volume occupied by pores, υ	0·02 (assumed)
Hydraulic head, h: m	50·97 (≈ 5 bar)
Test duration, t_p: s	259 200
Coefficient of permeability, K: m/s	
M0	$5{\cdot}21 \times 10^{-12}$
M30	$5{\cdot}47 \times 10^{-12}$
M50	$5{\cdot}34 \times 10^{-12}$
M100	$6{\cdot}13 \times 10^{-12}$

Table 3. Coefficients of permeability of control mix and various RCA concretes

continuity of the pores. In other words, it is not appropriate to conclude that concrete is permeable if its porosity is high (Neville, 1995).

Apart from the permeability of the cement paste, the permeability of the aggregate particles and the ITZ will also affect the behaviour of concrete. The microstructural features of the ITZ in concrete are considerably different from those of the bulk matrix and the ITZ is considered the 'weakest link' in concrete, providing a favourable path for the transportation of water. This is even more likely since the ITZ is also the locus of early microcracking. Moreover, on average, the ITZ occupies about 30–50% of the total volume of cement paste in concrete. For these reasons, the ITZ can be expected to contribute significantly to the permeability of concrete (Young, 1988). However, despite the higher porosity of the ITZ, the permeability of concrete is controlled by the bulk of the hardened cement paste, which is the only continuous phase in concrete (Larbi, 1993). On the other hand, although the old mortar of RCA might contain additional pores, the RCAs are enveloped by new cement paste so that RCA pores do not contribute directly and significantly to the permeability of concrete. On the whole, neither the aggregate particles nor the ITZ seem to contribute much to the permeability.

According to the comparable strength test results obtained in this study, the control mix and RCA concretes should achieve more or less similar permeability for the new cement paste. However, the major difference still lay in the attached mortar, whereby it reduced the path length for moisture movement and resulted in relatively higher permeability of concrete. Nonetheless, this effect was minimised because the permeability of hydrated cement paste was still the major contributory factor that governed the permeability of concrete. By and large, the permeability of the control mix and RCA concretes should not differ much.

Chloride ingress

Based on charge passed at the end of the testing duration, the concrete specimens with various RCA contents were categorised into different permeability classes in accordance with table 1 of ASTM C1202-09 (ASTM, 2009a). The majority of the concrete mixes fell within the permeability class of 'moderate' while a few were classified as 'low'. Unlike specimens of the control mix with all having charge passed in the range 2000 C to 3300 C, some of the RCA concrete specimens recorded values of less than 2000 C. On average, the charge passed for M0, M30, M50 and M100 was 2100–2530 C, with RCA concretes showing less charge passed than M0 (see Figure 13). This phenomenon could be attributed to the latent chloride binding capacity of cement hydrates contained in RCA.

In fact, it is not the total chloride content that is relevant to corrosion. The rate of chloride penetration into concrete is affected by the chloride binding capacity of the concrete. Concrete is not inert relative to the chlorides in the pore solution. A part of the chlorides is physically bound by adsorption onto the surface of calcium silicate hydrate (CSH) while another part of the chlorides is chemically bound by the products of hydration of cement, namely the AFm phase (a group of minerals). It is only the third part of the chlorides, known as free chlorides, that is available for the aggressive reaction with steel. Nevertheless, the distribution of chloride ions among the three forms is not permanent as there is an equilibrium situation where some free chloride ions are always present in the pore solution. It follows that only the chloride ions in excess of those needed for this equilibrium can become bound (Marinescu and Brouwers, 2009; Neville, 1995). As the binding removes chlorides from the pore solution, it affects the time for corrosion initiation in two ways – the chloride ingress rate is decreased and the chloride threshold value, expressed as total chloride content (free and bound), is increased (Nilsson *et al.*, 1996). Other than the composition of cement, the resistance to chloride diffusion also depends on the concentrations of free chlorides in the pore solution, the w/c ratio, the temperature, degree of carbonation and pH of the pore solution (Marinescu and Brouwers, 2009).

The presence of adhered mortar on the surfaces of RCA might provide an additional source of calcium silicate hydrate and AFm phase to enhance the chloride binding capacity of RCA concrete. Conversely, the influence of porosity on the chloride ingress rate must be taken into account and these two effects may counteract each other or one may prevail over the other. Hence, the chloride binding capacity of RCA concrete has to be demonstrated and quantified. Villagrán-Zaccardi *et al.* (2008) confirmed that the influence of w/c ratio on chloride ingress rate was more important

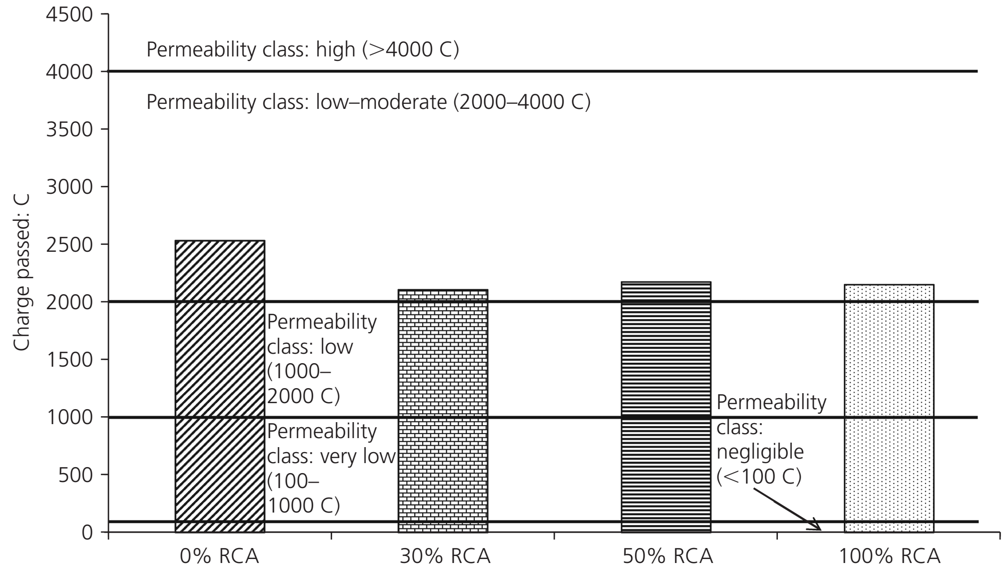


Figure 13. Classification of chloride permeability classes for M0, M30, M50 and M100

than that of aggregate porosity. They also reported that, due to the introduction of supplementary binding capacity to the cement matrix, RCA concrete possessed a larger binding capacity than the control mix. However, the key factors contributing to the binding capacity of the matrix were the type and amount of cementitious materials, with the former exerting a greater influence than the latter.

The findings of Villagrán-Zaccardi *et al.* (2008) could possibly be applied in this study with regard to the better performance of RCA concrete over the control mix in the aspect of chloride diffusion. Based on the same type of cement used and constant w/c ratio, all the concrete mixes should demonstrate some level of consistency in the chloride binding capacities while the chloride ingress rates should be in a close range. Owing to the presence of old mortar, RCA concrete might acquire more products of cement hydration than the control mix. As a result, the excess free chloride ions that exist in pore solution would be more readily bound by the hydration products of cement, both chemically and physically. Hence, the concentrations of free chlorides in the pore solution due to ionic movement decrease with an increase in RCA content. In turn, the total charge passed registered by the datalogger would reduce accordingly. Since porosity tends to modify the structure of the ITZ and develop into a preferential path for ion transport, the advantage of the higher chloride binding capacity of RCA concretes might be partially overridden by their porous nature.

Sulphate resistance

Concrete is rarely, if ever, attacked by solid and dry chemicals. In order to produce significant attack on concrete, corrosive chemicals must be in solution form and above some minimum concentration. Thus, the standard exposure solution used in this study contained 50 g/l of sodium sulphate and the concrete prisms were immersed in the solution for up to 15 weeks. The length change was measured using a length comparator at stipulated intervals.

The linear expansions (longitudinal surface) of M0, M50 and 1
M100 were found to increase with an increase in RCA content,
as shown in Figure 14. However, the expansions remained within 2
a relatively narrow band (0·0103–0·0120%) and did not show any significant difference at the 95% confidence level. In addition, the RCA concretes showed a rapid expansion at the early stage, which remained after 10 weeks of monitoring whereas the control mix expanded at a fairly constant rate throughout the testing period. The trend observed could be due to the readily available pathways for ion diffusion within the internal structure of RCA concrete and an equilibrium state would be realised sooner as the

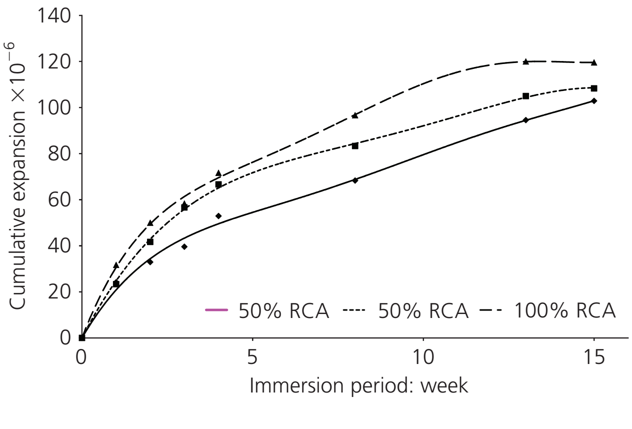


Figure 14. Effect of sulphate solution on the concrete mixes with various RCA replacement levels

concentration gradient tend to diminish at a faster pace. Again, the expansion experienced by the specimens could be partially due to the continued hydration of cement, which results in some additional swelling so that there was a net increase in dimensions. This scenario was made possible since the specimens were stored in a solution mainly made up of water for a sufficient duration. Moreover, the tested specimens did not seem to behave in unusual ways such as warping by placing on a plane surface or the development of visible cracks.

These observations indicate that the performance of RCA concrete in terms of resistance to external sulphate attack was comparable to that of the control mix and the influence of RCA on the migration of sulphate ions from an outside source was minimal. As long as the sulphate content of RCA is maintained at an acceptable level, RCA concrete should not be susceptible to damage from sulphate attack.

Conclusions

It is crucial to formalise a quality control protocol for the production of aggregates recovered from inert waste in order to safeguard the integrity of concrete that incorporates RCA. The establishment of acceptance criteria to provide adequate assurance in the quality of RCA is deemed necessary. Despite the differences in properties of RCA and NCA, concrete containing RCA can be formulated and proportioned so that there is minimal, if any, impact on either the fresh or the hardened properties of new concrete. In a nutshell, RCA concrete can be designed in its own right. The test data obtained in this research study have clearly demonstrated that mechanical properties (i.e. compressive strength, flexural strength and tensile splitting strength) of RCA concrete comparable to those of the control mix are achievable without adjustment to the w/c ratio. Furthermore, although some of the other engineering properties and durability characteristics (i.e. creep, initial surface absorption and water permeability) of RCA concrete might not be on par with the corresponding properties of a control mix, these differences were narrowed by use of the proposed rational design method.

Further to laboratory testing, a three-storey building (the Samwoh eco-green building) was constructed using concrete containing up to 100% RCA for all the structural elements. Since its completion in 2009, extensive structural health monitoring has been conducted using fibre optic sensors to analyse the structural behaviour of the RCA concrete. To date, deformation of the building has stabilised and no abnormality has been observed. The successful construction of the Samwoh building showcases a breakthrough in concrete technology, with the hope that RCA will become a common concrete constituent in the future.

Acknowledgements

Thanks go to Samwoh Corporation Pte Ltd (Samwoh) for generous funding of the entire project, kind permission granted for the use of the laboratory and the supply of materials for the research works. The Ministry of National Development and the Building & Construction Authority (BCA) of Singapore are gratefully acknowledged for their partial funding and full support of the research project. Apart from the aforementioned organisations, thanks also go to Mr Koh Hoon Lye (Samwoh) and Er. 3
Punithan Shanmugam (BCA), who formed part of the research team, for their advice, suggestions and contributions to the research project.

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1: Figure 14 shows 2 curves for 50% RCA: please advise
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