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Cement & Concrete Composites 30 (2008) 283–289
Cement & Concrete Composites
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The effect of aggregate-to-cement ratio and types of aggregates on the properties of pre-cast concrete blocks

Chi Sun Poon *, Chi Sing Lam

Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Received 9 January 2006; received in revised form 17 October 2007; accepted 22 October 2007
Available online 3 December 2007

Abstract

The effects of aggregate-to-cement (A/C) ratios and types of aggregates on the properties of pre-cast concrete blocks are evaluated in this study. A/C ratios between three and six and three types of aggregates (i.e., natural crushed aggregate (NCA), recycled crushed aggregate (RCA) and recycled crushed glass (RCG)) were used in the experiments. It was found that the compressive strength of the paving blocks decreased as the A/C ratio increased. The results showed that the strength was directly proportional to the crushing strength of the aggregates (i.e., 10% fines value). Moreover, the water absorption of the blocks had a good correlation with the water absorption ability of the aggregate particles.

The use of RCA as a replacement of NCA in the production of concrete blocks reduced the density and strength but increased the water absorption of the blocks. However, the potential high water absorption of the blocks as a result of the incorporation of RCA could be ameliorated by the use of RCG since RCG particles had a low water absorption value.

Keywords: Recycled aggregates; Aggregate to cement ratio; Pre-cast; Concrete blocks

1. Introduction

Recycled aggregates are mainly produced from building and demolition (C&D) wastes. When suitably processed and sorted to remove contaminants, the coarse portion of the recycled aggregates has been used as a replacement of the natural aggregates. The potential benefits and drawbacks of using recycled aggregates in concrete are well documented. It has been found that the workability of concrete would be affected by the presence of recycled aggregate [1,2]. This phenomenon is mainly attributed to the angular shape and rough surface texture of the recycled aggregates. The high water absorption due to the presence of the old mortar in the recycled aggregate further decreases the workability of the fresh concrete.

Hasaba et al. [3] reported that the drying shrinkage of concrete prepared with coarse recycled aggregate and natural sand was 50% higher than that of conventional concrete. When both coarse and fine recycled aggregates were used, the drying shrinkage of recycled aggregate concrete was as much as 70% higher than that of conventional concrete. Hansen and Boegh [4] reported that recycled aggregate concrete had 15% to 30% lower modulus of elasticity and 40% to 60% higher shrinkage than those of conventional concrete. Olorunsogo et al. [5] found that the water sorptivity of concrete prepared with 100% recycled aggregate was about 39% higher than that of natural aggregate concrete at the curing age of 28 days. Dhir et al. [6] showed that the compressive strength of concrete with 100% coarse and 50% fine recycled aggregates was between 20% and 30% lower than that of the corresponding natural aggregate concrete. Poon and Kou [7] demonstrated that one of the most practical ways to utilize a higher percentage of recycled aggregates in concrete is "precasting" with an initial steam curing stage immediately after casting.

But the use of recycled aggregates for masonry production is still relatively new. An early attempt was made by Collins et al. [8] who used recycled aggregates in the

* Corresponding author. Tel.: +852 2766 6024; fax: +852 2334 6389.
E-mail address: cecspoon@polyu.edu.hk (C.S. Poon).

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doi:10.1016/j.cemconcomp.2007.10.005

manufacture of blocks for a beam-and-block floor system. The blocks were 440 mm long, 215 mm wide and 100 mm high. Recycled aggregates were used to substitute 25% to 75% by weight of both natural coarse and fine aggregates. For blocks with a recycled aggregate replacement level of 75%, a compressive strength of 6.75 MPa and a transverse strength of 1.23 MPa were reported. On the other hand, Jones et al. [9] suggested that the C&D waste can be used in concrete building blocks. However, they found that high recycled aggregate replacement level had an adverse effect on properties of the blocks, but it was expected that the target strength can be achieved by using a lower replacement level, whilst maintaining an economical cement content.

Furthermore, Poon et al. [10] used recycled aggregates as a replacement of natural aggregates in making pre-cast concrete paving blocks using a dry-mixed method which complied with the relevant specifications with a compressive strength of not less than 30 MPa. Lam et al. [11] also investigated the possibility of enhancing the performance of pre-cast concrete block by incorporating waste glass and found that the both the addition of supplementary cementitious materials like PFA and metakaolin was able to suppress the aggregate silica reaction in the glass blocks. Although previous research studies had demonstrated that it was feasible to produce masonry blocks using recycled aggregates, there is still a need to further understand the factors affecting the engineering properties of the masonry products in order to optimize the production.

According to pervious studies [12], aggregate to cement (A/C) ratio and the types and qualities of the aggregates are important factors affecting the mechanical properties of concrete blocks. Therefore, this study aims to quantify the effects of A/C ratio and aggregate properties on the properties of the blocks prepared with recycled materials such as recycled crushed aggregate (RCA) and recycled crushed glass (RCG).

2. Materials

2.1. Ordinary portland cement

In this study, OPC complying with BS 12 [13] was used. The cement was commercially available in Hong Kong.

2.2. Aggregate used

In this study, natural crushed granite was used as the natural crushed aggregates (NCA), the recycled crushed aggregate (RCA) was mainly concrete rubbles sourced from a C&D waste recycling facility in Hong Kong. The recycled crushed glass (RCG) used was mainly post-consumer beverage bottles sourced locally. The glass bottles were washed, crushed mechanically, and sieved in the laboratory. The RCG was a blend of three different types of beverage glasses with three different colors (30% colorless, 40% green and 30% brown). The maximum size of all the aggregates was less than 5 mm. The grading of all the aggregates used satisfied the requirement for fine aggregates according to BS 882:1992 [14]. The properties of the aggregates are shown in Fig. 1 and Table 1, respectively.

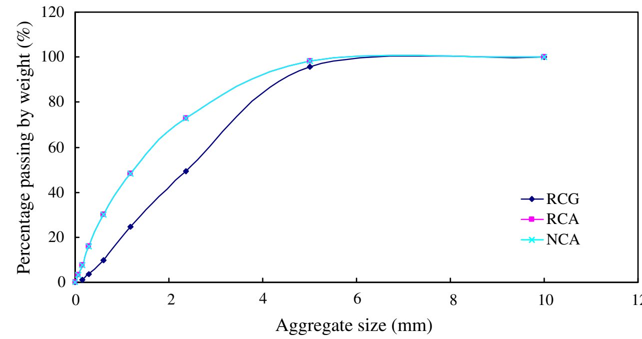

Fig. 1. Grading curves of NCA, RCG and RCA.

Table 1
Properties of natural crushed aggregate (NCA), recycled crushed glass (RCG) and recycled crushed aggregate (RCA)

Materials	Density (kg/m^3)	Water absorption (%)	10% Fine value (kN)
RCG	2500	~0	107
NCA	2630	1.2	150
RCA	2530	10.3	120

3. Mix proportions

The study was divided into two parts. The first part aimed to determine the effects of A/C ratios on the properties of blocks prepared with different types of aggregates. The second part aimed to evaluate the influences of the combinations of aggregates on the properties of the blocks.

In part one, three series of concrete block mixtures were prepared. Series I, II and III were prepared with NCA, RCA and RCG as shown in Table 2. In each series, aggregate-to-cement (A/C) ratios of three, four and six were used to investigate the effects of different A/C ratios on the properties of the blocks. In addition, mixtures with A/C ratios of 10 and 13 were also prepared in Series III in order to further investigate the effect of low cement content on properties of the blocks prepared with RCA. The results are useful for block works that are intended for non-loadbearing applications (e.g., partition blocks).

In part two, three mores series of concrete block mixtures were prepared. Three concrete blocks mixtures were prepared in Series IV in which the blocks were prepared with 50% RCG and 50% RCA but with varying A/C ratios from 3 to 6. The results were then compared with those of Series II and III to determine the effects of blending two types of aggregates on the properties of the blocks. In Series V, RCA was used to replace 25%, 50%, 75% and 100% NCA in the production of the con-

Table 2
Mix proportions of concrete block mixtures

Notations	RCG (kg)	NCA (kg)	RCA (kg)	Cement (kg)	A/C ratio	Added water (kg)
Series I						
NCA-3	–	23	–	7.7	3	2.1
NCA-4	–	23	–	5.8	4	2.0
NCA-6	–	23	–	3.8	6	2.0
Series II						
RCG-3	23	–	–	7.7	3	2.0
RCG-4	23	–	–	5.8	4	2.1
RCG-6	23	–	–	3.8	6	2.0
Series III						
RCA-3	–	–	23	7.7	3	2.5
RCA-4	–	–	23	5.8	4	2.3
RCA-6	–	–	23	3.8	6	2.3
RCA-10	–	–	23	2.3	10	2.1
RCA-13	–	–	23	1.8	13	2.0
Series IV						
50RCA/RCG-3	11.5	11.5	–	7.7	3	2.2
50RCA/RCG-4	11.5	11.5	–	5.8	4	1.9
50RCA/RCG-6	11.5	11.5	–	3.8	6	1.9
Series V						
NCA-4	23	–	–	5.8	4	2.3
25RCA/NCA-4	–	17.2	5.8	5.8	4	2.2
50RCA/NCA-4	–	11.5	11.5	5.8	4	2.1
75RCA/NCA-4	–	5.8	17.2	5.8	4	2.1
RCA-4	–	–	23	5.8	4	2.0
Series VI						
RCG-4	23	–	–	5.8	4	2.3
25RCA/RCG-4	–	17.2	5.8	5.8	4	2.1
50RCA/RCG-4	–	11.5	11.5	5.8	4	2.1
75RCA/RCG-4	–	5.8	17.2	5.8	4	2.0
RCA-4	–	–	23	5.8	4	2.1

crete blocks using an A/C ratio of four. Similarly, in Series VI, RCG was used to replace 25%, 50%, 75% and 100% RCA in the block mixtures prepared with an A/C ratio of four. The effects of incorporating RCG on the properties of RCA blocks were addressed.

4. Block fabrication

Blocks were fabricated in steel moulds with internal dimensions of $200 \times 100 \times 60$ mm using a dry-mixed method which simulated the actual industrial production process of concrete blocks (mixes were prepared with only sufficient water to produce a cohesive mix but with no slump/workability). After mixing the materials in a pan mixer, about 3 kg of the materials were placed into the mould in three layers. The first two layers were compacted manually by hammering a wooden plank on the surface layer to provide an evenly distributed compaction. The last layer was prepared by slightly overfilling the top of the mould (approximately 5 mm) and the overfilled materials were subjected to a static compaction twice by using a compression machine. The load was increased at a rate of 600 kN/min until 500 kN was reached for the first compaction. After removing the excessive materials with a trowel, a second compaction was applied at the same rate until 600 kN was reached. The blocks were demoulded after 24 h and were cured in water for 28 days.

5. Test methods

The tests of compressive strength, tensile splitting strength, skid resistance and abrasion resistance of paving blocks were conducted according to BS 6717 [15]. The cold water absorption and density of the blocks were determined in accordance with AS/NZS 4456 [16] and BS 1881 Part 114 [17] using a water displacement method for hardened concrete, respectively.

6. Results and discussion

In this paper, each presented value is an average of three measurements. The test results of Series I–VI are summarized in Table 3.

6.1. Compressive strength

The results presented in Fig. 2 indicate that the A/C ratio was an important parameter which governed the compressive strength. In the first four series of this study, it was found that the compressive strength was inversely proportional to the A/C ratio. It can also be noted that the difference in strength between each series when the A/C ratios were three and six was less compared to that when the A/C ratio was four. The difference could be explained by the different contributions of aggregate strength, bonding

Table 3
Test results of the blocks in Series I–VI

Mixtures		Density (kg/m^3)	Compressive strength (MPa)	Tensile splitting strength (MPa)	Skid resistance (BPN)	Abrasion resistance (mm)	Water absorption (%)
NCA-3	Series I	2371	85.8	5.0	90	20.5	2.9
NCA-4		2368	79.9	4.2	100	19.5	3.1
NCA-6		2329	50.0	3.1	110	23.0	5.2
RCG-3	Series II	2279	78.0	4.2	90	20.0	4.2
RCG-4		2247	48.6	3.5	105	20.0	3.3
RCG-6		2174	39.1	3.3	105	23.0	2.3
RCA-3	Series III	2288	77.7	5.1	95	20.0	4.1
RCA-4		2242	64.8	3.8	105	20.0	6.3
RCA-6		2175	37.6	2.5	105	22.5	8.4
RCA-10		2166	29.7	2.0	120	25.0	10.0
RCA-13		2120	12.6	0.9	130	26.0	12.0
RCA/RCG-3	Series IV	2250	73.9	4.6	95	19.5	3.2
RCA/RCG-4		2260	58.2	3.4	105	20.5	4.3
RCA/RCG-6		2169	40.0	2.8	105	23.5	5.4
NCA-4	Series V	2368	79.9	4.2	100	19.5	3.1
25RCA/NCA-4		2323	67.4	4.0	105	19	3.5
50RCA/NCA-4		2303	65.8	4.6	102	20	5.1
75RCA/NCA-4		2285	63.5	4.0	98	20	4.8
RCA-4		2242	64.8	3.8	105	20.0	6.3
RCG-4	Series VI	2247	48.6	3.5	105	20.0	3.3
25RCA/RCG-4		2270	57.4	3.1	101	21	3.3
50RCA/RCG-4		2260	53.6	3.4	106	20	4.3
75RCA/RCG-4		2275	60.1	3.9	108	19	4.7
RCA-4		2242	64.8	3.8	105	20.0	6.3

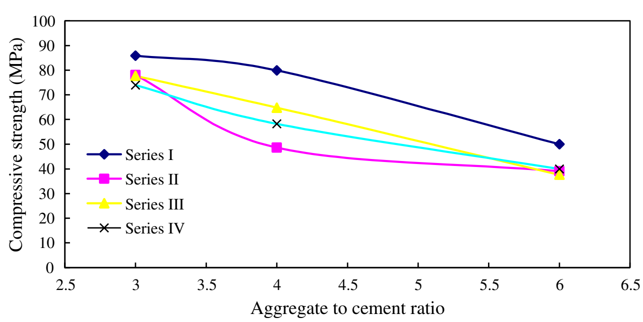

Fig. 2. Relationship between strength and A/C ratio for concrete mixtures in Series I, II, III and IV.

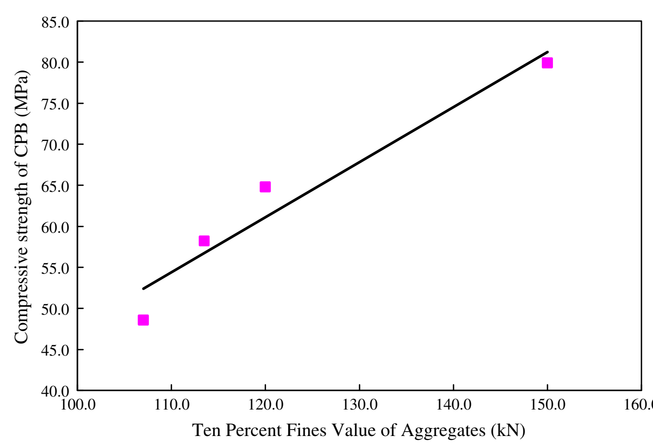

Fig. 3. Relationship between strength and 10% fines value of concrete mixtures prepared with A/C ratio of 4 in Series I, II, III and IV.

strength and the strength of the cement matrix to the overall strength of the blocks. With the A/C ratio was as low as three, the cement matrix was more dominant and the strength of the blocks was mainly dependent on the strength of the cement matrix.

When the A/C ratio was increased to four, the difference in strength between the blocks prepared with different types of aggregates became significant. It was found that the block strength was directly proportional to the corresponding aggregates strength as shown in Fig. 3 which used 10% fines value as an indication of the crushing strength of the aggregate.

But when the A/C ratio was further increased to six, it was believed that the bonding between the cement matrix and the RCA and RCG became relatively weak, thus rendering a lower strength. But the strength of the blocks prepared with the natural crushed aggregate was still the highest probably due to a better intrinsic strength of NCA.

A simple binomial relationship can be used to estimate the strength of blocks prepared with RCA with different A/C ratios ranging from 3 to 13 as shown in Fig. 4.

As mentioned before, it was believed that the aggregate strength (i.e. crushing strength) also affected the compressive strength of the blocks. It was found that the compressive strength of blocks prepared with 50% RCA and 50% RCG was approximately the average of

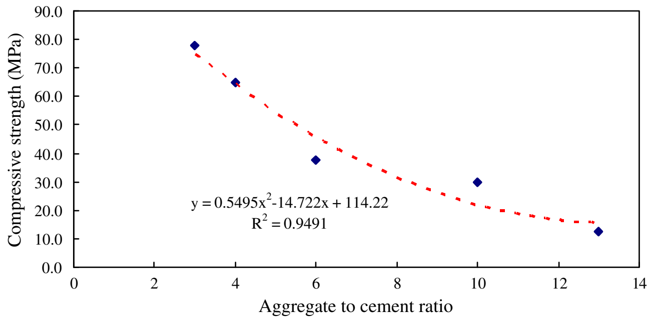

Fig. 4. Relationship between strength and A/C ratio for concrete mixtures in Series III.

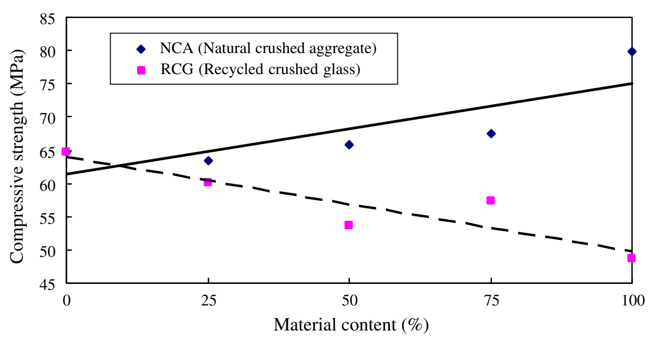

Fig. 5. Relationship between 28-day compressive strengths and different material content.

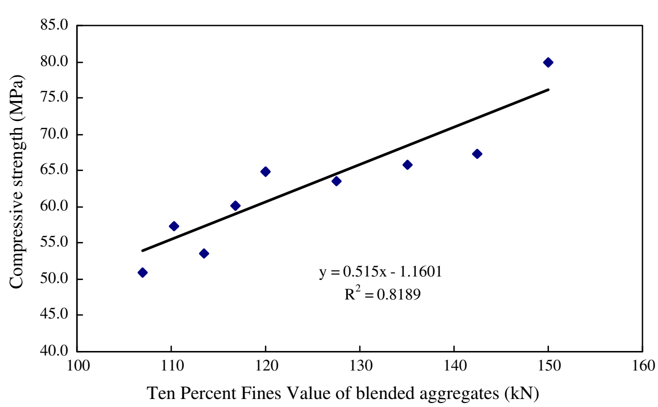

Fig. 6. Relationship between 28-day compressive strengths and 10% fines values of blended aggregates.

those of blocks prepared with only one type of aggregate (i.e., RCA or RCG). To further study the effects of aggregate strength on the compressive strength of blocks, NCA was partially or entirely replaced by RCA in the concrete mixtures in Series V. The results indicate that the use of RCA lowered the compressive strength (Fig. 5). In Series VI, the incorporation of RCG as a replacement of RCA also reduced the compressive strength of blocks as shown in Fig. 5. These results demonstrated the importance of aggregate strength in affecting the mechanical strength of the blocks.

Table 4
Requirements of paving blocks prescribed by ETWB of Hong Kong [19]

Properties		Grade A	Grade B
Characteristics compressive strength (MPa)	For pedestrian	≧30	≧30
	For vehicles	≧45	≧45
Skid resistance (BPN)		≧45	–
Abrasion resistance (mm)		≦23	–
Cold water absorption (%)		≦6	–

The results are further illustrated by plotting the compressive strengths of the blocks in Series V and Series VI against 10% fines values of the blend aggregates as shown in Fig. 6. It was found that the compressive strength of the blocks had a good correlation with 10% fines values of the blend aggregates. This result was consistent with those of the previous study [18]. Nevertheless, all the specimens tested in this study fulfilled the minimum compressive strength requirements prescribed by ETWB of Hong Kong for Grade B paving block for pedestrian areas [19] (Table 4).

6.2. Density

The results of the density measurements in Series I to VI are shown in Table 3. It was found that the density of the blocks reduced as the A/C ratio increased as shown in Fig. 7. This phenomenon could be attributed to (1) the density of cement (~3150 kg/m^3) was higher than that of the aggregates. Therefore, the density of paving blocks was affected by the ratio of cement to aggregate in the block, and (2) cement, a very fine powder, could easily fill up the voids between the aggregates, thus increasing the density of block.

On the other hand, the results also showed the density of the blocks was affected by the particle density of the aggregate. Fig. 8 shows that the increasing use of NCA increased the density of the blocks. The result was expected because NCA had a higher particle density compared to that of RCA. However, the change in the density of the blocks was not significant when RCG was used as a replacement of RCA. This was attributed to the similar particle densities between RCA and RCG.

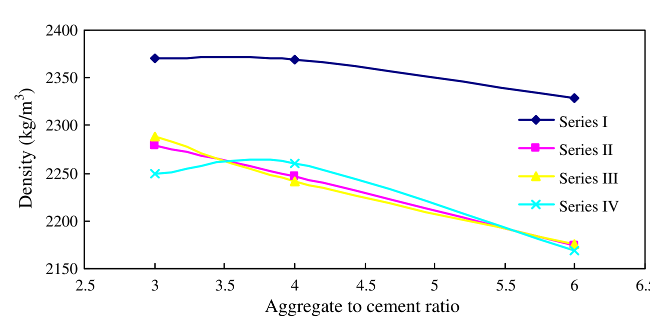

Fig. 7. Relationship between density and A/C ratio.

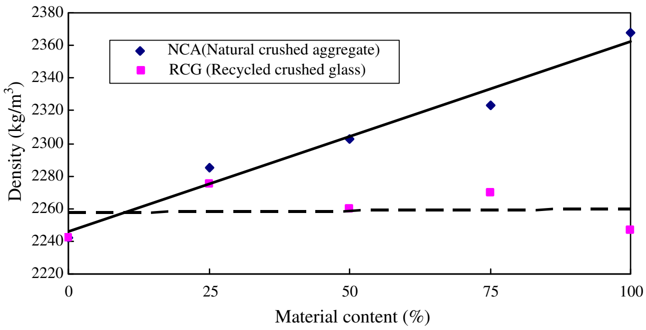

Fig. 8. Relationship between density and different material content in Series V and Series VI.

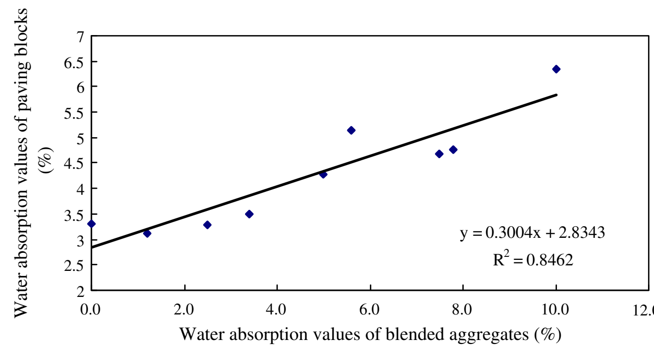

Fig. 11. Relationship between water absorption values of blocks and water absorption of the corresponding blended aggregates.

6.3. Water absorption

The magnitude of water absorption increased as the A/C ratio increased as shown in Fig. 9. When the A/C ratio was low, cement grains could fill up the pores, thus reducing the water absorption. In addition, the water absorption of the aggregates also played an important role in determining the water absorption of the blocks. Fig. 10 shows that the use of aggregates, with low water absorbability (NCA and RCG) as replacements of RCA, reduced the water absorption of the blocks significantly.

The water absorption values of the blocks are plotted against the water absorption of the corresponding blended aggregates as shown in Fig. 11. An expected trend was observed which showed that the water absorption value of the blocks was directly proportional to the water absorption of the corresponding blended aggregates.

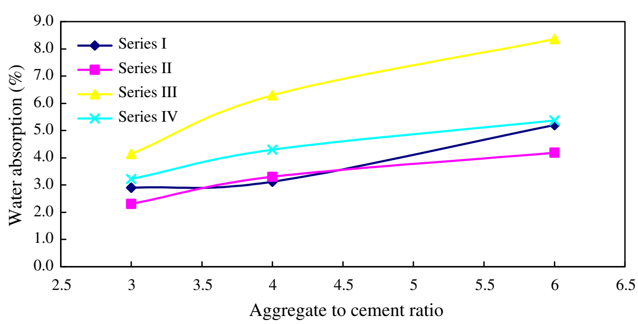

Fig. 9. Relationship between water absorption values and A/C ratio.

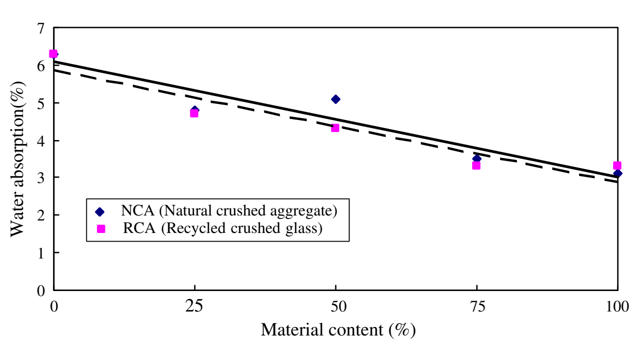

Fig. 10. Relationship between water absorption values and material content in Series V and VI.

In practice, it is found that the block prepared with 100% RCA did not meet the water absorption requirements prescribed by ETWB of Hong Kong for Grade A paving blocks which specifies a cold water absorption limit of 6%. However, when RCG was used as a 25% replacement of RCA, the water absorption of the blocks could be controlled to within 6%. Also, an alternative way to reduce the water absorption value of the blocks was to decrease the A/C ratio to less than four.

6.4. Skid and abrasion resistances

When the blocks are used for paving application, skid resistance and abrasion resistance are important. The results of skid resistance and abrasion resistance are shown in Table 3. All the specimens tested in Series I to VI were able to satisfy relevant standards with respect to skid resistance. In Series I to IV, the skid resistance of all the specimens prepared with an A/C ratio of three were slightly lower than the other specimens prepared with A/C ratios of four and six. This was mainly due to the surface texture of blocks being smoother with an increasing cement content. However, the nature of the aggregates used did not have a significant effect on the skid resistance results since the aggregates, in most cases, were embedded in the cement matrix.

The results of the abrasion resistance show that paving blocks prepared with A/C ratios of three and four exhibited satisfactory performance (<23 mm). But the abrasion resistance of the specimens prepared with an A/C ratio of six was only marginal. This was because in those specimens, the cement content was not sufficient to firmly bind the aggregate. This result also agrees with others that the ability of concrete to withstand abrasion improves with an increase in the concrete strength [20].

6.5. Tensile splitting strength

Although the tensile splitting strength of the concrete blocks is not a requirement in Hong Kong, it was also mea-

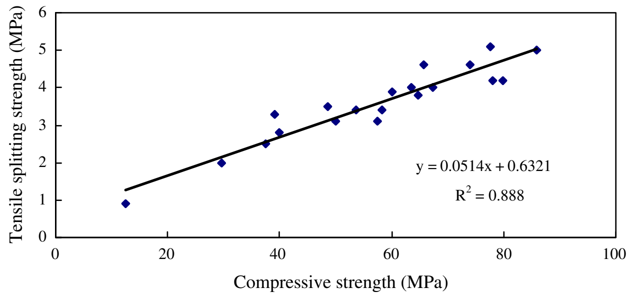

Fig. 12. Relationship between tensile splitting strength (MPa) and compressive strength (MPa).

sured as additional information in this study. The results of the first three series showed that the tensile splitting strength decreased as the A/C ratio increased. The results in Series V indicated that the use of RCA as a replacement of NCA reduced the tensile splitting strength. Similar to the results of compressive strength, the increasing use of RCG as a replacement of RCA tended to decrease the tensile splitting strength of the blocks. Moreover, it was found that the compressive strength and the tensile splitting strength had a close relationship as shown in Fig. 12.

7. Conclusion

In this paper, the factors affecting the properties of concrete blocks were investigated and the results can be summarized as follows:

1. The compressive strength increased with a decrease in A/C ratio.
2. The compressive strength was directly proportional to strength of the blended aggregate.
3. The blocks prepared with 100% RCA could not meet the requirements of water absorption unless the A/C ratio was decreased to 3.
4. The use of NCA or RCG as a replacement of RCA reduced the water absorption of the blocks.
5. The water absorption of the blocks was closely related to the water absorbability of the aggregate particles.
6. The abrasion resistance and skid resistance of the blocks were affected by the A/C ratio. When the A/C ratio was higher than four the abrasion resistance was marginal. However, there was no direct relationship between the aggregate types and the abrasion or skid resistance of the blocks.
7. To make use of recycled materials to produce eco-friendly (100% recycled materials as aggregates) concrete blocks with good quality, it is recommended to prepare the blocks with 50% recycled crushed glass (RCG) and 50% recycled crushed aggregate (RCA) and with an A/C ratio of 4 or below.

Acknowledgements

The authors would like to thank the Environment and Conservation Fund, the Woo Wheelock Green Fund and the Hong Kong Polytechnic University for funding support.

References

[1] Rashwan MS, Abourizk S. The properties of recycled concrete. Concr Int 1997:56–60.
[2] Poon CS, Shui ZH, Lam L, Kou SC. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of hardened concrete. Cem Conc Res 2004;34(1):31–6.
[3] Hasaba S, Kawamura M, Kazuyuki T, Kunio T. Drying shrinkage and durability of concrete made from recycled concrete aggregates. Trans Jap Concr Inst 1981;3:55–60.
[4] Hansen TC, Boegh E. Elasticity and drying shrinkage concrete of recycled aggregate. J Am Concr Inst 1985;82(5):648–52.
[5] Olorunsogo FT, Padayachee N. Performance of recycled aggregate concrete monitored by durability indexes. Cem Concr Res 2002;32(2):179–85.
[6] Dhir RK, Limbachiya MC, Leelawat T. Suitability of recycled concrete aggregate for use in BS 5328 designated mixes. Proc ICE: Struct Build 1999;134(4):257–74.
[7] Poon CS, Kou SC. Properties of steam cured recycled aggregate concrete. In: Limbachiya MC, Roberts JJ, editors. Proceedings of the international conference on sustainable waste management and recycling: construction demolition waste, London, Kingston University; 2004. p. 2–12.
[8] Collins RJ, Harris DJ, Sparkes W. Blocks with recycled aggregate: beam-and-block floors. BRE Report IP 14/98, Building Research Establishment, United Kingdom; 1998.
[9] Jones N, Soutsos M N, Millard S G, Bungey J H, Tickell R G. Developing precast concrete products made with recycled construction and demolition waste. In: Limbachiya MC, Roberts JJ, editors. Proceedings of the international conference on sustainable waste management and recycling: construction demolition waste, London, Kingston University; 2004. p. 133–40.
[10] Poon CS, Kou SC, Lam L. Use of recycled aggregates in moulded concrete bricks and blocks. Constr Build Mater 2002;16(5):281–9.
[11] Lam CS, Poon CS, Chan D. Enhancing the performance of pre-cast concrete blocks by incorporating waste glass-ASR consideration. Cem Concr Compos 2007;29:616–25.
[12] Shackel B. Design and construction of interlocking concrete block pavement. London and New York: Elsevier Applied Science; 1990.
[13] BS 12. Specifications for Portland cement, British Standards Institution; 1996.
[14] BS 882. Specifications for aggregates from natural sources for concrete, British Standards Institution; 1992.
[15] BS 6717. Precast, unreinforced concrete paving blocks-requirements and test methods, British Standards Institution; 2001.
[16] AS/NZS 4455. Masonry units and segmental pavers. Australian/New Zealand Standard; 1997.
[17] BS 1881, Part 114. Testing concrete: methods for determinations of density of harden concrete, British Standards Institution; 1983.
[18] Poon CS, Chan D. Paving blocks made with recycled concrete aggregate and crushed clay brick. Const Build Mater 2007;21:164–75.
[19] Works Bureau Technical Circular, ETWB TCW No. 24/2004, Specifications facilitating the use of concrete paving units made of recycled aggregates; 2004.
[20] Mindess S, Young JF, Darwin D. Concrete. 2nd ed. Englewood Cliffs (NJ): Prentice-Hall; 2003.