Cement & Concrete Composites 33 (2011) 286–291

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete

Shi-Cong Kou [a], Chi-Sun Poon [a,*], Miren Etxeberria [b]

[a] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Department of Construction Engineering, Faculty of Civil Engineering, 08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 18 February 2008
Received in revised form 5 October 2010
Accepted 6 October 2010
Available online 30 October 2010

Keywords:
Long-term properties
Porosity
Mechanical properties
Recycled aggregate concrete

ABSTRACT

This paper presents the results of a study of the long term mechanical properties and pore structures of recycled aggregate concrete. In this study, two different sources of recycled aggregates were used to replace natural aggregate at a level of 100%. The compressive and splitting tensile strength of the concrete were tested, and the pore structures of the concrete were analyzed. The results showed that after 5 years of curing, the recycled aggregate concretes had lower compressive strength and higher splitting tensile strength than the corresponding natural aggregate concrete. However, from 28 days to 5 years, the increase of compressive and splitting tensile strengths was more in the recycled aggregate concretes. After 5 years of curing, the concrete made with 100% of crushed old concrete aggregate had the lowest porosity. Good correlations were found between compressive and tensile strength and porosity.

1. Introduction

For a variety of reasons, reuse of construction and demolition (C&D) materials by the construction industry has become more significant. In addition to environmental protection, conservation of natural aggregate resources, shortage of waste disposal land, and increasing cost of waste treatment prior to disposal are the main reasons for the growing interest in recycling C&D materials [1]. Already many countries have introduced legislation and policy measures to encourage the use of recycled aggregates in civil engineering works. The potential benefits and drawbacks of using recycled aggregate in new concrete have been extensively studied [2–8].

Although much information is already available on the effect of recycled aggregate on the mechanical properties of the concrete up to a curing age of 90 days, the literature contains only a limited number of research results on the long term mechanical properties of recycled aggregate concrete [9–11].

The porosity of recycled aggregate concrete (RAC) is generally higher than that of natural aggregate concrete (NAC) due to the adhered mortar present in recycled aggregates [12]. The porosity and the pore size distribution are the most important characteristics of the pore system of concrete which influence the ingress of foreign substances to the interior of concrete [13,14]. It is therefore important to understand the development on the pore system in order to assess the durability properties of the recycled aggregate concrete.

According to Gomez-Soberon [15], RAC that were prepared with 100% recycled concrete as coarse aggregates (with natural sand and fine aggregates) had higher porosity than that of NAC. From the curing age of 28 days to 90 days, the total porosity of both the RAC and NAC was reduced but the reduction in the RAC was higher. Unfortunately data on the longer term (beyond 90 days) relationship between porosity and concrete properties of RAC are not available.

In this study, the influence of the two different sources of recycled aggregates on the long term mechanical properties and pore system of RAC that were prepared with 100% substitution of natural coarse aggregates was assessed. The effect of long-term (up to 5-years) water curing on the mechanical properties of the RAC was quantified.

2. Experimental details

2.1. Materials

2.1.1. Cement

ASTM Type I Portland cement was used in all concrete mixes and the corresponding properties are shown in Table 1. The water used was ordinary tap water. No superplasticizer was used in all the concrete mixes.

2.1.2. Aggregates

Natural and recycled aggregates were used as the coarse aggregates in the concrete mixtures. A locally available crushed granite was used as the natural coarse aggregate.

* Corresponding author. Tel.: +852 2766 6024.
E-mail address: cecspoon@polyu.edu.hk (C.-S. Poon).

0958-9465/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2010.10.003

Table 1
Chemical composition of cement.

Chemical composition	(%)
SiO_2	19.61
Fe_2O_3	3.32
Al_2O_3	7.33
CaO	63.15
MgO	2.54
SO_3	2.13
Loss on ignition (LOI)	2.97
Density (g/cm^3)	3.16
Specific area (cm^2/g)	3519

Two sources of recycled coarse aggregates were used. Both were recycled C&D waste sourced from two recycling facilities in Hong Kong. The first one, RA, contained mainly crushed natural stones such as granite and marble sourced from excavated work, and some old concrete rubbles and a very small amount of other impurities (0.2%), such as small pieces of wood, tiles and metals. The impurities were not removed before the experiment as the very small percentage of impurities should not have a significant effect of the properties of the aggregate [6]. The second source of recycled aggregate contained almost entirely of crushed concrete rubbles obtained mainly from building demolition projects. To ascertain that the this batch of recycled aggregate contained only crushed concrete, a hand picking step was also made to select crushed concrete lumps (>100 mm 100% old concrete) from the recycled aggregate obtained from the second recycling plant and they were further crushed in the laboratory using manual and mechanical means. This specifically sorted recycled aggregate was referred to as RCA. The constituents of the recycled aggregate are shown in Table 2.

Recycled and natural coarse aggregates used had the same nominal size, 10 mm and 20 mm. The properties of the natural and recycled aggregates were tested according to British Standard methods [16,17] as shown in Table 3. The MIP porosities of the aggregates were determined using a method reported previously [8]. Moreover, natural river sand with a fineness modulus of 2.11 was used as the fine aggregate in all the concrete mixtures.

2.2. Concrete mix proportions

A total of three concrete mixes were produced namely, control concrete (CC) and two RAC concretes (with 100% recycled coarse aggregates) namely RCA-C and RA-C, respectively. All concrete mixes were prepared with a constant water-to-cement ratio (w/c) of 0.55 and a cement content 355 kg/m^3. The mix proportions were designed by assuming the aggregates were in saturated-surface-dry condition and appropriate moisture adjustments were made to cater for the different water absorption properties of the aggregates before batching. The absolute volume method was adopted to design the concrete mix proportions as shown in Table 4. In each concrete mixture, the 10 and 20 mm coarse aggregates were used in a ratio of 1:2.

Table 2
Constituents of recycled aggregates.

Material	Constituents (% by weight)	
	RA	RCAL
Old concrete	10	100
Excavated natural stone	89.8	0
Other impurity (tile, timber, etc.)	0.2	0

Table 4
Mix proportions of concrete mixtures.

Notation	Recycled aggregate (%)	Constituents (kg/m^3)				
		Water	Cement	Sand	Granite	Recycled aggregate
CC	0	195	355	690	1127	0
RCA-C	100				0	1038
RA-C	100				0	1068

Table 5
Compressive strength of concrete mixtures.

Notation	Recycled aggregate (%)	Compressive strength (MPa)			Gain from 28 days to 5 years (%)
		28 days	1 year	5 years	
CC	0	43.8	53.7	58.9	34
RCA-C	100	34.3	48.8	55.4	62
RA-C	100	35.6	49.2	54.1	52

2.3. Specimen preparations

100 × 100 × 100 mm cubes and 200 × 100 diameter cylinder specimens were cast to determine the compressive strength, splitting tensile strength and the pore structures of the concretes. All specimens were cast in steel molds and compacted using a vibrating table. After casting, the specimens were covered with a plastic sheet, cured in air for a period of 24 h, and then demolded. After demolding, the specimens were cured in a water tank at 27 ± 1 °C until the test ages (28 days, 1 year and 5 years) were reached.

For the Mercury Intrusion Porosimetry (MIP) test, two small concrete cores, of 21 mm in diameter × 25 mm in length, from the centre of the cast specimens were extracted with a diamond drill. The extracted concrete cores were soaked in acetone for stopping the hydration, and then dried in a vacuum oven at 60 °C for 48 h before MIP testing.

2.4. Testing

The compressive and splitting tensile strength tests were measured at the curing time of 28 days, 1 year and 5 years by a Denison compression machine with a loading capacity of 3000 kN. The loading rates for the compressive and splitting tests were

Table 3
Properties of natural and recycled coarse aggregates.

Type	Nominal size (mm)	Density (kg/dm^3)	Water absorption (%)	Strength-10% fines value (kN)	MIP porosity (%)
Crushed granite	10	2.62	1.12	159	1.62
	20	2.62	1.11		
Recycled concrete aggregate (RCA)	10	2.35	7.42	110	8.46
	20	2.45	5.63		
Recycled aggregate (RA)	10	2.41	3.42	131	3.02
	20	2.52	2.63		

Table 6
Splitting tensile strength of concrete mixtures.

Notation	Recycled aggregate (%)	Splitting tensile strength (MPa)			Gain from 28 days to 5 years (%)
		28 days	1 year	5 years	
CC	0	2.43	2.94	3.32	37
RCA-C	100	2.21	3.12	3.64	65
RA-C	100	2.26	3.07	3.52	56

200 kN/min and 57 kN/min in accordance with BS 1881 Part 16 [18] and BS 1881 Part 117 [19], respectively. The testing of MIP was performed with a 'Micromeritics Poresizer 9320' mercury intrusion porosimeter according to BS7591 Part 1 [20].

3. Results and discussion

3.1. Compressive and splitting tensile strength

The results of compressive strength of the prepared concrete mixes are shown in Table 5. Each presented value is the average of three measurements. It can be seen that at the first two test ages the compressive strength of the recycled aggregate concretes were lower than that of the CC. At 28 days, the compressive strength of the RCA-C and RA-C, were reduced by 21.7% and 18.8%, respectively, when compared with the CC. However, the reduction of compressive strength had decreased after 5 years to 6.3%, and 8.9%, respectively.

Table 5 displays the strength gain of the concrete from 28 days to 5 years. The concrete mixture RCA-C had the highest strength gain of more than 60%. Although the control concrete (CC) had the highest compressive strength at 28 days, it showed the lowest strength gain after 5 years.

The splitting tensile strengths of the concrete mixes are presented in Table 6. At 28 days, when compared with CC, the splitting tensile strength of the two types of RAC, RCA-C and RA-C, were lowered by 10.0% and 7.0%, respectively. The 5-years results indicated that there was significant improvement in splitting tensile strength of the RAC and the strength values are higher than that of the control. Table 6 indicates that the splitting tensile strength of the CC had increased by 37% between 28 days and 5 years. RCA-C had the highest splitting tensile strength gain of 65% and RA-C 56%.

The higher strength gain after 5 years of curing, in particular the splitting tensile strength, of the RAC might be due to the fact that the presence of the recycled concrete aggregate improved the microstructure of the interfacial transition zone (ITZ) and

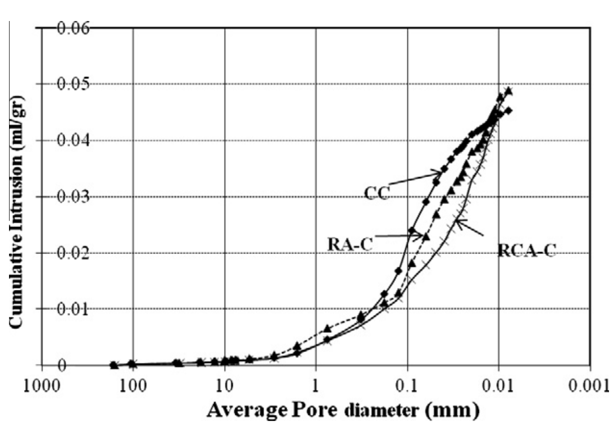

Fig. 1. Pore size distribution of concretes at 28 days.

increased the bond strength between the new cement paste and the old aggregates after continuous hydration. An improvement in bond would induce a higher increase in tensile strength rather than compressive strength [21]. The self-cementing ability of recycled aggregate may also have contributed to the increase in strength [22].

3.2. Porosity and pore size distribution

The pore structures of the samples CC and RA-C were also measured at 28 days, 1 year and 5 years. However, the pore structures

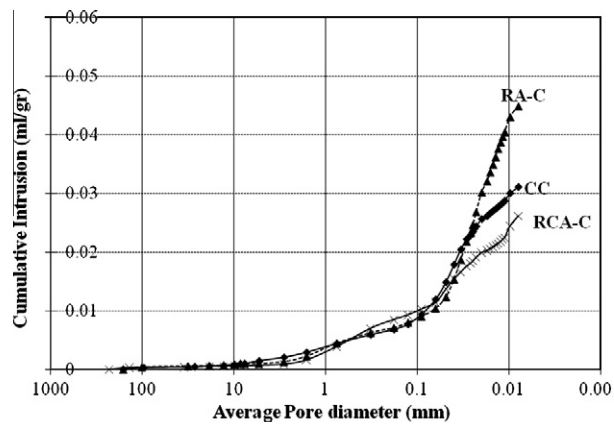

Fig. 2. Pore size distribution of concretes at 5 years.

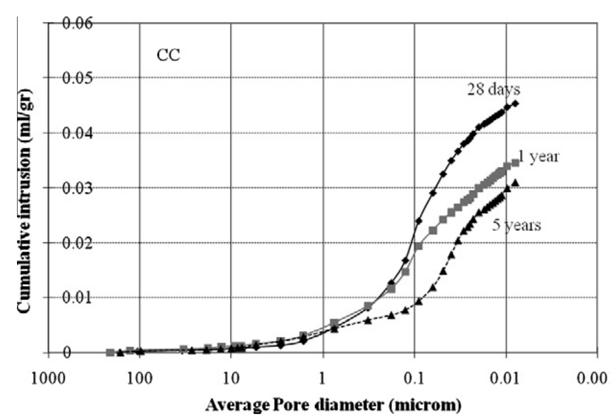

Fig. 3. Development of pore size distribution in CC mixtures at 28 days, 1 year and 5 years.

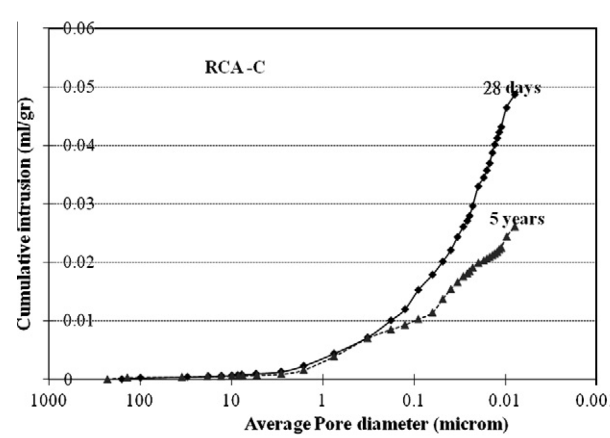

Fig. 4. Development of pore size distribution in RCA-C mixtures at 28 days and 5 years.

Table 7
Porosity of concretes.

Notation	Porosity (%)			% Decrease from 28 days to 5 years	Average pore diameter (μm)		
	28 days	1 year	5 years		28 days	1 year	5 years
CC	10.21	8.21	7.26	28.94	0.047	0.043	0.031
RA-C	10.79	10.44	9.99	7.37	0.024	0.025	0.028
RCA-C	10.91	ND	6.01	44.89	0.029	ND	0.023

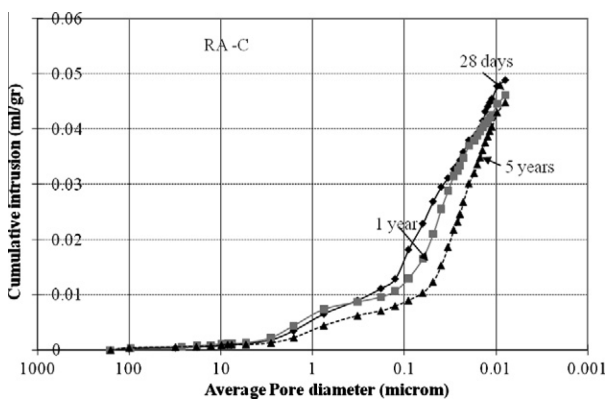

Fig. 5. Development of pore size distribution in RA-C mixtures at 28 days, 1 year and 5 years.

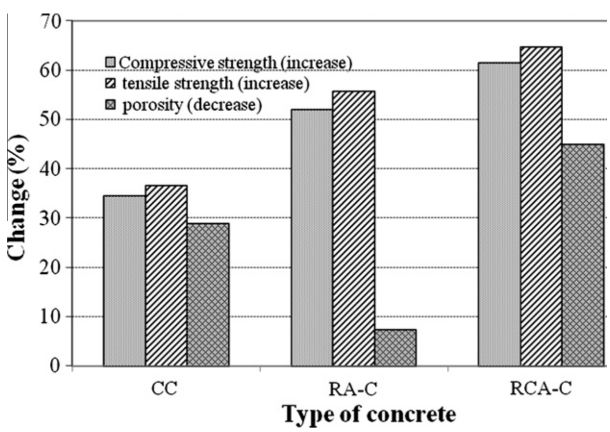

Fig. 6. Strength increases and porosity reduction in all concretes from 28 days to 5 years.

of RCA-C were only measured at 28 days and 5 years due to a mistake in sample storage. Each presented data in the figures and tables below is the average of two measurements.

3.2.1. Pore structure of the concrete

As shown in Fig. 1, at 28 days, the total intruded volumes in all concretes were similar. After 5 years, significant differences were noticed in the total intruded volume in the different samples (see Fig. 2). RCA-C had the lowest cumulative intruded volume, followed by CC, and the RA-C had the highest intruded volume. The developments of pore structure in each of the concrete from 28 days to 5 years are illustrated in Figs. 3–5. It can be easily observed that there were significant reductions in the total porosity of all the samples after 5 years of curing. In Table 7, we find that the greatest reduction in porosity was experienced by the RCA-C (44.9%) followed by CC (28.9%) and RA-C (7.4%).

3.2.2. Average pore diameters

A comparison of the average pore diameters of the concrete mixes is also shown in Table 7. The data show that there were reductions in the average pore size for the RCA-C and CC mixes but the average pore size of the RA-C mix remained more or less the same.

3.3. Correlation between porosity and mechanical properties of the concretes

Fig. 6 indicates that the compressive and splitting tensile strengths increased, the porosity decreased in all the concrete mixes from 28 days to 5 years. The concrete made with the highest percentage of crushed concrete as coarse aggregate (RCA-C) experienced a higher increment in strength and a higher porosity reduction followed by CC, and the RA-C.

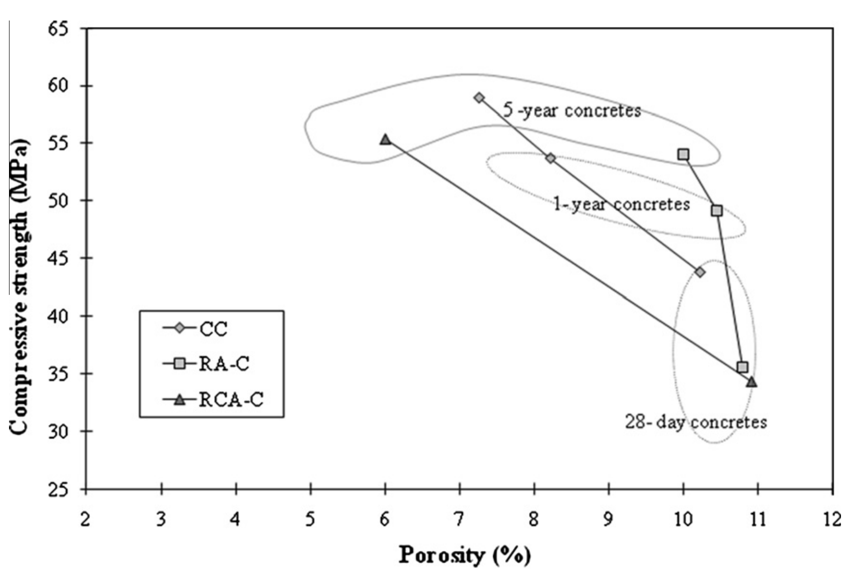

Fig. 7. Correlation between compressive strength and porosity at 28 days, 1 year and 5 years.

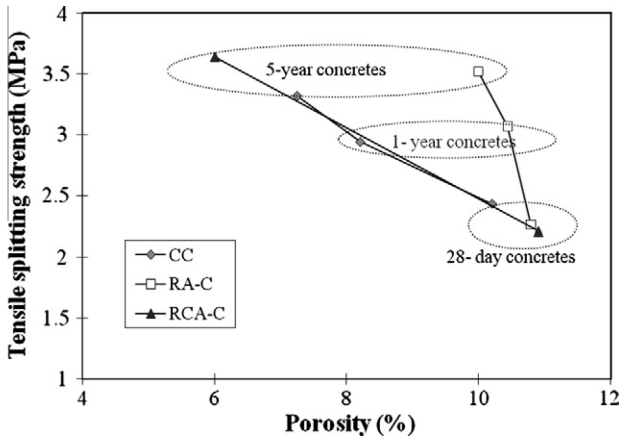

Fig. 8. Correlation between splitting tensile strength and porosity at 28 days, 1 year and 5 years.

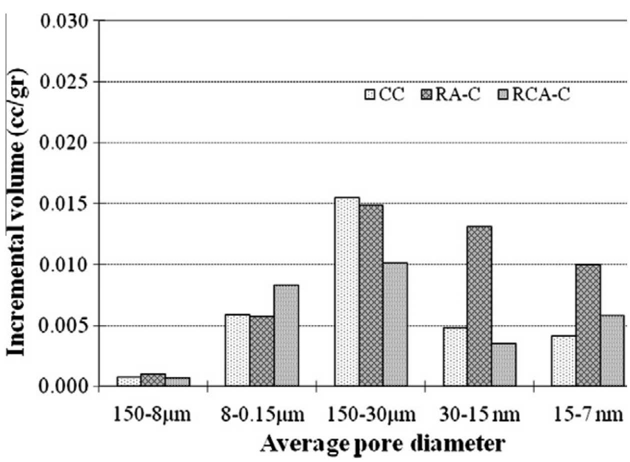

Fig. 9. Distribution of pore diameters at 5 years.

Figs. 7 and 8 display the correlations between compressive and splitting tensile strength with porosity, respectively. At 28 days, the CC concrete had the highest strengths and lowest porosity. The RCA-C concrete had the lowest strength and the highest porosity. The gradients of the lines for the CC and RCA-C were similar. But an obvious difference was noticed for the lines describing the relationships between the strength values and porosity for the RA-C mix. This may be explained by the presence of natural stone in the recycled aggregate.

From 28 days to 5 years, the CC mix had the lowest increment of strength and a modest decrease in porosity due to the fast hydration of the cement within the first 28 days in comparison with the slower hydration from 28 days to 5 years.

For the RA-C mix, the reason why it only experienced a small reduction of porosity is probably because it contained a significant proportion of natural stones with very smooth surface. During concrete production, bleed water might have accumulated near the surface of the natural stones and this has resulted in the higher porosity at the aggregate–cement interface which could not be filled even with continuous hydration. The pore size distribution diagram (Fig. 9) of the RA-C does show the presence of the very fine pores in the concrete. RCA-C experienced the highest increment of mechanical properties and also the highest reduction in porosity from 28 days to 5 years. This may be attributed to the further hydration of the old cement mortar and the improved interfacial bonding between the new cement paste and the old cement mortar in the RCA-C as it was prepared with 100% recycled aggregate that was entirely crushed concrete.

4. Conclusions

- Recycled aggregate concretes had lower compressive strength but higher splitting tensile strength than normal aggregate concrete after 5 years of water curing.
- From 28 days to 5 years, the increase in compressive and splitting tensile strengths for the recycled aggregate concretes was more than that in normal aggregate concrete.
- Normal aggregate concrete and recycled aggregate concrete, made with two different sources of RA and RCA, had similar porosity at 28 days of curing. But after 5 years of water curing, significant differences in porosity were observed in the different types of concretes.
- After 5 years of water curing the concrete made with 100% crushed concrete aggregate had the lowest porosity. The porosity was reduced by 45% between 28 days and 5 years. Concrete made with recycled aggregate, which contained mainly natural stone, had the highest porosity after 5 years of curing. The porosity was only reduced by 7% between 28 days and 5 years.
- The recycled aggregate that was made up with crushed concrete significantly improved the long-term interfacial properties of the new concrete probably due to the long term self cementing effects of the old cement mortar and the interaction of the new cement paste and the old cement mortar.

Acknowledgement

The authors wish to acknowledge the support of the Research Grants Council (PolyU 5259/06E) and the Hong Kong Polytechnic University for funding support.

References

[1] Limbachiya MC, Roberts JC. Sustainable waste management and recycling: construction and demolition waste. Thomas Telford; 2004.
[2] Oikonomou ND. Recycled concrete aggregates. Cem Concr Comp 2005;27:315–8.
[3] Eguchi K, Teranishi K, Nakagome A, Kishimoto H, Shinizaki K, Narikawa K. Application of recycled coarse aggregate by mixture to concrete construction. Constr Build Mater 2007;21:1542–51.
[4] Evangelista L, De Brito J. Mechanical behavior of concrete made with fine recycled concrete aggregate. Cem Concr Comp 2007;29:397–401.
[5] Etxeberria M, Vazquez E, Mari A, Barra M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem Concr Res 2007;37:735–42.
[6] Poon CS, Chan D. The use of recycled aggregate in concrete in Hong Kong. Resour Conserv Recycl 2007;50:293–305.
[7] Sagoe-Crentsil KK, Brown T, Taylor AH. Performance of concrete made with commercially produced coarse recycled coarse aggregate. Cem Concr Res 2001;31:707–12.
[8] Poon CS, Shui ZH, Lam L, Fok H, Kou SC. Influence of moisture states of natural and recycled aggregates on the properties of fresh and hardened concrete. Cem Concr Res 2004;34:31–6.
[9] Topcu B, Sengel S. Properties of concretes produced with waste concrete aggregates. Cem Concr Res 2004;34:1307–12.
[10] Xiao JZ, Li JB, Zhang C. Mechanical properties of recycled aggregate concrete under uniaxial loading. Cem Concr Res 2005;35:1187–94.
[11] Kou SC, Poon CS. Mechanical properties of 5-years-old concrete prepared with recycled aggregates obtained from three different sources. Mag Concr Res 2008;60:57–64.
[12] Etxeberria M, Vázquez E, Marí AR. Microstructure analysis of hardened recycled aggregate concrete. Mag Concr Res 2006;58:683–90.
[13] Garboczi EJ. Permeability, diffusivity and micostructural parameters: a critical review. Cem Concr Res 1990;20(4):503–14.
[14] Atzeni C, Massidda L, Sanna U. Effect of pore size distribution on strength of hardened cement pastes. In: Proceedings of the first international RILEM congress on pore structure and material properties. Paris and London: Chapman & Hall; 1987. p. 195–202.
[15] Gomez-Soberon J. Porosity of recycled concrete with substitution of recycled concrete aggregate: an experimental study. Cem Concr Res 2002; 32:1301–11.

[16] BS812. Part 2: methods for determination of physical properties. British Standard Institution; 1975.
[17] BS812. Part 110: methods for determination of aggregate crushing value (ACV). British Standard Institution; 1990.
[18] BS 1881. Part 116: testing concrete part 116: method for determination of compressive strength of concrete cubes. British Standard Institution; 1983.
[19] BS 1881. Part 117: method of testing concrete part 117. method for determination of tensile splitting strength. British Standard Institution; 1983.
[20] BS 7591. Part 1: porosity and pore size distribution of materials. Part 1: method of evaluation by mercury porosimetry. British Standard Institution; 1992.
[21] Maso JC. The bond between aggregates and hydrated cement paste. In: Proc 7th Int congress on the chemistry of cement, Septima ed. Paris, I:VII 1/3-1/15; 1980.
[22] Poon CS, Qiao XC, Chan D. The cause and influence of self-cementing properties of recycled concrete aggregates on the properties of unbound sub-base. Waste Manage 2006;26:1166–72.