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Co-utilization of waste glass cullet and glass powder in precast concrete products

Jian-Xin Lu, Haibing Zheng, Shuqing Yang, Pingping He, Chi Sun Poon*

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

* Corresponding author: cecspoon@polyu.edu.hk (C.S. Poon)

Abstract

This study aimed at developing an eco-friendly precast concrete product by enhancing the application of waste glass. The waste glass was utilized as both fine aggregates and a partial binder in the form of glass powder (GP) in the paving blocks. The results showed that the strength was constant despite increasing amount of glass cullet (GC) was used in the paving blocks. The combined use of GC and fine GP was beneficial in reducing the water absorption and drying shrinkage of the paving blocks within permissible limits. Moreover, the addition of GP could successfully address the concern of ASR expansion resulting from GC.

Keywords: Waste glass; Glass cullet; Glass powder; Alkali-silica reaction (ASR); Precast concrete; Paving blocks

1. Introduction

1.1 Waste glass in Hong Kong

The large amount of waste glass generation (329 tonnes/daily in 2016 [1]) has become a serious concern in Hong Kong due to there is no glass manufacturing industry and the running out of landfill sites in Hong Kong. Actually, the Hong Kong Government has taken actions to expand the recycling outlets for waste glass to tie in with the imminent implementation of the Producer Responsibility Scheme on glass beverage bottles which aims at enhancing the recovery rate of waste glass in Hong Kong. Even so, the recycling rate of waste glass was only 7.7% in 2016 based on the Environmental and Protection Department (EPD) statistics [1], which was much lower when compared to other countries, such as Sweden (99%), Switzerland (98%), Belgium (96%) and Germany (85%) [2]. In Europe, the majority of waste glass bottles can be recycled back for making new beverage packaging to form a bottle-to-bottle closed loop cycle. But in Hong Kong, the deposit-and-return cycle has disappeared as all the local beverage manufacturers have moved their bottling plants outside the territory. Thereby, the current way of managing the waste glass is normally disposal at landfills. To reduce the environmental impacts and promote sustainable management of waste glass, further investigations are necessary to explore practicable means to increase the recycling of the waste glass.

1.2 Use of waste glass in concrete paving blocks

Beverage glass container is an artificial product produced with sand, soda ash and limestone, and is also called soda-lime-silica glass. It is chemically inert and possesses high intrinsic strength, therefore it has potential to be used as a secondary raw material. Besides reuse it for glass manufacturing, the utilization of waste glass in construction products is one of the most attractive approaches because it is potential to recycle a large amount of glass [3]. A number of studies had been conducted to evaluate the potential use of waste glass as aggregates in cement mortars and concrete [4-8]. However, there are still some technical limitations when using waste glass as fine aggregates in concrete. For example, the replacement of natural fine aggregates by the glass cullet (GC) normally results in inferior mechanical performance [9-11]. Furthermore, severe segregation and bleeding would be found as fine aggregates were fully replaced by GC [12]. Therefore, more attention was paid to investigate the feasibility of using waste GC as fine aggregates for the production of dry-mixed concrete paving blocks.

Poon and Lam [13] prepared an eco-friendly concrete block with 50% GC and 50% recycled aggregates. The result showed that the high water absorption of the concrete blocks resulting from the incorporation of recycled aggregates could be reduced by the use of GC. In addition, improvement of abrasion resistance was found in the concrete blocks prepared with glass aggregates incorporation [14]. Ling and Poon [15] indicated that the use of discarded cathode ray tube glass as an alternate fine aggregate in the dry-mixed concrete paving blocks was helpful to reduce the drying shrinkage and water absorption. But, the content of cathode ray tube glass for producing concrete blocks should be limited to about 25% glass due to the possible leaching of lead. The study of Lee et al. [16] showed that the inclusion of the very fine GC increased the compressive strength of concrete blocks due to the pozzolanic reaction of the very fine glass particles. In addition, the photocatalytic performance for removing air pollutants was improved when the GC was incorporated together with TiO_2 in paving block owing to the high light transmitting characteristic of the GC [17]. However, in terms of using GC in cement-based materials, a major concern is the potential alkali-silica reaction (ASR) expansion due to the presence of glass particles. According to a recent work [18], the larger pores in the dry-mixed glass concrete could accommodate the ASR gel, which made it effective to mitigate the expansion of ASR gel than the conventional wet-mixed glass concrete. Moreover, the addition of supplementary cementitious materials (SCMs) like fly ash and metakaolin could further suppress the ASR in the glass-based concrete blocks [19].

More importantly, the dry-mixed method for the production of concrete paving blocks is cost-effective because of its short production cycle time. Based on these advantages, in Hong Kong, the dry-mixed paving blocks prepared with waste glass have been widely applied in various road maintenance contracts, public works and housing projects since 2010 [20]. The technology for production of dry-mixed concrete paving blocks in the local industry is demonstrated in Fig. 1.

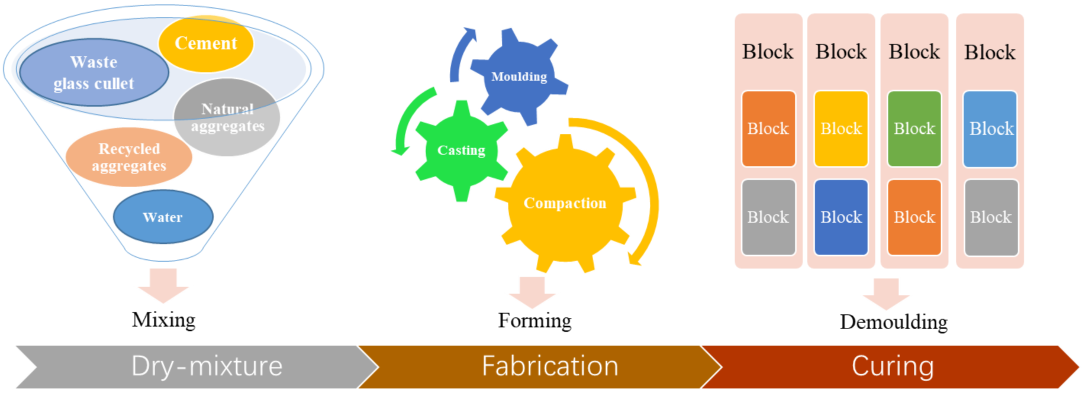

Fig. 1 Technology for production of concrete paving blocks in local industry

At present, up to 25% of total aggregates (including coarse and fine aggregates) are replaced by waste GC (as part of the fine aggregates) for the production concrete paving blocks. Therefore, it is needed to investigate the feasibility of increased an amount of waste glass in the paving blocks. The aim of this study was to design an eco-friendly concrete paving block by maximizing the application of waste glass. The waste glass was not only employed as fine aggregates but also as a SCM (in the form of glass powder) for replacing cement. The study focused on entirely replacing the fine aggregates with waste GC, meanwhile, up to 20% of cement was replaced by waste glass powder (GP) to further improve the performance of the paving blocks. Physical properties (density, water absorption), mechanical property (compressive strength) and durability (ASR, drying shrinkage) of the developed paving blocks were determined.

1.3 Research significance

A significant amount of waste glass is generated in Hong Kong, which imposes tremendous environmental problems due to its non-combustible and non-putrescible nature. Even worse, the shortage of waste disposal sites in Hong Kong poses a challenge to deal with this kind of solid waste. This study was conducted to maximize the application of waste glass in the concrete paving blocks, which may help expand the recycling of local waste glass. Furthermore, recycling the waste glass as a secondary raw material like aggregates can also alleviate the demand for virgin resources since the local quarry sites for aggregates production are expected to be exhausted soon. In order to maximize the application of waste glass in the production of concrete paving blocks, this study proposed two strategies for enhancing the waste glass content, which were: (i) the use of GC from locally generated waste glass bottles as fine aggregates, and (ii) the use of waste glass powder ground from GC as partial cement replacement. The results of this study were expected to provide a guidance to recycle waste glass in the concrete paving blocks for footpaths and carriageways applications (i.e. 30 MPa and 45 MPa, respectively). Previously, several studies [21-23] have been conducted on the performance of cement mortar and concrete prepared with GC and GP simultaneously. But no investigation was done on using GC and GP simultaneously in the production of concrete paving blocks.

2. Experimental design

2.1 Materials

The materials used to fabricate the concrete paving blocks were ASTM type I ordinary Portland cement (OPC, 52.5), natural coarse aggregates (CA, 5~10 mm), crushed fine aggregates (FA, 0~5 mm), waste glass cullet (GC, 0~5 mm) and waste glass powder (GP). The OPC was supplied by Green Island Cement in Hong Kong. The CA and FA were crushed granite sourced from a local aggregate supplier. The GC used in this study was provided by a local waste glass recycling facility which collected and crushed post-consumer beverage bottles to produce the GC. The gradation curves of GC and FA are presented in Fig. 2(a). The GP was obtained after grinding the GC with a laboratory ball mill for 2 hours (as shown in Fig. 3). The ball mill used was a cylindrical barrel with internal diameter of 260 mm and length of 330 mm. The rotation speed of ball mill was 60 r/min and the mass ratio of steel balls to GC was set to 6:1. Fig. 2(b) shows the particle size distributions of OPC and GP, indicating that the mean diameter of GP (47.9 μm) was larger than that of OPC (40.8 μm). The chemical compositions of OPC and GP were analyzed by X Ray Fluorescence and shown in Table 1. The densities of all the raw materials used in this study are listed in Table 2. It can be noted that the densities of GP and GC were lower than those of OPC and natural aggregates, respectively.

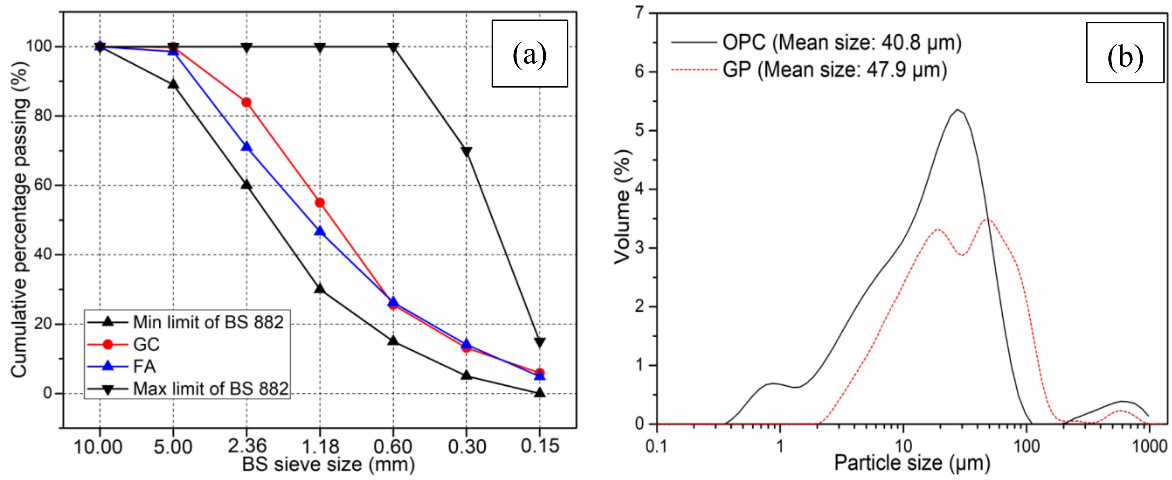

Fig. 2 Particle sizes of fine aggregates and GP, gradation of GC and FA (a); and particle size distribution of GP (b)

Fig. 3 Transition from glass cullet to glass powder

Table 1 Chemical compositions of cementitious materials

Chemical composition, %	OPC	GP
SiO_2	19.78	73.50
Al_2O_3	3.85	0.73
Fe_2O_3	3.15	0.38
CaO	65.21	10.45
MgO	1.50	1.25
Na_2O	-	12.74
K_2O	0.70	0.69
SO_4	5.49	-
TiO_2	0.27	0.09
MnO	0.06	0.01
Cr_2O_3	-	0.12

Table 2 Densities of cementitious materials and aggregates

Density (g/cm^3)	OPC	GP	CA	FA	GC
Value	3.03	2.37	2.59	2.59	2.48

2.2 Proportion of mix

In order to produce concrete paving blocks with a maximum content of waste glass, the recycled GC was used to replace 0%, 25%, 40%, 55% and 70% of the total amount of aggregates by weight. It should be noted that since the particle size of waste GC was less than 5 mm, it was only used to replace the fine aggregates. Furthermore, 20% of OPC was replaced by the GP to address the ASR problem to enhance the dosage of the waste glass in the blocks. The mixes were prepared with only sufficient amount of water to produce a cohesive mix but with no slump/workability, with the water-to-binder (*w*/*b*) ratios was 0.24~0.32. The aggregates-to-binder (*a*/*b*) ratio of the paving blocks mixtures were fixed at 4.0. The mix proportions of the paving blocks produced are listed in Table 3.

Table 3Mix designs of concrete paving blocks containing waste glass (kg/m^3)

Mix	OPC	GP	CA	FA	GC	Water	*a/b*	*w/b*
Density (g/cm^3)	3.03	2.37	2.59	2.59	2.48			
0GC	480	0	533	1387	0	153.6	4.0	0.32
25GC	480	0	533	907	480	153.6	4.0	0.32
40GC	480	0	533	619	768	134.4	4.0	0.28
55GC	480	0	533	331	1056	124.8	4.0	0.26
70GC	480	0	533	43	1344	115.2	4.0	0.24
70GC+20GP	384	96	533	43	1344	115.5	4.0	0.24

Note: The notations in the mix designations correspond to the percentages of waste GC/GP present in the aggregates/binder. For example, 25%GC means that 25% of the total amount of aggregates were replaced by GC (by weight), and the GC were only used to replace the fine aggregates due to their similar gradation and density. Based on practical experience in the industry, the maximum percentage of fine aggregates was 70% of the total aggregates in the blocks. Therefore, the levels of GC as aggregates replacement were based on such a level. GP was used as a supplementary cementitious material to *replace 20% of OPC by weight although the density of GP was lower than that of OPC.*

2.3 Preparation of paving blocks

The recycled GC was blended with the corresponding amount of cement, CA, and FA in accordance with Tables 2 to prepare the paving blocks. Then, water was introduced to the dry mix of the cement-aggregates until a homogeneous mixture was formed. The amount of water needed for blocks making were adjusted according to the moisture content of the mixtures. It is worth to point out that the incorporation of waste GC slightly reduced the amount of water required to produce the same mix cohesiveness since the water absorption of GC was negligible. Based on the actual industrial production, the mixed material was fabricated in steel moulds (100 mm×200 mm×60 mm). The freshly mixed mixture cast into the moulds in two separate layer and each layer was compacted by manual tamping in turn. Afterward, a maximum compressive force of 600 kN was applied for about 60 s to mechanically compact the mixture within the moulds. The fabricated blocks in the steel moulds were covered by a wet towel to reduce the initial moisture loss. The paving blocks were then demoulded after 24 h of casting. After demoulding, the mixes were cured in ambient temperature for 28 days to assess the various properties of the blocks.

2.4 Properties of paving blocks

The concrete paving blocks prepared were tested according to relevant standards (British Standards or American Society for Testing and Materials) with due reference to the relevant sections of the Hong Kong General Specifications for Civil Engineering Works, 2006 Edition.

2.4.1 Density

The density of paving blocks was determined using a water displacement method as per BS 1881 Part 114 for hardened concrete paving blocks [24]. After curing, the blocks were placed on a stirrup equipped in a balance, and fully immersed in water. The density was calculated using the following formula:

$$\rho = M_a/(M_a\text{-}M_w)$$

where:

ρ means the bulk density of the blocks after immersion (in g/cm^3);

M_a stands for the mass of the saturated specimen in air (in g);

M_w represents the mass of the saturated specimen in water (in g).

2.4.2 Water absorption

The water absorption values were determined in accordance with AS/NZS 4456.14 [25]. After completing the above density testing, the specimens were immediately transferred to a ventilated drying oven at a constant temperature of 105 °C for 24 h. After removing each specimen from the oven, they were allowed to cool in dry air. The water absorption of each specimen could be obtained using the formula:

$$A = [(M_a - M_o)/ Mo] \times 100\%$$

where:

A = water absorption of sample after immersion;

Mo = mass of oven-dried sample in air (in g);

Ma = mass of surface-dry sample in air after immersion (in g).

2.4.3 Compressive strength

The compressive strength of concrete blocks was determined using a compaction machine with a maximum capacity of 3000 kN. The testing method was in accordance with BS EN 12390-3:2009 [26]. The load was increased at a rate of 0.6 MPa/s until failure and the maximum force was recorded. For the rectangular blocks (100 mm×200 mm×60 mm), prior to the loading test, the thickness of each block was measured for calculating the compressive strength. The calculation equation for compressive strength was based on the Hong Kong General Specification for Civil Engineering Works [27], the compressive strength value was an average of measurements of two specimens.

$$C = 2.5F/ [A\times(1.5+L/H)]$$

Where:

C is the compressive strength (MPa);

F is the breaking load (N);

A is the nominal gross plan area (mm^2);

L is the minimum size of the two plan dimension (mm);

H is the thickness of the block (mm).

2.4.4 Drying shrinkage

The drying shrinkage of the block specimens was determined according to British Standard (BS ISO, Part 8: 1920) method [28]. The blocks were fabricated in steel moulds with internal dimensions of 25 mm×25 mm×285 mm. The specimens were demoulded after 24 h casting, then placed into the water tank for 7 days curing. The initial lengths of the block specimens were measured immediately after removing them from the curing tank. Then, the specimens were conveyed to a drying chamber at 25 °C and a relative humidity of 50% until further measurement at 1st, 4th, 7th, 14th, 21st and 28th day.

2.4.5 Alkali-silica reaction (ASR)

In order to measure the ASR expansion for glass-based paving blocks, an accelerated block bar test was carried out in accordance with ASTM C1260 [29]. The specimens with dimensions of 25 mm×25 mm×285 mm were cast. After demoulding, the block specimens were transferred into 80 °C water tank for 24 h and the length was recorded as the zero reading using a length comparator. Then, the specimen bars were transferred and immersed in 1M NaOH solution at 80 °C. The expansion values of the specimens were measured at 1st, 4th, 7th, 14th, 21st and 28th day.

2.4.6 Microstructure tests

Scanning Electron Microscopy and coupled with Energy Dispersive X-Ray Spectroscopy (SEM-EDX) analyses (Tescan VEGA3) were conducted to evaluate the mechanism on the effect of GC and GP on the ASR expansion of the paving blocks. After the ASR test, the block samples were broken into pieces and the cement mortars except the coarse aggregates were collected for morphology observation. The prepared mortar pieces were first immersed into ethanol for two weeks to stop further reaction, followed by drying in a vacuum chamber at 60 °C for another two weeks to remove the residual ethanol. Before testing by SEM-EDX, the mortar pieces were coated by Au for conduction purpose. Both the SEM images and EDS were obtained in a vacuum condition with a voltage of 20 kV and a working distance of about 10 mm. The magnification of each image was selected based on the sizes of GC and GP. The detailed information on the setting of SEM equipment was showed in the bottom side of SEM images. Mercury Intrusion Porosimetry (MIP, Micromeritics AutoPore IV 9500 Series) was employed to understand the influence of GP incorporation on the pore structure of glass-based paving blocks and explore the underlying mechanism of GP in ASR suppression. The samples prepared for MIP test was the same as the SEM test. The pore sizes measured by this method ranged from 150 μm down to 7 nm. A maximum mercury intrusion pressure of 207 MPa was performed for determining the pore structure.

3. Experimental results

3.1 Density and water absorption

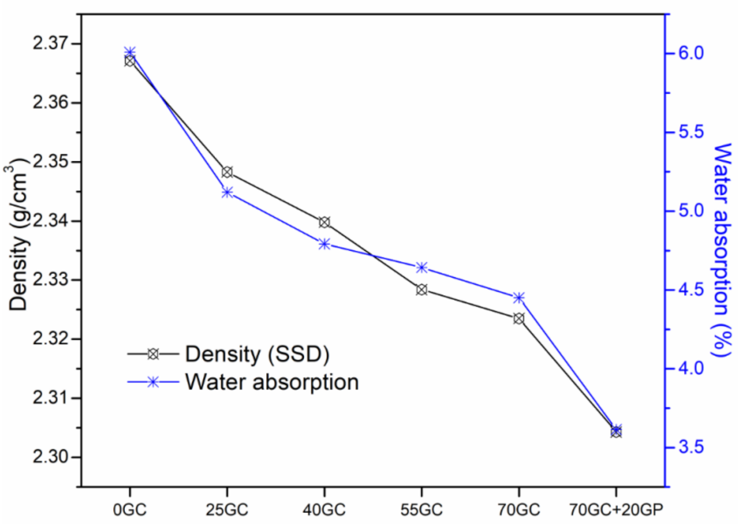

Fig. 4 Effect of GC and GP on the density and water absorption of paving blocks

Fig. 4 presents the density and water absorption values of the glass-based paving blocks. It is observed that both the density and water absorption of the paving blocks decreased when the amount of GC was increased. This can be attributed to the soda-lime-silica glass aggregates having a lower specify gravity (see Table 2) as compared to the crushed aggregates. Similar results were reported by Ismail and AL-Hashmi [30], who found that the density of concrete incorporating GC as fine aggregates was lower than that of the control concrete without GC. Furthermore, the replacement of cement by GP could decrease the hardened density of the paving blocks. This can also be explained by the lower inherent density of glass as compared to that of cement [31] which was also shown in Table 2.

As required by the Hong Kong specifications [27], the water absorption of the concrete paving blocks should be less than 6%. Apparently, the water absorption of the blocks incorporating GC did not exceed 6%, and the water absorption was significantly reduced when the GC content increased. This trend was due to the impermeable property of the GC [32]. The replacement of cement by GP further reduced the water absorption of the paving blocks. The reason for this behavior was attributed to the denser microstructure of the cement mortar in the mixture owing to the pozzolanic reaction of GP (to be discussed in Section 4). This trend of reduction in the water absorption was also found by previous studies on cement mortar [33] and concrete [34] incorporating 20% GP.

3.2 Compressive strength

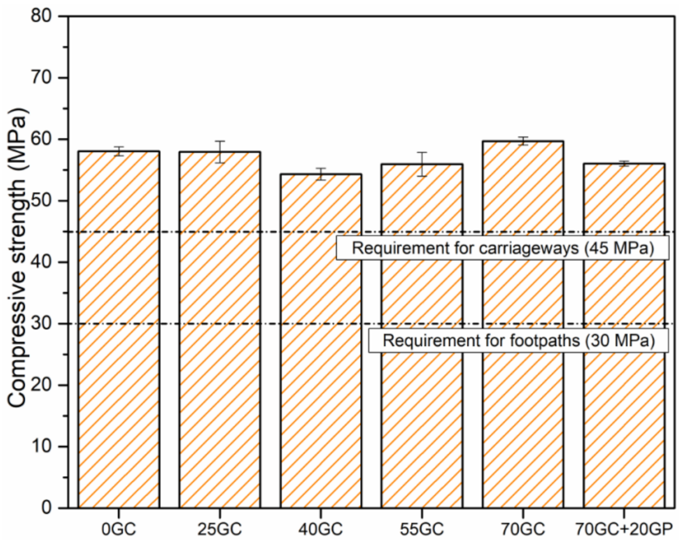

Fig. 5 Effect of GC and GP on compressive strength of paving blocks

Fig. 5 shows the influence of different GC contents and GP incorporation on the compressive strength of the paving blocks. It can be noticed that the 28-day compressive strength kept relatively constant at above 50 MPa when the amount of GC was increased from 0% to 70%. In other words, the increasing content of GC had no adverse effects on the compressive strength when it is used in concrete paving blocks which is contrary to the decreasing trend found in normal concrete [9-11]. The difference may be explained by the different casting methods of the concrete mixtures. As known, normal concrete is commonly cast by the wet-mixed method, which normally has a good workability to facilitate casting using normal means of compaction (e.g. vibrating table or poker vibrator). Using the wet-mixed method, the aggregate particles are wrapped relatively uniformly by the cement paste. Hence, the bonding between the aggregates and cement paste would be a principal factor in controlling the strength. For the case of normal concrete prepared with GC incorporation, the weak bonding between the cement paste and the GC due to the smooth surface of glass particles was mainly responsible for the reductions in strength. A pervious study [21] also verified the weak interfacial transition zone in the vicinity of the GC. Furthermore, it was also found that the higher porosity near the GC might cause a decrease in strength because the non-absorbent nature of the glass resulted in localized bleeding of water around the GC.

But in this study, the concrete paving blocks were produced by a dry-mixed casting method. The mixture was prepared with only a minimal amount of water with no workability and compacted via a specified compressive force into the moulds. Therefore, the packing of the concrete mixture associated with the gradation of aggregates might played a more important role in determining the strength. As showed in Fig. 2(a), the particle size of GC was finer than that of the replaced fine aggregates, making it easier to fill up the gaps between the coarse aggregate particles. Thus, the mixtures prepared with GC could be compacted to produce a denser matrix than those prepared with FA. This beneficial effect would counteract the adverse effect brought by the weak bonding between the GC and the cement paste. In addition, the lesser amount of water required for producing the block mixtures with the increase of GC content was also conducive to compensating the strength loss. Therefore, the better packing efficiency and low water to binder ratio may be the reasons why the compressive strength of paving blocks remained almost consistent when the GC percentage was increased up to the maximum content.

More importantly, it is found that all the compressive strengths of the paving blocks could satisfy the minimum limit of the Hong Kong requirements (as shown in Fig. 5), irrespective of the GC content. The sufficient strength strongly supports the feasibility of using more glass for making the concrete paving blocks. Moreover, it is interesting to notice that the replacement of 20% cement by GP only led to a slight reduction in the compressive strength. For using GP in cement-based construction materials, extensive studies [35-37] had demonstrated its pozzolanic reactivity. The relatively low pozzolanic activity of GP at the early age [21] was the main reason for the slight reduction of strength. However, the compressive strength achieved could still exceed the requirements for practical applications.

3.3 Drying shrinkage

The effects of the maximum GC content and GP incorporation on the drying shrinkage of the paving blocks are presented in Fig. 6. Apparently, the blocks without the GC had high drying shrinkage values with above 1000 micro-strains. When the maximum content of GC was used to fully replace the fine aggregates, the drying shrinkage decreased effectively and the ultimate value was half of that of blocks prepared without GC. The shrinkage of the blocks was largely caused by moisture loss from the hydrated cement materials upon exposure to the external drying conditions. A previous study [38] reported that a lower water to binder ratio led to a lower drying shrinkage value in the concrete. In this study, the negligible water absorption capacity of glass particles would result in less amount of evaporable water in the cementitious paste because a lower water to binder ratio was required in the mixture preparation. Therefore, the drying shrinkage of the paving blocks was reduced as the GC was introduced as fine aggregates. Similar reductions in the drying shrinkage were also reported for cement mortars [39] and normal concrete [40] incorporating GC. As recommended by the Australian Standard (AS1012.13 [41]), the drying shrinkage value of concrete should be less than 1000 micro-strains. Therefore, the introduction of the maximum amount of GC as fine aggregates in this study could successfully render the shrinkage of the paving blocks within the permitted limit.

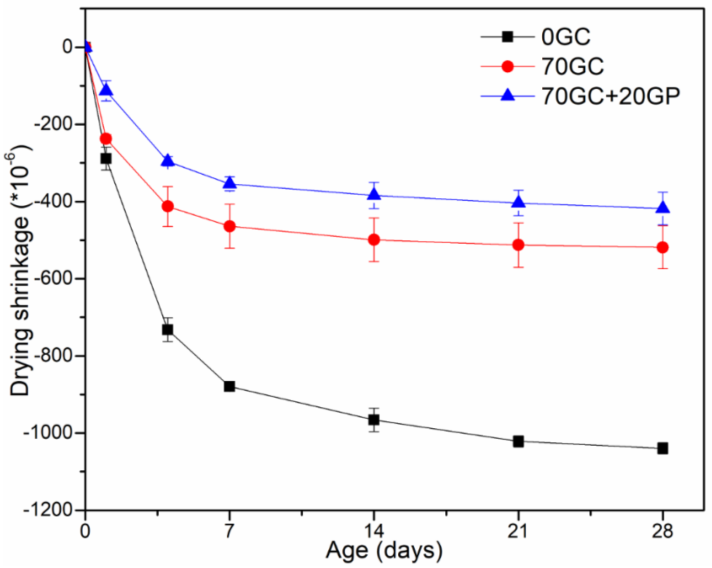

Fig. 6 Effect of GC and GP on the drying shrinkage of paving blocks

The replacement of cement by GP further reduced the drying shrinkage of the blocks. Moreover, most of the shrinkage on the paving blocks took place before 7 days of drying. Therefore, the pozzolanic effect of the GP occurring at the late age was not the key factor in controlling the drying shrinkage. On the one hand, the dilution effect due to the addition of GP was beneficial to reduce the shrinkage as the replacement of 20% cement by GP reduced the amount of cement hydration, which mitigated the volume contraction of the hydration products due to chemical reactions [6]. Furthermore, the beneficial effect of reduction in shrinkage may be related to the irregular shapes and high aspect ratios of the glass particles [21], which might act as micro-fibers in restricting the shrinkage of the cement mortar in the paving blocks.

3.4 ASR expansion

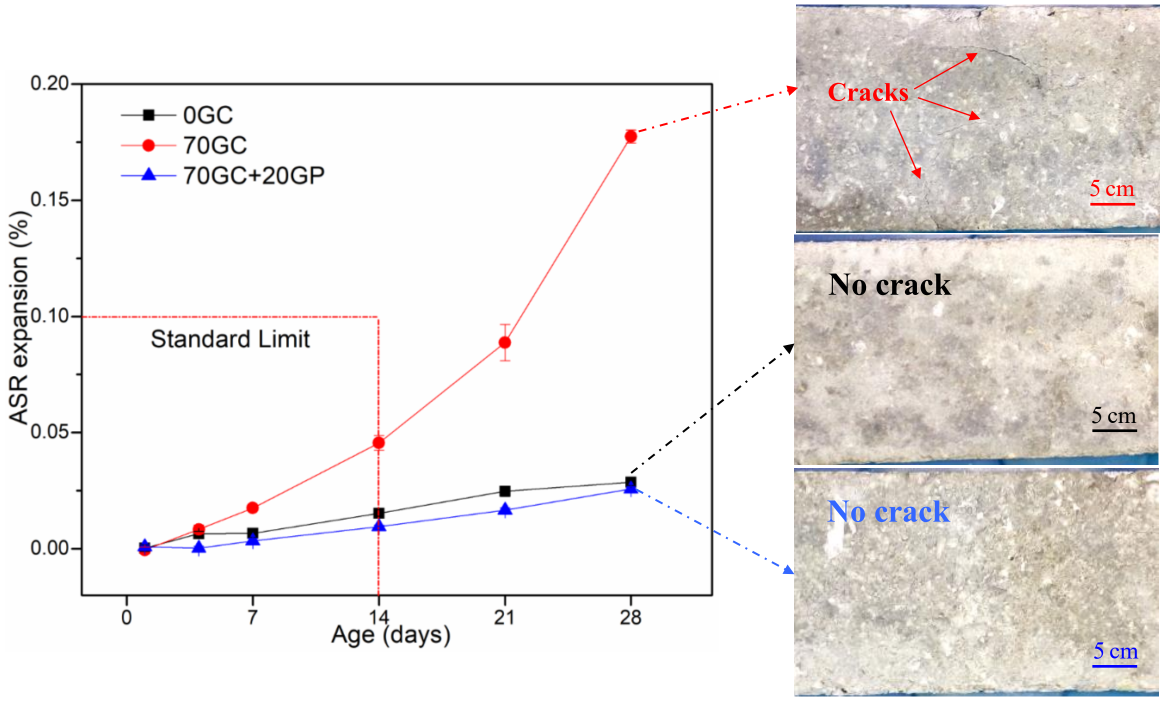

Fig. 7 Effect of GC and GP on the ASR expansion of paving blocks

As expected, the high content of GC in the paving blocks would cause excessive expansion when subjected to the accelerated test due to the alkali-silica reaction (ASR) expansion (as shown in Fig. 7). Although the ASR expansion within 14 days was below permissible limit, the severe expansion at later ages is still a concern. Indeed, the expansion of 70G specimen increased rapidly after immersion in the alkali solution for 14 days. This is because the process of silica dissolution from glass was slow under the attack of hydroxyl ions at the early age. After 14 days, the reaction between the alkali and the silica developed intensely in the glass aggregates and the accumulated swelling pressure due to the ASR gel incurred excessive expansion (to be discussed in Section 3.5). Apparently, deteriorated ASR cracks were observed on the surface of the block specimen when 70% of total aggregates was replaced by GC. This is attributed to the increased volume of ASR gel in the region of reaction sites resulted in expansive stress, which had exceeded the tensile strength of the cement paste [42].

By contrast, no ASR crack was observed in the control mixture (0GC) prepared without GC and the 70GC+20GP specimen in which GC and GP were used simultaneously. The results show that the use of GP as a replacement of cement was very effective in reducing and eliminating the potential ASR risk triggered by GC when 20% GP were cooperatively used with the maximum content of GC in the paving blocks. This encouraging result was consistent with previous findings [6, 43] that using 20% GP in the binder could successfully inhibit the ASR when cement mortars was prepared with 100% GC as aggregates. The reason for such high effectiveness might be due to the favorable composition of GP and its fine particle size. The explanation will be further elaborated in the following section. It can be concluded that the combined use of GC and GP can effectively eliminate the potential risk of ASR in the concrete paving blocks and further contribute to the durability and sustainability of the blocks.

3.5 Microstructure analysis

In order to better understand the underlying deterioration mechanism of the ASR expansion due to the GC incorporation and the beneficial roles of the GP in mitigating the ASR of the GC, SEM equipped with EDX studies were conducted. Fig. 8 presents the morphology and elemental compositions for the block specimens after the ASR test for 28 days. In the cases of the paving blocks prepared without GC, there were micro-cracks present within the aggregate particles (as seen in Fig. 8(a)). These cracks were likely associated with the dry-mixed fabrication process [18]. Also, cracks were found in the vicinity of the fine aggregates (see Fig. 8(b)) due to the poor bonding with the cement paste. However, it is obviously noticed that no expansive ASR gel was found within the cracks both in the interior and the surface of the aggregates. This means that little ASR risk was associated with the use of crushed granite as fine aggregates. In addition, the result correlated well with the low ASR expansion of the paving blocks prepared without GC.

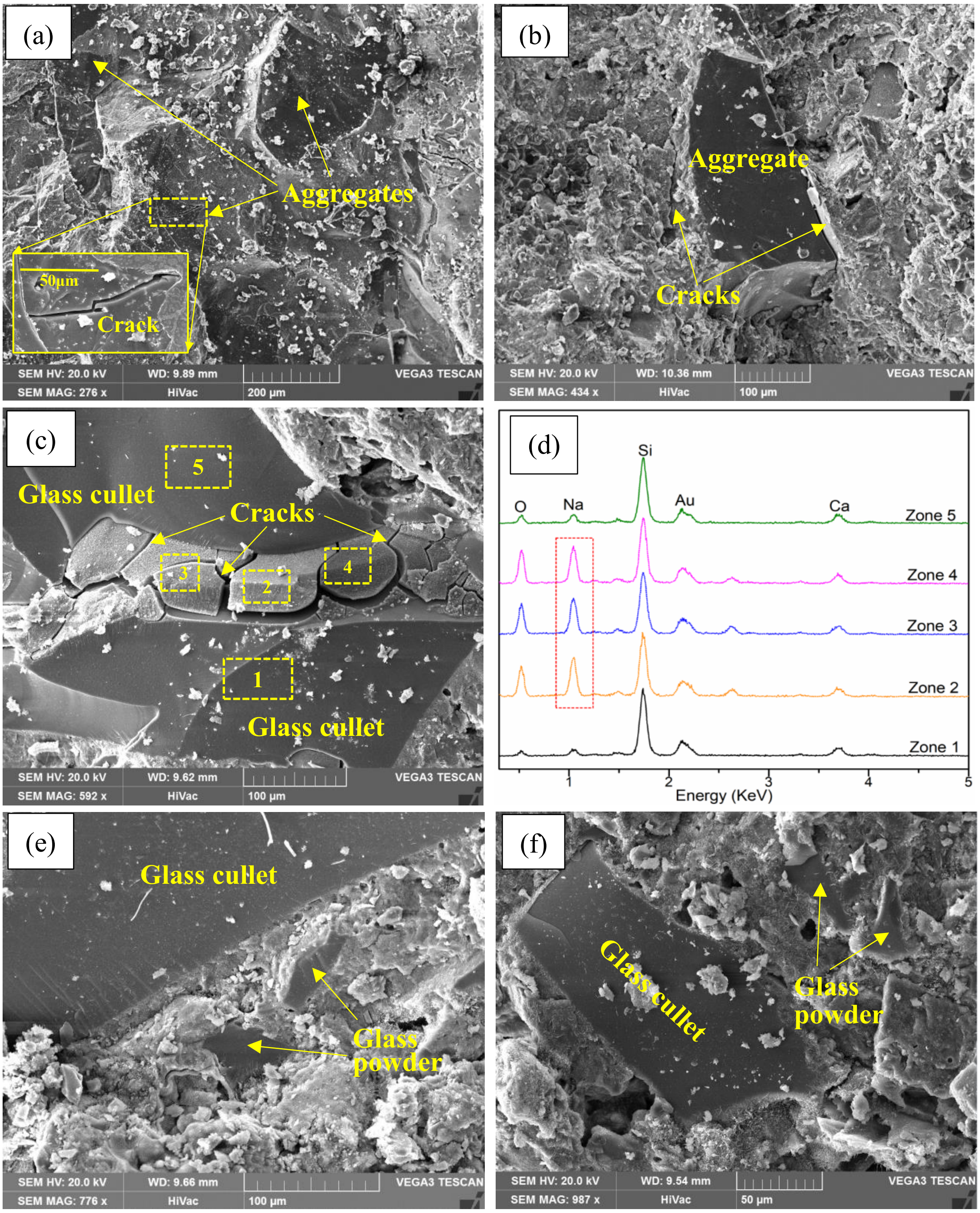

Fig. 8 Morphology observation of ASR expansion in paving blocks, 0GC (a, b); 70GC (c, d); 70GC+20GP (e, f)

Fig. 8(c) shows the microstructure of the block specimen prepared with 70% GC after 28 days of immersion in 80°C NaOH solution. It can be clearly observed that larger cracks were formed in the interior of the GC. Generally, ASR is considered to form on the surface of the reactive siliceous aggregates, which is dissolved by hydroxyl ion and the dissolved silicate react with the alkaline ions to form ASR gel [44]. However, in the case of the dry-mixed paving blocks, internal micro-cracks were likely to be generated initially within the glass aggregates due to the high pressure compaction procedure. The original micro-cracks inside the interior of the large glass particles provided a favorable condition for the formation of ASR gel because the dissolved silica and sodium ions present in the small space of the micro-cracks could hardly diffuse away [42, 45], leading to very high concentrations of silica and sodium and a low concentration of calcium in the cracks. Hence, the ASR gel was formed and accumulated within the GC.

To validate this assumption, EDX was used to analyze the ASR gel on the surface of the GC. Fig. 8(d) and Table 3 illustrate the elemental compositions of zones 1~5 of Fig 8(c). Fig. 8(d) shows similar elemental distributions in zones 1 and 5 with a relatively low sodium content. The high silica concentrations as indicated in Table 3 confirm that the zones 1 and 5 were the glass particles. In contrast, it can be seen in Fig. 8(d) that the zones 2, 3 and 4 contained much higher sodium contents. These results are verified in Table 3, which shows that the sodium concentrations in zones 2, 3 and 4 were more than twice of those in zones 1 and 5. Meanwhile, the amounts of calcium in zones 2, 3 and 4 were less than half than in zones 1 and 5 (GC). Therefore, it is highly likely that these alkali-calcium-silicate products in the interior of GC with extremely high Na/Si and Na/Ca ratios (see Table 4) were the expansive ASR gel, which led to excessive expansion by adsorption of water.

Table 4 Compositions of zones 1, 2, 3, 4 and 5 by EDX

Atomic%	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Ca	8	3	3	3	6
Si	43	17	17	17	35
Na	7	17	17	16	8
Ca/Si	0.19	0.18	0.18	0.18	0.17
Na/Si	0.16	1.00	1.00	0.94	0.23
Na/Ca	0.88	5.67	5.67	5.33	1.33

Another interesting result obtained was the low Ca/Si ratios (<0.2) in zones 2, 3 and 4 (ASR gel). As reported in previous studies [46, 47], ASR gel with Ca/Si ratios higher than 0.5 might have a high stiffness which did not expand as the composition and properties of ASR gel is close to those of normal C-S-H. On the contrary, the lower Ca/Si ratios of the ASR gel formed inside the GC could increase the potential expansion due to its lower stiffness. Subsequently, cracks would propagate from the GC [18] and extend to the surrounding cement paste matrix causing more cracking once the swelling stress exceeded the tensile strength of cement paste.

For the paving block prepared with GC and GP (Fig. 8(e, f)), it can be noticed that no observable ASR-induced cracks were found within and on the surface glass particles. This indicates that the addition of fine glass particles (i.e. GP) could effectively suppress the ASR expansion caused by the coarse glass particles (i.e. GC). The observation also supports the beneficial effect of GP as shown in Fig. 7. The possible explanations could be due to the composition and particle size effects of GP. As reported by Shehata and Thomas [48], the efficacy of fly ash in controlling ASR expansion increased as its silica content increased. Based on this mechanism, the addition of GP with a high silica content would play the same role in reducing ASR expansion. In addition, the alkali hydroxide would preferentially react with the small GP particles (large specific surface area) to form mature alkali silicate, which could further combine with calcium ions to form solid calcium alkali silicate, thus avoiding the formation of reaction rims around the reactive glass aggregate [49]. This explanation was supported by the study of Kamali and Ghahremaninezhad [50], which indicated that the dissolution of large-sized glass was significantly reduced in alkaline solution (1 N NaOH solution at 80°C) with GP addition. The reduced concentration of hydroxyl ions available near the coarse glass aggregates due to the prior reaction with the fine glass particles may be responsible for the reduction in the rate of silica dissolution from GC. Therefore, the incorporation of GP with finer particle size was effective in reducing ASR of the glass aggregates.

The Fig. 9 shows the characteristics of pore structure in the maximum GC incorporating paving blocks with and without 20% GP. The refinement of pore size due to the introduction of GP can be observed. The dense microstructure induced by the GP could be a reason for the reduced water absorption. Moreover, the number of finer pores was increased as the cement was replaced by the GP. This beneficial effect was mainly attributed to the formation of additional hydration products by the pozzolanic reaction between the GP and the calcium hydroxide. A previous study [21] also found that many fibrillar hydrates were formed in the cement-glass powder matrix due to the high amorphous silica content in the GP. These fibrillar shaped hydration products were conducive to filling the large pores and strengthening the matrix.

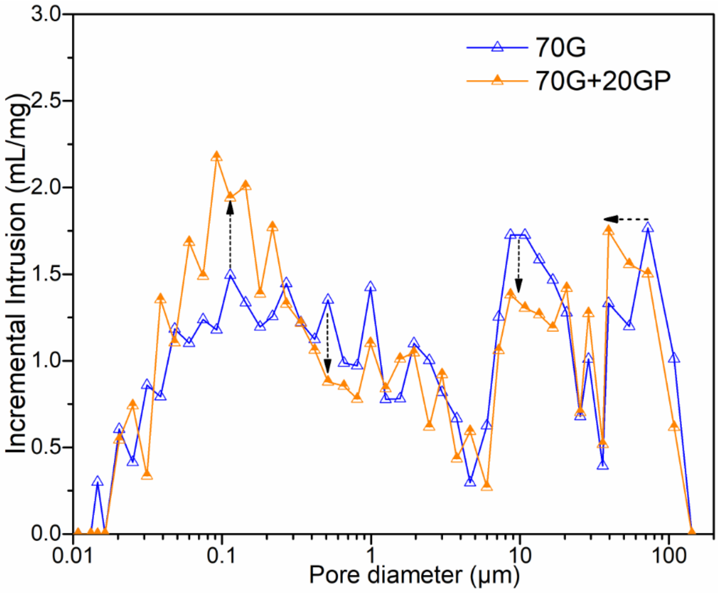

Fig. 9 Effect of GP incorporation on the pore structure of paving blocks prepared with 70% GC as aggregates

4. Discussion

The experimental results showed that the use of aggregates with a low water absorption (i.e. GC) as fine aggregates significantly reduced the water absorption of the concrete paving blocks. This indicates that the water absorption of the aggregates itself also played an important role in affecting the water absorption of the produced concrete products. Poon and Lam [13] found that the water absorption value of the concrete mixes was closely associated with the corresponding water absorption of the aggregates used. Therefore, the result of this study provides guidance to design concrete or paving blocks with specific water absorption through the selection of aggregate types. Moreover, it is encouraging to find that the replacement of cement by 20% GP can further result in the reduction of the water absorption of the paving blocks. Based on the pore structure analysis, the reduced large pores and increased number of small pores due to the introduction of GP may contribute to the reduced water absorption.

It is noteworthy that the drying shrinkage value of the paving blocks prepared with the maximum content of GC used in this study was far below the limit of 1000 micro-strains as recommended by the Australian Standard (AS1012.13) for concrete. On the basis of using the maximum amount of GC as fine aggregates, a further decrease in the drying shrinkage was found by partially replacing cement by GP. Due to most of the recorded shrinkage occurred in the early age, the physical characteristics (including irregular shape, higher aspect ratio and negligible water absorption) of the glass particles were thought to be responsible for this beneficial effect. Therefore, in terms of shrinkage performance, using the glass materials as fine aggregates and a binder would be able to reduce the shrinkage. More significantly, the experimental results showed that the compressive strength of the paving blocks did not decrease as the GC content was gradually increased to the maximum content. Moreover, the further use of 20% GP to replace cement did not affect the mechanical strength. Overall, the percentage of the glass materials that can be used in the concrete paving blocks can reach 60% of its total mass.

The major concern on using a large amount of glass materials in concrete products is the potential structure damage caused by the deleterious ASR expansion. As shown in the accelerated ASR test, the 14-day expansion of the paving block prepared with the maximum GC proportion as fine aggregates did not exceed the standard limit (0.1%). This was ascribed to the porous structure of the dry-mixed paving blocks, which could accommodate the volume increase caused by the formation of ASR gel [18]. However, due to the original micro cracks formed in the GC during the fabrication process, the paving blocks with GC still exhibited high ASR expansion because the ASR gel with high Na/Si and Na/Ca ratios preferentially formed in the original cracks. This was found to be potentially deleterious at the later age when only GC was used to replace nearly 100% of the fine aggregates. In order to prevent the ASR expansion, 20% of cement was further replaced by GP. Although soda-lime-silica GP also contains a high alkali content, the use of milled GP as cement replacement in the concrete paving blocks could greatly suppress the ASR induced by the GC. The beneficial effects of the GP were mainly attributed to its high silica content and its fine particle size.

5. Conclusions

The increasing amount of waste glass that needs to be disposal of at landfills has brought renewed interest in maximizing the application of waste glass in concrete products. This study demonstrated the use of glass powder (GP) as a supplementary cementitious material would be able to increase the waste glass cullet (GC) content in the concrete paving blocks. Based on the experimental results, the following conclusions can be drawn:

- Both the density and water absorption were significantly reduced with the increase of GC content in the concrete paving blocks. In addition, the water absorption values of the paving blocks incorporating the maximum amount of GC (70%) were much below the specified requirement of 6%. Further replacing 20% of the cement by GP could lead to greater reductions in the density and the water absorption.

- The incorporation of the maximum GC content in the concrete paving blocks could produce acceptable drying shrinkage values below 1000 micro-strains, as required by the Australian Standard AS1012.13. The replacement of cement by GP further reduced the drying shrinkage due to the cement dilution effect and the micro-fiber effect of the irregular shape and high aspect ratios of the glass particles.

- Increasing the replacement level of fine aggregates by GC did not have a significant negative effect on the compressive strength of the paving blocks. The paving blocks containing nearly 100% GC as fine aggregates and 20% GP as binder could still satisfy the Hong Kong specifications of the applications for footpaths and carriageways.

- Incorporating 20% GP with particle sizes less than 50 μm in the paving blocks could successfully suppress the ASR expansion caused by the use of a high GC content. The high Si content and the fine particle size of GP might play important roles in preventing the formation of ASR gel.

- Considering the improvements of physical, mechanical and durability performance, the production of this eco-friendly concrete block with GC and GP seems to be a promising alternate outlet for the recycling of waste glass.

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