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Review

Management and recycling of waste glass in concrete products: Current situations in Hong Kong

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ABSTRACT

Disposal of more than 300 tonnes waste glass daily derived from post-consumer beverage bottles is one of the major environmental challenges for Hong Kong, and this challenge continues to escalate as limited recycling channels can be identified and the capacity of valuable landfill space is going to be saturated at an alarming rate. For this reason, in the past ten years, a major research effort has been carried out at The Hong Kong Polytechnic University to find practical ways to recycle waste glass for the production of different concrete products such as concrete blocks, self-compacting concrete and architectural mortar. Some of these specialty glass-concrete products have been successfully commercialized and are gaining wider acceptance. This paper gives an overview of the current management and recycling situation of waste glass and the experience of using recycled waste glass in concrete products in Hong Kong.

Contents

1. Introduction

Waste reduction and recycling are very important elements in a waste management framework because they help to conserve natural resources and reduce demand for valuable landfill space. Discarded beverage glass bottles, being one of the significant municipal waste types has been a major concern in Hong Kong

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as only few recycling channels can be identified. Government data has shown that about 373 tonnes of glass waste is generated daily in Hong Kong, but, the recovery rate is less than 3.3% (EPD, 2010). Today, discarded waste glass already is a burden on the waste disposal facilities in many parts of the world. In most countries, generally glass bottles are just used once or a few times and then discarded. Unlike other forms of waste like paper or organic constitutes, waste glass bottles will remain stable after disposed of at landfills and it also constitutes a high proportion of the residues should incineration is used for waste treatment.

Ideally, the waste glass should either be reused or remanufactured to produce new glass containers. However, due to the lack of a glass manufacturing industry, opportunities for reusing and remanufacturing of waste glass in Hong Kong are rather limited. Also, during the waste collection processes, some of the collected waste glass becomes contaminated, colour-mixed or even broken, which render them unsuitable for reusing and remanufacturing of new glass products. There are keen interests to develop alternative markets to utilize recycled glass. Since all commercial glasses are based on silica, which consists of over 70% SiO_2, it is believed that waste glass can be crushed and sorted into desired particle sizes as aggregates or as a pozzolanic material for applications in the construction industry.

In this paper, the present management and recycling situation of waste glass in Hong Kong is reviewed. The research and development undertaken by The Hong Kong Polytechnic University (PolyU) on the use of recycled glass as an aggregate replacement in different concrete products is presented. Moreover, the existing and potential applications of the developed glass-concrete products in the construction industry are discussed.

2. Management options of waste glass

From the “Waste Statistics for 2010” and “Waste Reduction and Recovery Factsheet No.6” (EPD, 2010), 373 tonnes of waste glass are produced daily in 2010, which is equivalent to 4.1% of municipal solid waste. 83% of the waste glass is generated from households while the remaining 17% are from commercial and industrial sectors. In 2010, 4500 tonnes of the glass were recycled annually, the recycled percentage is 3.3%, and the remaining 96.7% was sent to landfill for direct dumping. The glass recycling and disposal statistics in the past 4 years are shown in Table 1.

Various options are available for managing waste glass. After waste prevention and re-use, the highest preference is recycling.

2.1. Disposal of waste glass

Post-consumer waste glass represents one of the major components of the solid waste stream in Hong Kong. In 2010, 96.7% of waste glass in Hong Kong (which is equivalent to 131,864 tonnes) was sent to landfill for direct dumping (EPD, 2010). While the three strategic landfills are projected to be full in 2015 (EPD, 2005), it is essential to find a sustainable way to reuse and recycle the glass.

2.2. Recycling of waste glass

Glass recycling is the process of turning waste glass into usable products. Traditional methods of waste glass recycling need to melt the waste glass to reproduce new glass containers. This technique has greatly reduced the energy needed in the furnace. Although it was found that 315 kg of CO_2 could be is saved per tonne of glass melted (Waste Online, 2008) Hong Kong does not have a local glass manufacturing industry base. Furthermore, the collected waste glass is usually colour mixed and with the presence of dirt which are barriers for its reuse for glass manufacturing. Comparatively, mechanically crushing of large quantities of waste glass into cullet and reuse as aggregate substitutes in concrete is a much more economical way for waste glass recycling. In addition, the cleanliness requirements of waste glass cullet to be used in concrete are also relatively lower compared with the traditional recycling method (WSDTED, 1993).

2.3. Current situation of waste glass recycling in Hong Kong

In Hong Kong, glass bottles are mainly used for holding drinks and beverages. Currently, there are four recycling/reuse methods for after-use waste glass bottles in Hong Kong, and they are:

(1) Recycled as a fine aggregate in eco-blocks.
(2) Collected through a deposit-and-refund system by local beverage manufacturers and reused.
(3) Collected and cleaned by individual shops for reuse for filling of other materials (e.g. kerosene and thinners).
(4) Collection, crushed and exported to overseas for recycling.

In the past, a typical recycling system of glass bottles called “deposit-and-return” was used quite extensively in Hong Kong at the retail level to recover glass bottles for re-filling (EPD, 2007a). However, nowadays the system is considered no longer cost-effective to operate and the quantity of glass bottles circulated in a “deposit-and-return” system has dropped to a low level. This situation became even worse after more local beverage manufacturers bottling plants had moved out of Hong Kong. This explains why the majority of local beverage manufacturers are opposed to implementing or maintaining the “deposit-and-return” recovery system.

The hindering factors for the low recycling rate are that glass has a low commercial value and the immature market for after-use products. Moreover, glass is heavy which increases the transportation and handling costs.

2.4. Existing collection channels for waste glass recycling in Hong Kong

EPD has initiated several partnership recycling programmes with different government departments and the business sectors. In November 2008, EPD has partnered with the Hong Kong Hotels Association to launch the first voluntary product responsibility scheme (PRS) in the territory for the Glass Container Recycling Programme of the Hotel Sector (EPD, 2008a). At present, there are 23 participating hotels accounting for 19% among the 118 member hotels in 2011.

With the help of Hong Kong Housing Authority (HKHA), EPD has launched a Pilot Programme on Source Separation of Glass Bottles in December 2010 at six public rental housing estates in East Kowloon. Recycling bins were set up in lift lobbies and near the 3-coloured waste separation bins. This one-year pilot scheme has recycled a total of 73 tonnes of glass.

In February 2012, EPD has cooperated with charities such as St. James’ Settlement, Boys’ Brigade, etc. to expand the scope of recycling for those are not covered by the Source Separation of Domestic Waste Programme. Glass is one of the three items identified for this recycling network. Community recycling booths are set up in parks, pedestrian walkways and housing estates in various districts every Sunday afternoon in promoting of this channel to the public. The waste glass bottles are collected by the Community Recycling Promotion Vehicles and transport to the Kowloon Bay Material Transfer Centre or Eco Park in Tuen Mun for pick up by local glass recyclers.

Besides the partnership recycling programme, non-government organizations have setup a limited territory-wide network for glass recycling. However, non-government organizations have limited

Table 1
Quantity of recovered recyclable materials (EPD 2007b, 2008b, 2009, 2010).

Year	Glass disposal to landfill[a] (tonnes)	Recovered glass[b] (tonnes)	Exported glass (tonnes)	Recovery rate (%)
2007	95,000	1000	70	1.3
2008	101,000	1000	0	1.5
2009	93,000	3000	0	2.9
2010	137,000	5000	11	3.3

[a] Figures are rounded off to the nearest 1000 tonnes.
[b] The quantity does not include glass beverage bottles recovered through deposit-and-refund system operated by local beverage manufacturers.

resources and the locations for drop-off are inconvenient for most citizens, thus the collection rate is low.

2.5. Legislation and waste charges

Another major factor contributing to the low glass recycling rate in Hong Kong is the lack of legislation or other mandatory policies to promote glass recycling and the lack of a charging scheme for MSW disposal. Unlike many other dense metropolis in Europe, the US and Japan, Hong Kong has no government policy or legislation requesting producers (e.g. producers' responsibility schemes) of waste glass to be responsible for its proper management (i.e. recycling or disposal). Furthermore, the cost for disposal of municipal solid waste to landfills, including waste glass, in Hong Kong is currently born entirely by government out of the general revenue, and waste producers do not need to pay directly for any waste disposal fee. Therefore, little financial incentive is in place to encourage reducing and recycling of waste glass.

3. Background on the use of recycled glass in cement mortar and concrete

Since 1963, the first study had been carried out on the use of glass chips to produce architectural exposed aggregate for concrete (Schmidt and Saia, 1963). Later, owing to the excellent hardness of glass, extensive researches have been carried out to utilize recycled glass as aggregate in concrete (Topçu and Canbaz, 2004; Sangha et al., 2004; Park et al., 2004; Ismail and AL-Hashmi, 2009; Limbachiya, 2009). However, with the use of high content glass aggregates in concrete, a serious alkali–silica reaction (ASR) maybe induced which resulted in a lower strength and durability of concrete (Byars et al., 2004).

Thus, most of the recent work concentrated on studying the feasibility of milling the glass cullet into powder form (glass powder) and used it to replace cement in concrete. This is because glass powder contained high silica content that can function as a pozzolanic material to react with Portlandite in hydrated cement to form C–S–H in enhancing the strength and durability of concrete (Shao et al., 2000; Shayan and Xu, 2004; Shi et al., 2005; Shayan and Xu, 2006; Özkan and Yüksel, 2008; Schwarz et al., 2008; Taha and Nounu, 2008). The glass cullet when crushed to fine powder sizes have been proved to be innocuous of in terms of alkali silica reaction (ASR) in concrete (Shi and Zheng, 2007).

4. Research and development undertaken by PolyU on the use of recycled glass as aggregate in different concrete products

4.1. Converting waste glass to valuable materials

Currently, there is a general move to adopt new operation strategies aiming at effectively recycle waste glass from the municipal solid waste stream. Fig. 1 shows the steps of converting waste glass to valuable materials such as aggregates and pozzolanic additives in construction materials. The waste glass bottles are delivered to the processing facility for washing and crushing. The particle size grading of glass cullet should pass the 10 or 5 mm sieve depending on the effect desired. The crushed glass cullet possesses reasonable intrinsic strength, low water absorption and the ability to withstand extreme temperature without signs of deterioration. The 5 mm glass cullet is then milled into glass powder with a median grain diameter of 75–150 μm to be used as a pozzolan for cement replacement in concrete.

4.2. Use of recycled glass in concrete block

As there is a need to explore other management alternatives of waste glass in Hong Kong, an extensive research has been carried out at Hong Kong PolyU to produce concrete paving blocks and bricks made with glass aggregates (Lam, 2006; Lam et al., 2007; Poon and Chan, 2007; Poon and Cheung, 2007; Chen and Poon, 2009a,b; Lee et al., 2011). The laboratory production process used a semi-mechanized moulding method for fabricating the blocks (see Fig. 2). Using such a technique, the semi-dry mixed materials are moulded under a strong compacting action so that the requirement for maintaining a low workable mix can be achieved. Only

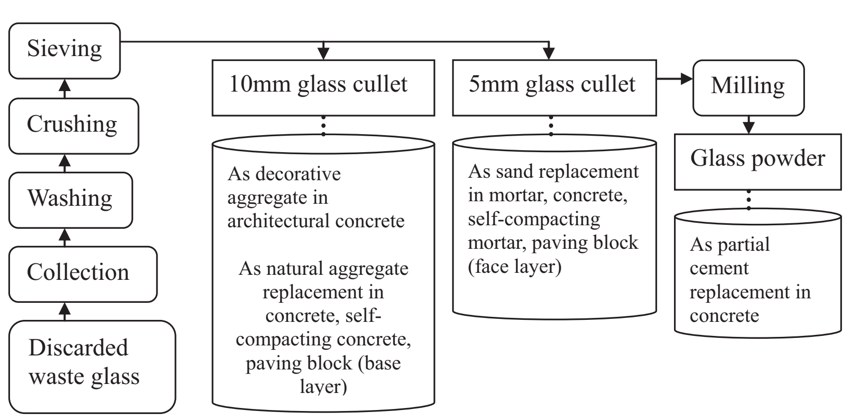

Fig. 1. Steps of converting waste glass to valuable materials and its applications.

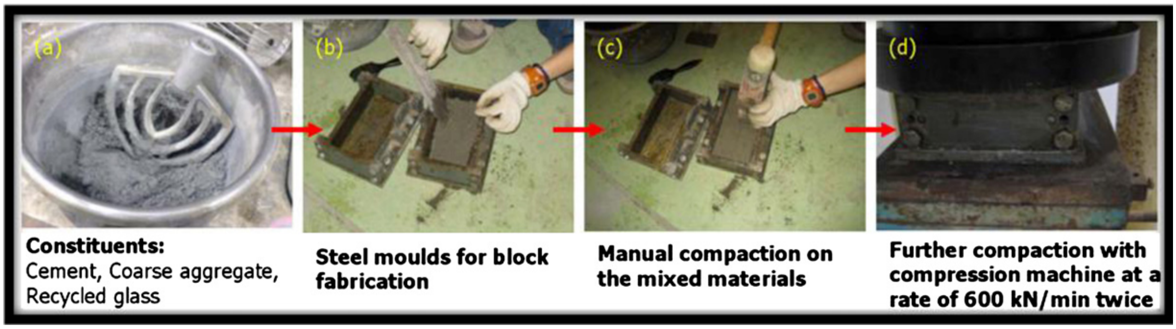

Fig. 2. Glass-concrete paving block making process.

a minimal amount of water was needed to make the mixture fluid enough to be compacted.

Table 2 shows the typical mix proportions and strength results of concrete blocks prepared with different glass contents. As the replacement of natural aggregate by glass increased from 25 to 75%, there was a slight reduction in the splitting tensile strength and no noticeable effect on compressive and flexural strength (Lam et al., 2007). Turgut (2008) reported that at 9.4% glass content, the compressive strength and flexural strength of the glass blocks were 21.1% and 77.3% respectively higher than that of the control masonry block. Turgut and Yahlizade (2009) also reported that when 20% of fine aggregate was replaced by <1.18 mm fine glass, there was an improvement of the compressive strength, flexural strength, splitting tensile strength and abrasion resistance of paving blocks by 69%, 90%, 47% and 15%, respectively. However, the improvement is reduced when the 4.75 mm coarse glass was used instead of the fine glass. Furthermore, Lam (2006) found that the compressive strength of the masonry and paving blocks were related to the fineness modulus (FM) of the aggregates (including crushed glass cullet) used. He suggested that the most suitable particle size range of aggregate for dry-mixed concrete paving block was with FM values ranged from 3.5 to 4.5.

The presence of high silica content in glass cullet can react with alkali to cause expansion due to ASR in the cement matrix. But the results of Lam et al. (2007) and Lee et al. (2011) indicated that the ASR problem was less critical in dry-mixed concrete blocks as compared to wet-mixed concrete (concrete block specimens prepared with a glass content of less than 20% induced negligible ASR expansion). This may be due to the higher porosity in dry-mixed concrete which can accommodate the expansive pressure. Similarly a total of 96 mixes of semi-dry concrete products were tested by Byars et al. (2004) and the results showed that up to 52 weeks almost all the specimens exhibited zero ASR expansion.

Based on the laboratory results obtained at PolyU, the optimized mix proportions were selected for pilot scale plant test production in a local block manufacture. At the plant, two independent mixers were used with appropriate capacities to produce the blocks with a two-layer block structure (a base layer and a surface layer, Fig. 3).

For the base layer, the aggregates (including natural, recycled and glass aggregates and cement were mixed in mixer. After the dry mixing, water was added to the materials until the desired moisture content was obtained. The mixtures were transferred from the mixer to a feed hopper. The hopper discharged the correct amount of the prepared mixture into the mould in the block moulding machine. The mould was filled and the first vibration and compaction was applied. Immediately afterward, the face mix for the surface layer (sand, <2.36 mm glass cullet and cement, prepared in parallel to that of the base layer) was poured into the mould on top of the first layer before the 2nd and final compaction and vibration were applied.

The pilot plant test results showed that high quality glass-concrete blocks could be successfully produced in an industrial setting. The test results showed that recycled glass cullet can be used as a replacement for natural aggregate in the production of concrete blocks without affecting the properties. Indeed some aspects the performance is enhanced (such as reduced water absorption value, higher abrasion resistance). Novel colours of glass and special light reflections due to the presence of glass can be obtained (Meyer et al., 2001).

An attempt was made by Chen and Poon (2009a) to combine the use of glass cullet as aggregates and titanium dioxide as photocatalytic materials in preparing the surface layer of the paving blocks.

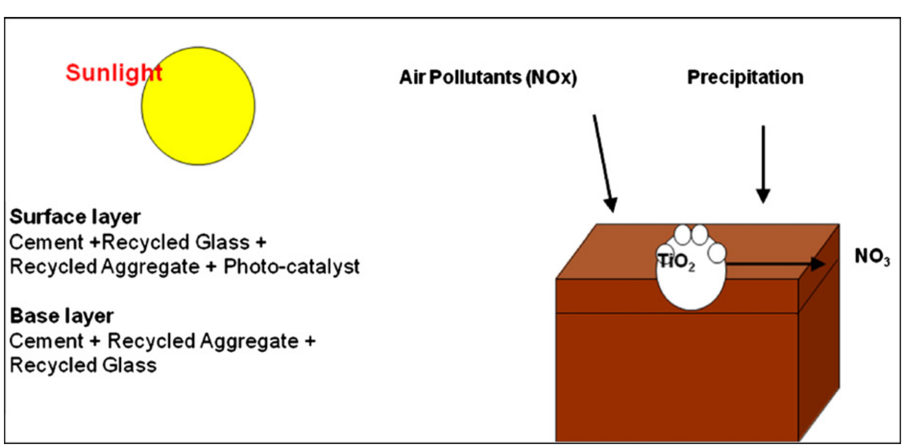

Fig. 3. Two-layer block structure prepared with different ingredients.

Table 2
Summary results on strengths of concrete block made with different percentage of glass aggregate.

Reference	Size of glass used	Type of replacement	Cement (kg/m^3)	W/C	% of replac.	28-day Strength, MPa		
						Com.	Flex	Tensile
Lam et al. (2007)	<5 mm, waste beverage glass bottles	Recycled fine aggregate	380	N/A	25	56	–	3.90
					50	54	–	3.36
					75	57	–	3.10
Turgut (2008)	99.8% passing 1.18 mm	Lime stone	212	0.30	0	27.5	4.15	–
					6.2	30.7	5.86	–
					9.4	33.3	7.36	–
Turgut and Yahlizade (2009)	<1.18 mm[a], <4.75 mm[b]	Fine aggregate	350	0.35	0	23.5	3.41	2.62
					20	39.7[a], 25.2[b]	6.48[a], 3.77[b]	3.84[a], 2.55[b]
					30	28.8[a], 31.5[b]	5.09,[a] 3.93[b]	2.72[a], 2.33[b]

[a] Replacement by fine glass (<1.18 mm).
[b] Replacement by coarse glass (<4.75 mm).

The results showed that nitric oxide (NO) removal increased when a higher percentage of glass cullet was incorporated. It is likely that light could be carried to a greater depth when the glass cullet are present so that a larger amount of TiO_2 can be activated within the inner part of the surface layer. Concrete surface layer made with clear glass cullet exhibited three times more efficiency to remove NO than surface layer made with river sand. In comparison, concrete surface layers containing clear glass also had a better photocatalytic activity than the darker coloured (dark green, brown) ones, probably due to clear glass has a better light-transmitting characteristic. The proposed mechanism of the enhanced phtocatalytic activity is illustrated by Fig. 4.

4.3. Use of recycled glass in self-compacting concrete

Self-compacting concrete (SCC) was first developed in Japan which has the ability to consolidate by its own weight without the requirement for external vibration. Since then, it has been used widely in construction industry due to the achievement of better flow and higher filling capacity to facilitate the casting of complex shaped members and highly congested steel reinforced structural members. An attempt was undertaken in PolyU to investigate the feasibility of using recycled glass for the production of SCC (Kou and Poon, 2009). Recycled glass cullet with two particle size ranges (<5 mm and 5–10 mm) were used to replace river sand and 5–10 mm granite. The fresh properties results showed that the slump flow and blocking ratio of concrete mixes increased with the increase of recycled glass cullet contents. A similar increasing trend of slump flow for the case of LCD-glass was also reported by Wang and Huang (2010). A possible explanation for the enhanced on fresh properties may be due to the hydrophobic nature of the glass cullet which can reduce the water requirement which would enhance the workability in SCC.

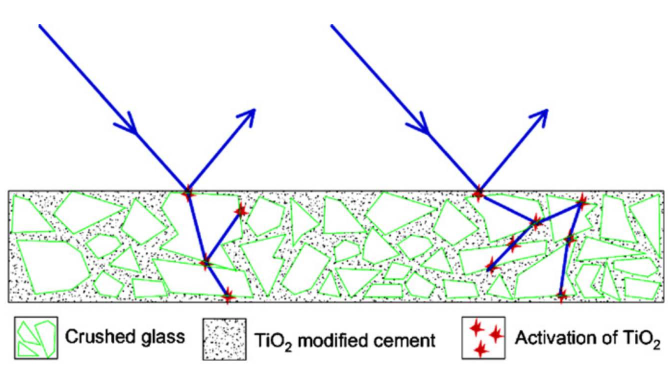

Fig. 4. Pathways of light and activation of TiO_2 in concrete block surface layer using glass as aggregates.
Sourced from Chen and Poon (2009a).

Compressive strength, tensile strength and static elasticity modulus of SCC decreased with the increase of recycled glass content due to the weak bonding between the cement paste and the glass aggregate. The compressive strength was decreased by about 1.5%, 4.2% and 8.5% as the glass content in concrete was increased to 15%, 30% and 45%, respectively (Kou and Poon, 2009). In terms of resistance to chloride ion penetrability and drying shrinkage, the two durability properties were significantly improved due to the very low water absorption and porosity of the glass cullet (Kou and Poon, 2009). The ASR results indicated that deleterious expansions and cracks might occur if the glass content was >45%. However, the ASR expansion of all the SCC specimens can be significantly reduced by the use of fly ash a part of binder.

Recently, studies on high temperature properties of SCC prepared with recycled glass have been carried out by Ling et al. (2012) and Ling and Poon (2012). The results demonstrated that SCC containing recycled glass showed two distinct patterns after exposure to the elevated temperatures. In the temperature range of 20–600 °C, the use of recycled glass decreased the residual strength of the concrete. However, after exposure to 800 °C, a beneficial effect of using glass aggregate in concrete was observed, particularly for the water soprtivity and elastic modulus of the concrete. This is because at this relatively high temperature, the partially melted glass aggregate in the concrete could fill the internal cracks and led to an enhanced pore structure and interfacial transition zone (ITZ) after the concrete has been cold down to room temperature (resolidification).

4.4. Use of recycled glass in architectural mortar

One of the most exciting applications of recycled glass appears to be in the field of architectural and decorative concrete (due to the aesthetic properties of the waste glass). In order to make the architectural and decorative concrete products more attractive, the percentage waste glass cullet in them must be as much as possible. Furthermore, good aesthetic effect can also be achieved by selective use of glass of different sizes. Ling and Poon (2011) have demonstrated that the use of particle size ranged from 2.36 to 5 mm or 5 to 10 mm can significantly increase the aesthetic of the glass architectural mortar (AM) produced.

A series of experimental work has been carried out at PolyU to assess the feasibility of using as much recycled glass as possible for the production of glass-architectural mortar (Ling et al., 2011). White cement (WC), metakaolin (MK), natural sand, recycled glass (RG), water and superplasticizer (SP) were used to prepare the self-compacting based glass-architectural mortars. The binder to aggregate ratio at 1:2 was used. All the mixtures were proportioned with a fixed water-to-binder (w/b) ratio of 0.4 and the SP dosage was varied in order to obtain the targeted mini-slump flow

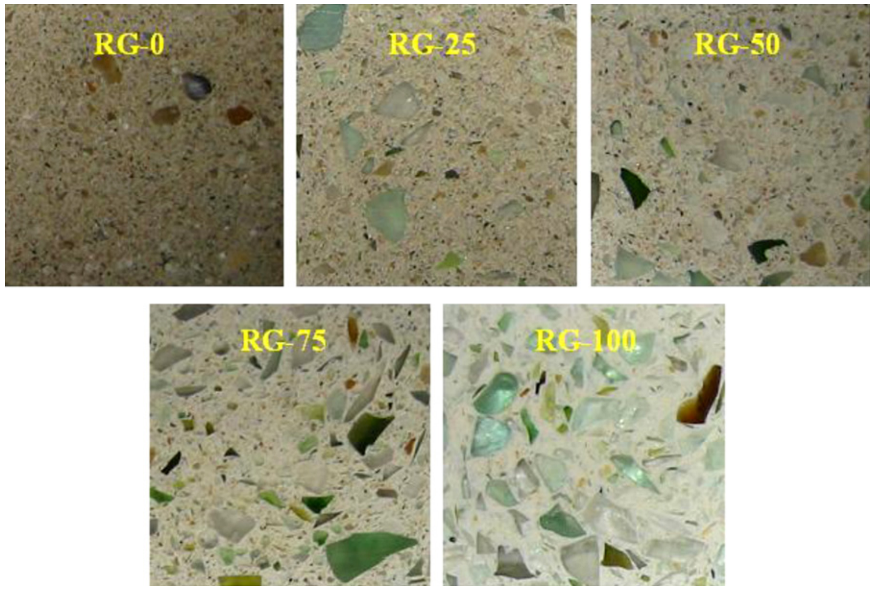

Fig. 5. Glass-architectural mortar featuring different replacement level of RG.

Sourced from Poon and Ling (2010).

values of 250 ± 10 mm. The RG was added to the AM mixtures as a partial replacement of the sand at the level of 25%, 50%, 75%, and 100% by mass.

The experimental work revealed that it is feasible to utilize 100% recycled glass as decorative aggregate in the production of self-compacting based AM. The AM prepared with 100% RG achieved a 28th day compressive strength of 44 MPa and a flexural strength of 6 MPa which are sufficient for various applications in the construction industry purposes. The use of MK at 20% level was able to suppress the ASR expansion below the limiting level. Fig. 5 shows the surface colour and aesthetic performance of the AM incorporating different amounts of RG. It was clearly observed that as the RG replacement ratio increased, the surface colour was brighter. Improved aesthetic performance and its colouration would cause significant attractive and acceptance when the AM was used for decorative application.

4.5. Current and potential application of developed glass-concrete products in construction industries

Fig. 6 shows the current and potential applications of the developed glass-concrete products in the construction industry. The glass-concrete block technology developed been commercially

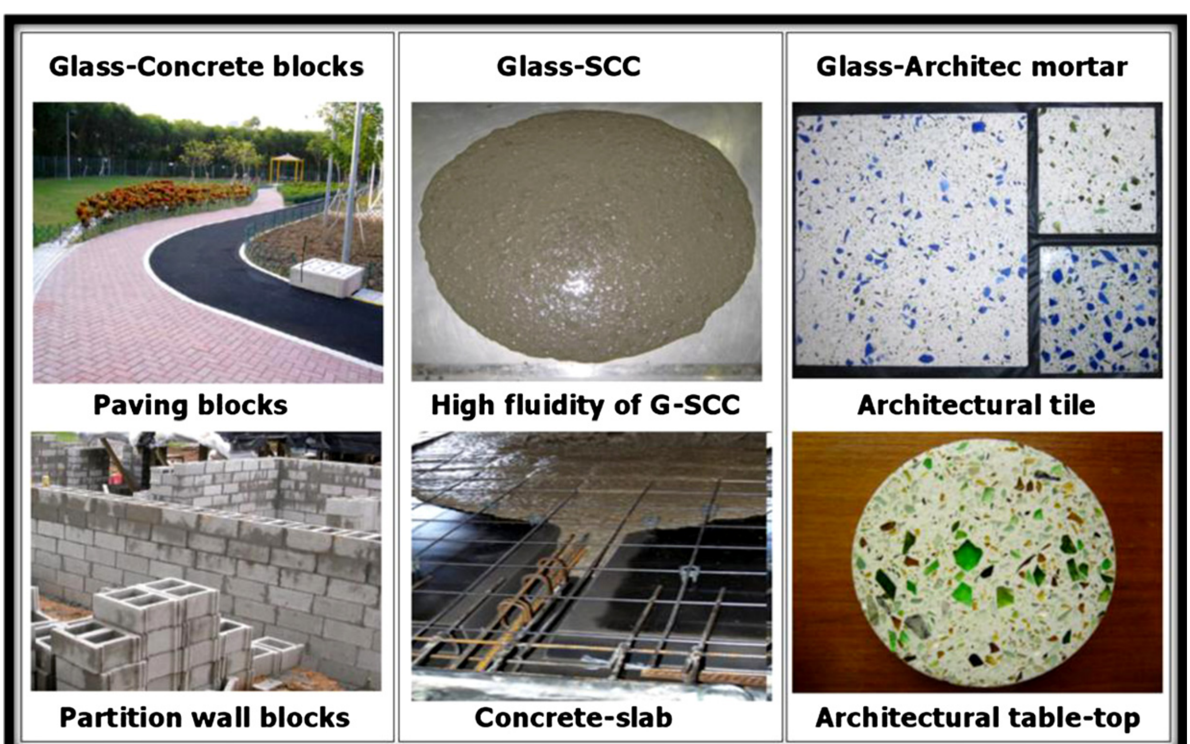

Fig. 6. Current and potential application of developed glass-concrete products in construction industries.

transferred to the local block manufacture and the blocks have already been put into successful uses at various different sites in Hong Kong, including the public pavements, housing and industrial estates, schools and parks. Recently, the Hong Kong Government Highway Department, has stipulated that the glass-concrete blocks should be preferentially used in all its maintenance work. Besides, the architectural glass mortar technology is also close to being commercialized. AM also shows high potential be used in floor tiles, building façade element and table top counter products for architectural applications.

4.6. Benefits of recycling the waste glass in concrete products

Recycling of waste glass in concrete products offers several advantages:

- Reduce the solid waste disposal problem in landfill.
- Reduce the use of natural material in construction.
- Utilize the reflective properties and aesthetic potential of glass for novel effects on concrete surfaces.
- Enhance the fluidity of fresh concrete due to its smooth surface.
- Reduce water absorption and drying shrinkage of concrete due to its impermeable properties.
- Improve the durability of concrete due to its high resistance to abrasion and acid.

5. Conclusions

Although a number of initiatives have been made both by the government and the private sector to promote waste glass recycling in Hong Kong, but there is still over 300 tonnes of waste glass require landfill disposal every day. There is a need to find alternative ways to recycle and develop a reliable market for this waste type.

The research and development work conducted at Hong Kong PolyU to assess the feasibility of using recycled waste glass in different concrete products (concrete blocks; self-compacting concrete; and architectural mortar) has attained promising results.

Further development in policy and legislative measures (e.g. landfill disposal charges, product responsibility scheme), change of engineering specifications (allow the use of glass architectural mortar in building projects) are needed to further enhance the recycling rate of waste glass in Hong Kong.

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