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Enhancing the performance of pre-cast concrete blocks by incorporating waste glass – ASR consideration

Chi Sing Lam, Chi Sun Poon *, Dixon Chan

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

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Abstract

There is a growing interest of using recycled crushed glass (RCG) as an aggregate in construction materials especially for non-structural applications. Although the recycled crushed glass is able to reduce the water absorption and drying shrinkage in concrete products due to its near to zero water absorption characteristics, the potential detrimental effect of using glass due to alkali–silica reaction (ASR) in cementitious materials is a real concern. The extent of ASR and its effect on concrete paving blocks produced with partial replacement of natural aggregates by crushed glass cullet are investigated in this study. This study is comprised of two parts. The first part quantified the extent of the ASR expansion and determined the adequate amount of mineral admixtures that was needed to reduce the ASR expansion for concrete paving blocks prepared with different recycled crushed glass contents using an accelerated mortar bar test in accordance with ASTM C 1260 (80 °C, 1 N NaOH solution). In the second part, concrete paving blocks were produced using the optimal mix proportion derived in the first part of this study and the corresponding mechanical properties were determined.

It was found from the mortar bar test that the incorporation of 25% or less RCG induced negligible ASR expansion after a testing period of 28 days. For mixes with a glass content of higher than 25%, the incorporation of mineral admixtures such as pulverized fuel ash and metakaolin was able to suppress the ASR expansion within the stipulated limit but the results need to be confirmed by other test methods such as the concrete prism test.

The study concluded that the optimal mix formulation for utilizing crushed waste glass in concrete paving blocks should contain at least 10% PFA by weight of the total aggregates used.

Keywords: Recycled aggregates; Recycled glass; ASR; Concrete paving blocks

1. Introduction

In Hong Kong, about 300 tonnes of waste glass is generated everyday. However, due to the lack of a glass manufacturing industry, the glass recycling rate is low and about 98% of the waste glass is disposed of at landfills. In other countries, besides using waste glass as cullet in glass manufacturing, waste glass is crushed into specified sizes for use as aggregates in applications like water filtration, grit blasting, sand cover for sport turf and sand replacement in concrete [1].

Recycled crushed glass (RCG) has been used as a sand replacement in concrete pavement [2]. However, the concrete strength is found to be reduced by 5% and 27% when the glass replacement levels are at 5–30%, respectively. Nevertheless, low drying shrinkage is observed for concrete prepared with RCG as a partial replacement of sand. According to New York State Energy Research and Development Authority (NYSERDA) [3], RCG is employed as aggregates in the production of concrete masonry in the United States. Test results show that the use of RCG reduces the strength and water absorption of the concrete blocks. Furthermore, both the Commonwealth Scientific and Industrial Research Organization (CSIRO) and NYSERDA found that alkali–silica reaction (ASR) would

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

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occur when crushed glass is used in cement-based materials like concrete. ASR occurs in concrete when alkalis from cement reacts with free silica presented in certain aggregates to form alkali–silica gels [3,4]. The alkali–silica gels have the property of taking in water and expand, which causes permanent damage to the concrete. Nevertheless, the reaction only occurs if and only if all three conditions take places at the same time: (1) the presence of alkalis in the cementitious system, (2) the presence of a reactive aggregate, and (3) a supply of water.

Nevertheless, ASR can be prevented or reduced by adding mineral admixtures in the concrete mixture. Common mineral admixtures used to minimize ASR are pulverized fuel ash (PFA), silica fume (SF) and metakaolin (MK). A number of studies [3,5,6] have proven the suppressing ability of these materials on ASR. In addition, Turanli et al. also found that it was possible to use ground clay brick as a pozzolanic material to minimize the ASR reaction [7].

On the other hand, there are also growing interests in using recycled aggregates derived from construction and demolition wastes for the production of concrete blocks but the high water absorption characteristics of recycled aggregates renders the produced blocks not suitable for high grade applications. According to a pervious study [8], for a similar block density, the incorporation of RCG would slightly decrease the strength of concrete blocks which are prepared by using 100% recycled aggregate as the aggregate, but the high water absorption of the blocks could be ameliorated by the use of RCG since RCG particles had a lower water absorption value.

This study, divided into two parts, aimed to develop an appropriate mix proportion for concrete paving blocks which can utilize a high percentage of RCG (i.e. >50%). Because glass contains a high content of reactive SiO_2, the concern of potential ASR on the durability of the produced blocks would need to be addressed.

In the first part of the study, seven series of mortar bars incorporating different percentages of RCG were prepared. The adequate amount of mineral admixtures (e.g. PFA) required to suppress the ASR of the mortar bars prepared with different glass contents would be determined. Based on the optimal mix proportion derived from the first part of this study, the mechanical properties of the paving blocks prepared with the optimal mix design would be quantified in the second part of the study.

2. Materials

2.1. Cementitious materials

In this study, Ordinary Portland cement (OPC) complying with BS 12 [9] was used as the principal cementitious material. Pulverized fuel ash (PFA) and Metakaolin (MK) were used as supplementary cementing materials (SCM) to suppress ASR in the mortar bar test. The properties of OPC, PFA and MK are shown in Table 1. Reference source not found. Both OPC and PFA were commercially available in Hong Kong whereas the MK was imported from Indonesia.

2.2. Sand

River sand was used as a natural fine aggregate in this study. The density of the sand used was about 2650 kg/m^3. The sieve analysis and properties of the sand are shown in Fig. 1 and Table 2, respectively.

Table 1
Properties of cementitious materials

Properties	Cement	PFA	MK
SiO_2 (%)	19.61	56.79	53.20
Fe_2O_3 (%)	3.32	5.31	0.38
Al_2O_3 (%)	7.33	28.21	43.90
CaO (%)	63.15	<3	0.02
MgO (%)	2.54	5.21	0.05
Na_2O (%)	0.13	0.45	0.17
K_2O (%)	0.39	1.34	0.10
SO_3 (%)	2.13	0.68	–
Loss on ignition (%)	2.97	3.90	0.50
Density (kg/m^3)	3160	2310	2620
Specific surface area (cm^2/g)	3520	3960	12680

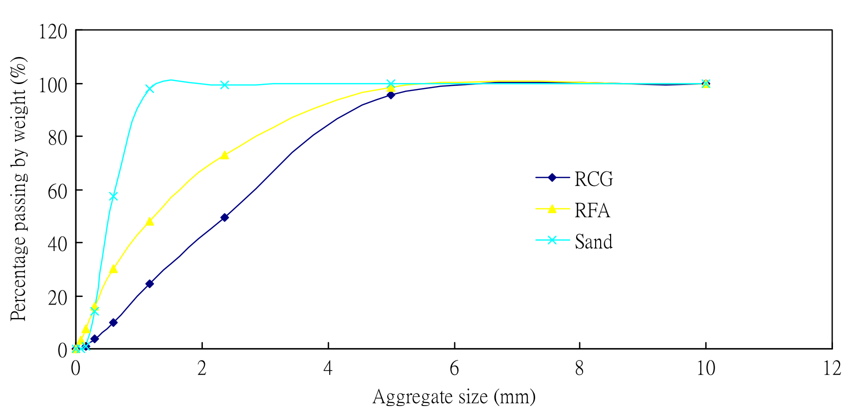

Fig. 1. Sieve analysis of three types of fine aggregates.

Table 2
Properties of recycled crushed glass (RCG), recycled fine aggregates (RFA) and sand

	Density (kg/m^3)	Water absorption (%)	Crushing strength (10% fines value, kN)	Fineness modulus
Sand	2620	1.0	–	2.11
RCG	2500	∼0	107	4.25
RFA	2530	10–11	120	3.54

2.3. Recycled Crushed Glass (RCG)

The RCG was mainly waste beverage glass bottle and was provided by the Environmental Protection Department (EPD) of Hong Kong through a contractor who carried out the collection, washing and crushing process. The RCG was a blend of 3 different colors of glasses (30% Colorless, 40% Green and 30% Brown). The mixed RCG was used as aggregates for producing the mortar bars and concrete paving blocks. The grading of the RCG satisfied the requirement for fine aggregates as per BS 882 [10]. The sieve analysis and properties of the RCG are shown in Fig. 1 and Table 2, respectively.

2.4. Recycled fine aggregates (RFA)

The recycled aggregates used were mainly crushed concrete rubbles sourced from a construction and demolition waste recycling facility in Hong Kong. In this study, the size fraction of the recycled aggregates used was less than 5 mm. The sieve analysis and properties of the RFA are shown in Fig. 1 and Table 2, respectively.

3. Mix proportions

3.1. Mortar bar mixtures

The potential ASR expansion of the prepared mortar bars (wet mix method) was assessed in accordance with ASTM C1260 [11]. Seven series of mortar bars were prepared in total. In Series I, three mortar bar mixes were prepared with RCG and sand in different proportions (Table 3) in order to determine the ASR expansion of mortar bars without any suppressant. Since the incorporation of mineral admixtures is known to be able to mitigate the potential expansive reaction as a result of ASR, mortar bars with 50% RCG and 50% sand were prepared with the incorporation of PFA and MK in Series II and III, respectively, (Table 3) to evaluate the effectiveness of using PFA and MK as a suppressant of ASR. The dosages of PFA and MK were 2.5%, 5% and 10% by weight of the total aggregates. Based on the results of Series I, II and III, the use of either PFA or MK as the ASR suppressant for the subsequent tests was determined.

In the subsequent tests, a similar approach as in Series I, II, and III was used to evaluate the ASR reactivity of RCG when it was blended with recycled fine aggregates (RFA).

Table 3
Mix proportions of mortar bars in Series I–III

Notations	Cement (g)	RCG (g)	Sand (g)	PFA (g)	MK (g)
Series I					
100G	440	990	–	–	–
50G50S	440	495	495	–	–
100S	440	–	990	–	–
Series II					
50G50S2.5M	440	495	495	–	24.8
50G50S5M	440	495	495	–	49.5
50G50S10M	440	495	495	–	99.0
Series III					
50G50S2.5P	440	495	495	24.8	–
50G50S5P	440	495	495	49.5	–
50G50S10P	440	495	495	99.0	–

Note: G = RCG, S = Sand, M = MK, P = PFA.

Table 4
Mix proportions of mortar bars in Series IV–VII

Notations	Cement (g)	RCG (g)	RFA (g)	PFA (g)
Series IV				
75G25R	440	742.5	247.5	–
50G50R	440	495	495	–
25G75R	440	247.5	742.5	–
100R	440	–	990	–
Series V				
75G25R5P	440	742.5	247.5	49.5
75G25R10P	440	742.5	247.5	99.0
75G25R15P	440	742.5	247.5	148.5
Series VI				
50G50R5P	440	495	495	49.5
50G50R10P	440	495	495	99.0
50G50R15P	440	495	495	148.5
Series VII				
25G75R5P	440	247.5	742.5	49.5
25G75R10P	440	247.5	742.5	99.0
25G75R15P	440	247.5	742.5	148.5

Note: G = RCG, R = Recycled aggregate, P = PFA.

Four mortar bar mixes were prepared with RFA and RCG in different proportions without any mineral admixtures in Series IV (Table 4) to determine the maximum allowable RCG content without the use of suppressant. In Series V, PFA (found to be the better suppressant) was added at 5%, 10% and 15% by weight of total aggregates to the mortar bars samples which were prepared with 75% RCG and 25% RFA. Similarly, PFA was added at the same dosages to the mortar bar samples which were prepared with 50% RCG and 50% RFA, and 25% RCG and 75% RFA in Series VI and VII, respectively (Table 4). According to the results of Series V–VII, the adequate amount of PFA needed to suppress the ASR for different RCG contents were summarized.

3.2. Concrete mixtures for paving blocks production

A total of three series of mixtures were prepared (dry mix method) for producing the paving blocks prepared

Table 5
Mix proportions of concrete paving blocks

Notations	Cement (kg)	PFA (kg)	RCG (kg)	RFA (kg)
Series VIII				
75G25R	5.75	–	5.75	17.25
75G25R5P	5.75	1.15	5.75	17.25
75G25R10P	5.75	2.30	5.75	17.25
75G25R15P	5.75	3.45	5.75	17.25
Series IX				
50G50R	5.75	–	11.5	11.5
50G50R5P	5.75	1.15	11.5	11.5
50G50R10P	5.75	2.30	11.5	11.5
50G50R15P	5.75	3.45	11.5	11.5
Series X				
25G75R	5.75	–	17.25	5.75
25G75R5P	5.75	1.15	17.25	5.75
25G75R10P	5.75	2.30	17.25	5.75
25G75R15P	5.75	3.45	17.25	5.75

Note: G = RCG, R = Recycled aggregate, P = PFA.

with RCG and RFA. The RCG to RFA ratios were 3–1, 1–1 and 1–3 in Series VIII, IX and X, respectively. The PFA was added at dosages of 5%, 10% and 15% by the weight of total aggregates in each series. The mix proportions are shown in Table 5 and an aggregate-to-cement ratio of 4 was used.

In this paper, the SCM are used in addition to (not as partial replacement of) Portland cement. Accordingly, samples containing SCM will have less aggregates and more binder per unit volume compared to control samples with no SCM.

4. Fabrication

The mortar bars were fabricated according to ASTM C1260 using a wet-mixed method with a water to cement ratio of 0.47 (mixes were prepared with sufficient water to achieve adequate workability). The sieved aggregates were mixed with the cementitious materials in different proportions. Then, the mixes were fabricated into steel moulds which had internal dimensions of $285 \times 25 \times 25$ mm.

On the other hand, concrete paving blocks were fabricated by a dry-mixed method (mixes were prepared with only sufficient water to produce a cohesive mix but with no slump/workability) in steel moulds with internal dimensions of $200 \times 100 \times 60$ mm. 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 mortar bar test was carried out in accordance with ASTM C1260 (80 °C, 1 N NaOH solution) but the duration of the ASR test was extended to 28 days (the standard test period is 14 days). The expansion of the mortar bars were measured at 1, 4, 7, 14 and 28 days.

The tests of compressive strength, tensile splitting strength, skid resistance and abrasion resistance of paving blocks were conducted according to BS 6717 [12]. The cold water absorption and density of the blocks were determined in accordance with AS/NZS 4456 [13] and BS 1881 Part 114 [14] using a water displacement method for hardened concrete, respectively.

The presented results are the average of three measurements of triplicate samples.

6. Results and discussion

6.1. Mortar bars

The results of the mortar bars test in Series I are shown in Fig. 2 which indicate that the ASR expansion was extremely high and was not able to meet the requirements prescribed in ASTM C 1260 (<0.1% within 14 days) when the mortar bars were prepared with 100% RCG. In addition, it was also observed that serious cracks were found on the surface of the mortar bars. Although the mortar bars prepared with 50% RCG and 50% sand were able to meet the requirements at 14 days, serious expansion and cracks was observed at 28 days. In comparison, the expansion of the control mortar bars in which only river sand was used as aggregates was minimal.

The results in Figs. 3 and 4 show that, although all the specimens were able to comply with the ASR expansion requirements stipulated in ASTM, the ASR suppressing ability of PFA was better than that of MK in the mortar bars with the same glass content. When considering the 28-day ASR expansion, 2.5% PFA was able to suppress the ASR expansion effectively whereas 5% MK was needed for the same mortar bars. Therefore, the use of PFA is a better choice as an effective and economical ASR suppressant and it was used for the subsequent tests.

Fig. 5 shows the ASR expansion of the mortar bars prepared in Series IV in which natural sand was replaced by recycled fine aggregate. Although there are some scatters of results in the first few days of measurement due errors in measuring the small dimensional changes, the long term results indicate that the expansion of mortar bars was not able to meet the requirements of ASR expansion when the RCG content was higher than 50% by weight of total aggregates. However, the ASR expansion was insignificant when the RCG content was less than 25%. Compared with Fig. 4, the sample 50G50R (in Fig. 5) has less expansion

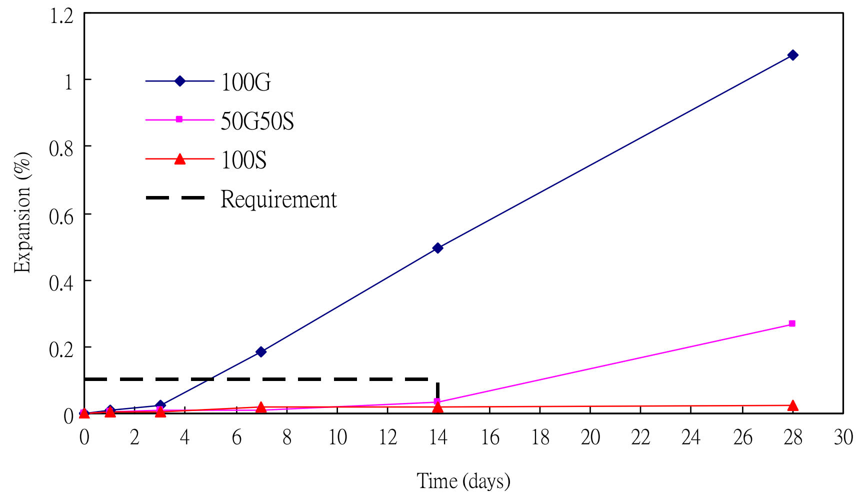

Fig. 2. Results of ASR expansion of the mortar bars prepared in Series I.

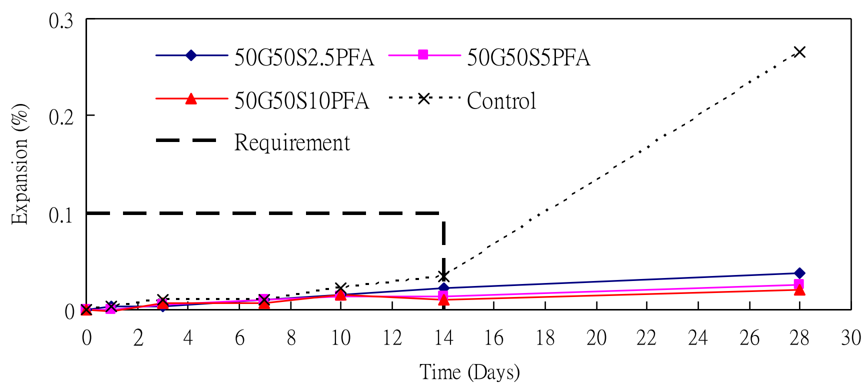

Fig. 3. Results of ASR expansion of the mortar bars prepared in Series II.

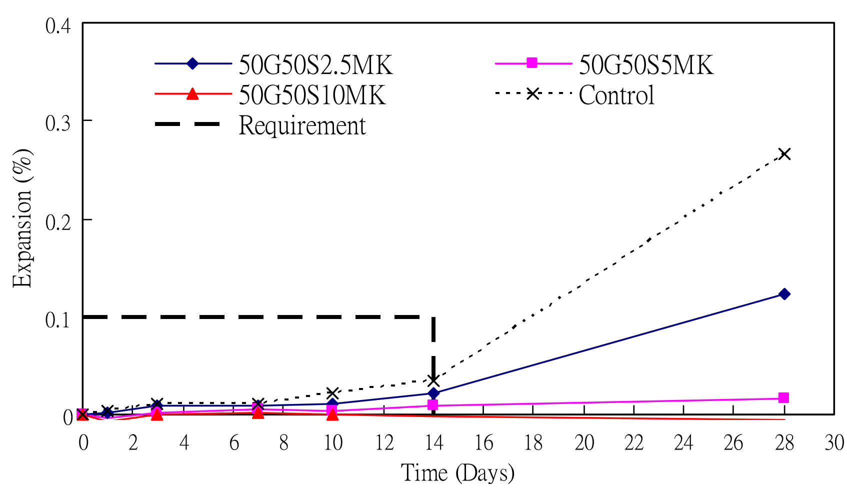

Fig. 4. Results of ASR expansion of the mortar bars prepared in Series III.

than the sample 50G50S (in Fig. 4). This is probably due to porous nature of the recycled aggregates which can accommodate the volume changes induced by the ASR of the glass.

Since it had been shown that PFA was an effective suppressant of the ASR expansion, different percentages of PFA were then incorporated into the mortar bar samples prepared with 75%, 50% and 25% RCG in Series V, VI and VII, respectively, in order to determine the optimal dosage of PFA for different RCG contents.

The ASR expansion results of the mortar bars prepared in Series V, VI and VII are shown in Figs. 6–8, respectively.

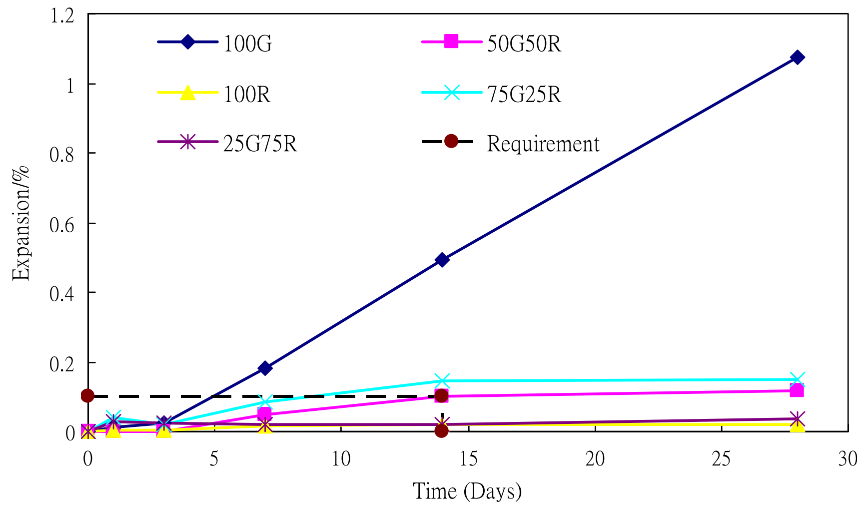

Fig. 5. Results of ASR expansion of mortar bars prepared in Series IV.

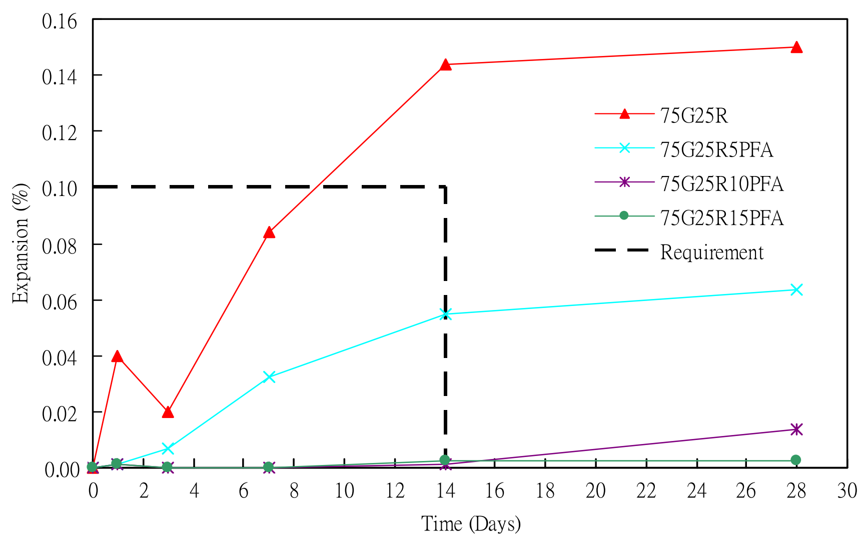

Fig. 6. Results of ASR expansion of mortar bars prepared in Series V.

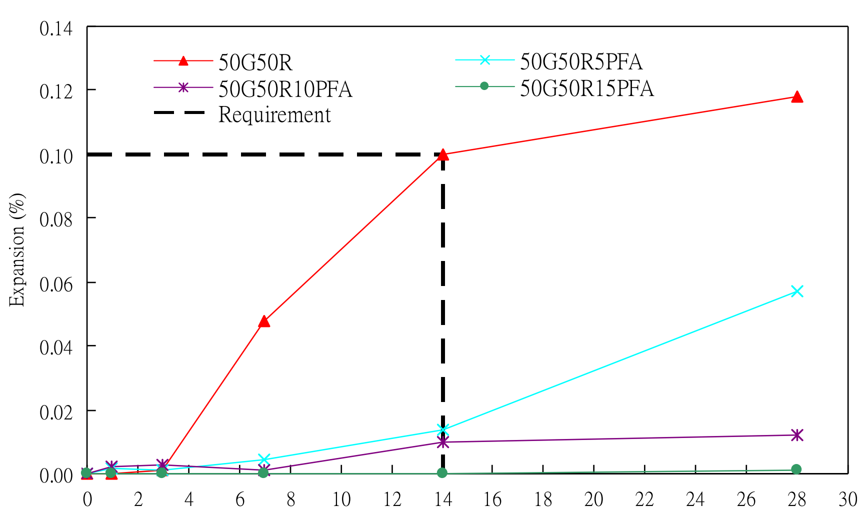

Fig. 7. Results of ASR expansion of mortar bars prepared in Series VI.

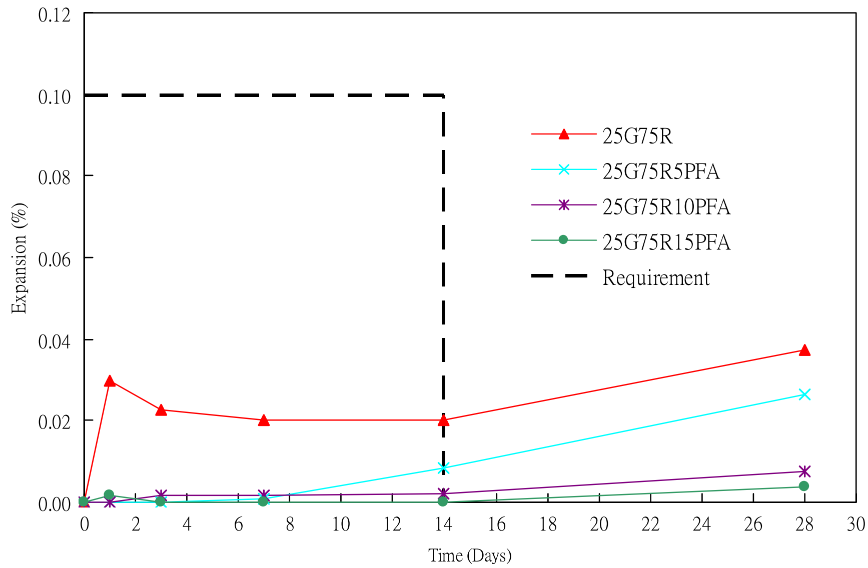

Fig. 8. Results of ASR expansion of mortar bars prepared in Series VII.

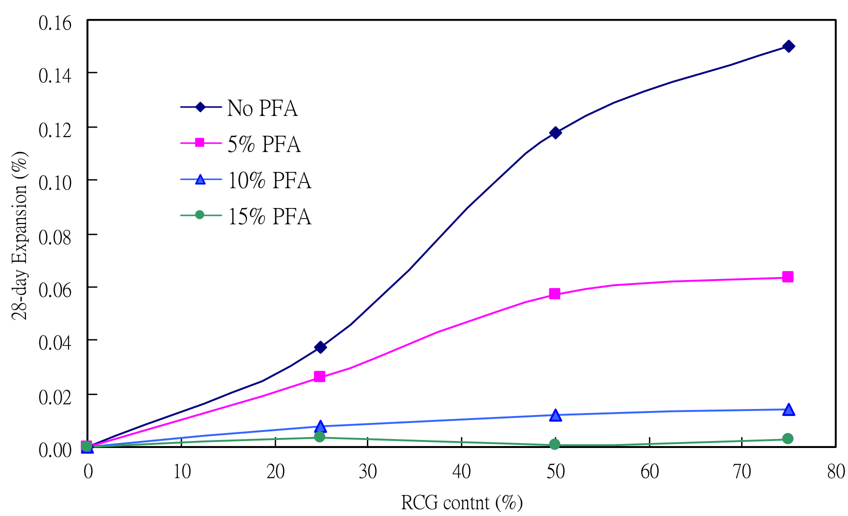

Fig. 9. Results of 28-day ASR expansion with different RCG content and PFA dosage.

The results indicate that 10% PFA by weight of total aggregate could effectively minimize the ASR expansion in the mortar bars prepared with 50% and 75% RCG. The mortar bars contained less than 25% RCG had little dimensional change even without the use of PFA after the 28-day test period.

In Fig. 9, the 28-day expansion of the mortar bars was plotted against the RCG contents. The results show that the ASR expansion can be controlled to a safe limit if 10% by weight of total aggregate of PFA is added into the concrete mixture or the RCG content is limited to 25% by weight of total aggregate.

6.2. Properties of concrete paving blocks prepared with RCG

After the determination of the proper mix design for different glass contents, concrete paving blocks were produced by using the same mix proportion and their corresponding mechanical properties were measured. The test results are summarized in Table 6 and Figs. 10–13.

Fig. 10 shows the compressive strength of the concrete paving blocks. The results indicate that the effect of the addition of PFA on 28-day strength was less significant compared to that of the 90-day strength which increased notably as the PFA content increased from 0% to 15%. The strength gain from 28 days to 90 days of the concrete mixtures at different glass and PFA contents is shown in Fig. 11, which shows that the gain in strength became more significant when the PFA content increased. The result could be attributed to pozzolanic reaction of the PFA particles at late test ages and the result was consistent with the previous study [15].

However, it is worth to note that except for the mixes prepared with no PFA addition (0% PFA), the compressive strength gain increased with increase in RCG content.

Table 6
Test results of paving blocks prepared in Series VIII, IX and X

Notations	Density (kg/m^3)	Compressive strength (MPa)		Tensile splitting strength (MPa)	Abrasion resistance (mm)	Skid resistance (PBN)	Water absorption (%)
		28-day	90-day				
Series VIII							
75G25R	2270	57	57.4	3.10	20	110	3.31
75G25R5P	2253	61	82.5	3.73	21	110	2.84
75G25R10P	2245	63	86.5	3.67	21	105	3.48
75G25R15P	2236	59	94.8	3.28	20	95	2.80
Series IX							
50G50R	2260	54	53.6	3.36	20	110	4.29
50G50R5P	2262	61	73.1	4.09	19	105	3.78
50G50R10P	2242	70	82.3	4.03	19	105	4.26
50G50R15P	2225	61	85.3	3.31	21	95	3.55
Series X							
25G75R	2275	56	60	3.90	21	110	4.72
25G75R5P	2235	60	73.1	3.31	20	110	4.91
25G75R10P	2220	62	70.2	4.02	19	105	5.40
25G75R15P	2207	61	74	3.94	20	95	4.29

This may be due to coarser particle size of the RCG used (Fineness modulus: 4.25) which would results in better packing of the over paving blocks produce as reflected in the density values presented in Fig. 13. A study by Lam [16] shows that for the production of concrete paving blocks, for a given aggregate to cement ratio, an aggregate fineness modulus value range from 3.5 to 4.5 would be most suitable.

Moreover, Table 6 shows that an increase in the PFA content resulted in a lower skid resistance of the paving blocks. Since the addition of PFA produced a more homogeneous mix which led to a smoother surface texture, thus reducing the skid resistance of the paving blocks. However, it was found that the abrasion resistance was not affected by the PFA contents.

Fig. 12 shows that the effect of the addition of PFA on the water absorption of the concrete paving blocks was less compared to that of the use of RCG. It has been shown previously [8] that the water absorption of the paving blocks was strongly related to the water absorbability of the aggregate particles. Since RCG particles had a relatively lower water absorption property, it was of no surprise that the water absorption of the paving blocks decreased as the RCG content increased.

Furthermore, it was found that the density of the paving blocks (Fig. 13) decreased as the PFA content increased. A comparison between the density of the aggregates, cement and PFA can easily show that PFA has the lowest density. Since the addition of PFA decreased the proportion of other ingredients in a unit volume in the paving blocks, the density of the blocks decreased accordingly after the addition of PFA. But as discussed before, for mixes that were prepared with the addition of PFA, the increasing use of RCG content in the mixes would increase the density of paving blocks produced which would also result in higher compressive strength.

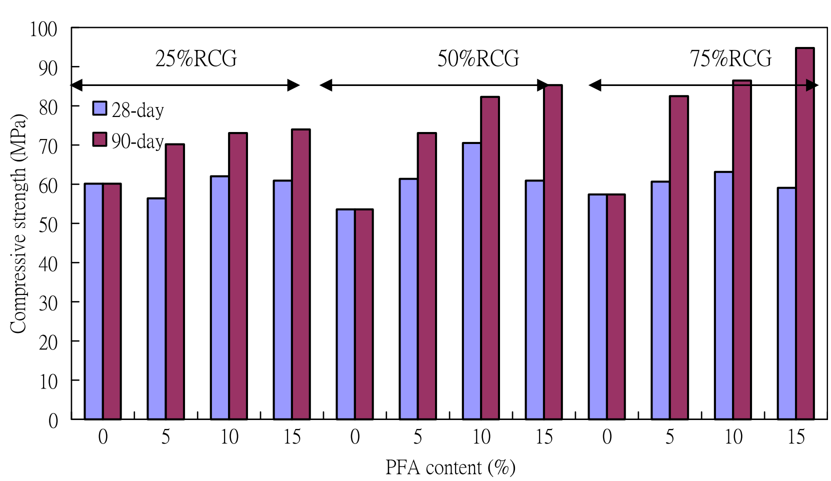

Fig. 10. Results of 28-day and 90-day compressive strengths of concrete paving blocks prepared with different glass and PFA contents.

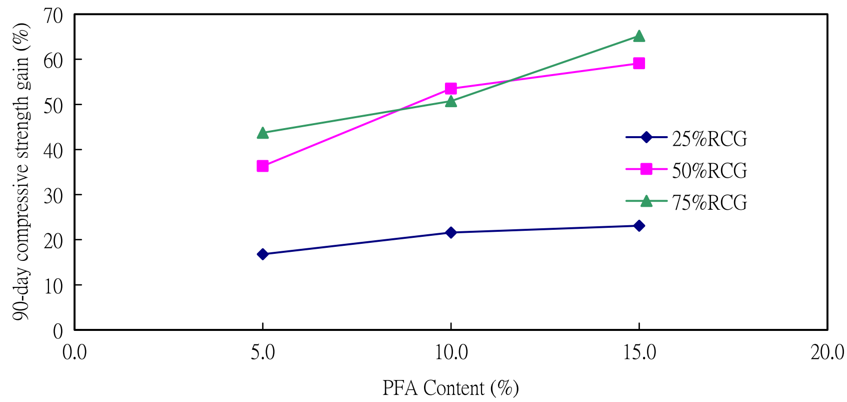

Fig. 11. Strength gain of concrete paving blocks prepared with different glass and PFA contents.

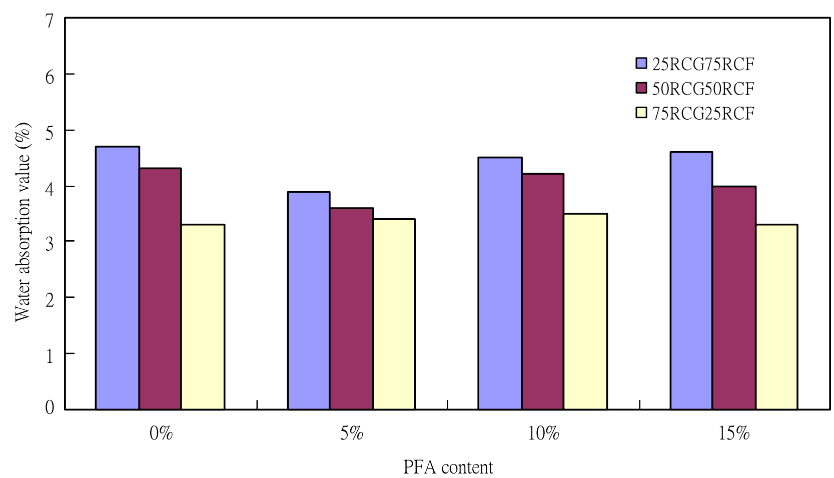

Fig. 12. Results of water absorption of concrete paving blocks prepared with different glass and PFA contents.

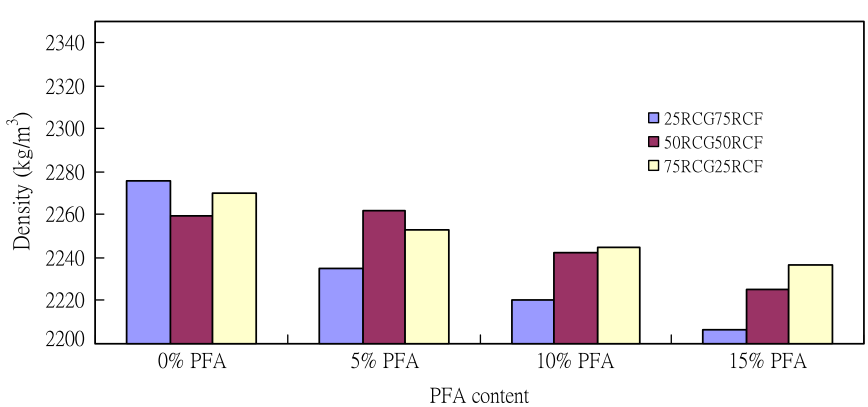

Fig. 13. Results of density of concrete paving blocks prepared with different glass and PFA content.

7. Conclusions

This study is comprised of two parts. In the first part, the adequate amount of mineral admixture required to suppress the ASR of the mortar bars prepared with different RCG contents was determined. In the second part, the mechanical properties of concrete paving blocks prepared with RFA and RCG were measured. The effects of adding PFA on the mechanical properties of the blocks were also studied. The following conclusions can be drawn:

1. It was not feasible to produce durable concrete paving blocks with the use 100% RCG without the use of mineral admixtures as ASR suppressant.

2. Both PFA and MK could suppress ASR expansion efficiently. However, PFA was a better choice due to its higher effectiveness and lower material cost.
3. Relatively small ASR expansion was detected when the mortar bars were prepared with 25% RCG or less.
4. It is recommended that 10% by weight of total aggregate of PFA was added into the concrete mixture to control the ASR expansion if the RCG content was 25% or greater.
5. At the same PFA content, the 90-day strength of concrete paving blocks increased with an increase in the RCG content.
6. The skid resistance and density reduced as the PFA content increased. However, the water absorption and abrasion resistance were not affected by the PFA content.
7. The water absorption of the paving blocks prepared with recycled aggregates decreased as the RCG content increased.
8. Good quality and environmentally friendly paving blocks can be produced by 100% recycled material as aggregate which consists of 50% RCG and 50% RFA with an addition of 10% by weight of total aggregate of PFA.
9. But the ASR expansion results need to be confirmed by other test methods such as the concrete prism test. Also, the results obtained above are based on one source of RCG. RCG from other sources may behave differently.

Acknowledgements

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