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Sustainable reuse of waste glass and incinerated sewage sludge ash in insulating building products: Functional and durability assessment

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Abstract

Using thermal insulating materials for internal walls construction is an effective way for improving the energy-saving of buildings. This study reports the development of a green concrete partition wall block using recycled glass as aggregates and incinerated sewage sludge ash (ISSA) as a partial replacement of Portland cement. Functional (density, porosity, compressive strength, thermal conductivity) and durability (drying shrinkage, fire resistance) performances were assessed. The experimental results showed that the eco-friendly blocks had sufficiently high strength to serve as a building partition material. Furthermore, the densities of the blocks were reduced with the incorporation of the glass aggregates and ISSA. Encouragingly, the combined use of glass aggregates and ISSA significantly reduced the drying shrinkage of the partition blocks. In terms of thermal insulation, the thermal conductivity of the blocks decreased considerably when the recycled glass and the ISSA were utilized simultaneously. Especially, the fire resistance of the partition blocks was improved effectively when the glass aggregates were used to totally replace the fine aggregates. Based on the findings, joint applications of waste glass and ISSA in producing partition wall blocks are appealing as it not only provides an alternative approach to reuse the wastes, but also achieve superior performance as an insulating wall material.

Keywords: Waste glass; Incinerated sewage sludge ash (ISSA); Thermal conductivity; Fire resistance; Partition blocks

1. Introduction

1.1 Waste glass and ISSA in Hong Kong

Waste glass beverage containers generated from restaurants, pubs-bars and residential areas is one of the major solid wastes in Hong Kong. There are approximate 300 tonnes of waste glass generation each day in 2017 according to statistics from the Hong Kong Environmental Protection Department (EPD, 2017). As compared to Europe, the recovery rate of waste glass in Hong Kong is very low (74% in Europe (FEVE, 2016) vs. 7.7% in Hong Kong (EPD, 2016)). Most of the waste glass bottles are just dumped in landfills instead of recycling. However, disposal of waste glass has increasingly become an environmental challenging as the current landfill sites will be full in a few years. Therefore, the Government encourages public works contractors and the private sector to use construction products incorporating waste glass to promote the development of waste glass recycling in Hong Kong.

Another type of solid waste in Hong Kong is incinerated sewage sludge ash (ISSA), which is the residual generated from the incineration process of dewatered sewage sludge from the Sludge Treatment Facility (T·PARK). Although the incineration treatment can lead to a significant reduction (88%) in the amount of the waste, more than 100 tonnes of ISSA per day are still generated (EPD, 2017). Currently, the only disposal method of ISSA in Hong Kong is landfilling. However, this method is not considered sustainable as ISSA may pose potential risks to the environment and human health. Therefore, to save the capacity of landfill space and turn wastes into resources, studies should be carried out to find alternative and practical solutions for ISSA recycling.

Due to the waste glass and ISSA contain significant amounts of silicon, aluminum, calcium (Lu and Poon, 2019; Donatello and Cheeseman, 2013), reuse and recycling of them into building and construction products could be a practical strategy. Moreover, the potential huge market in the construction industry makes it an attractive recycling option.

1.2 Use of waste materials in partition blocks

Partition blocks are usually used as non-structural internal partitions of buildings, which require a relatively low strength as compared to conventional structural concrete products. Low thermal conductivity and good fire resistance are two primarily parameters for the partition wall blocks, with the aim of reducing heat transfer (energy-saving) and improving fire safety. To promote sustainable building and reduce costs, producing internal partition blocks with waste materials attracts growing interests recently.

However, it is known that waste materials generally have adverse effects on the properties of the construction products due to their inferior quality. Kou et al. (2012) fabricated partition wall blocks using fresh concrete waste (FCW) as fine aggregates, and they indicated that the drying shrinkage of the blocks increased as the percentage of the FCW increased because of the high water absorption of FCW. Moreover, the resistance to elevated temperatures of the blocks decreased with an increase of the FCW content. Another investigation by Xiao et al. (2011) also showed that the water absorption of the partition blocks increased as clay brick aggregates (CBA) were introduced as coarse and fine aggregates. However, the incorporation of CBA could improve the fire resistance of the partition blocks due to the inherent fire-resistant properties of CBA. In order to reduce the thermal conductivity, Yan et al. (2018) utilized crushed foamed polystyrene to replace recycled concrete aggregates in partition blocks, but the incorporation of recycled polystyrene resulted in severe deterioration in strength of the blocks.

In terms of using waste materials as binders in partition blocks, non-cement based building blocks were developed with the use of fly ash–lime–phosphogypsum (Kumar, 2003) and flue gas desulfurization gypsum (Vasconcelos, et al., 2010) as cementitious binders. Nevertheless, these cementless blocks exhibited low compressive strength (less than 5 MPa). Yazıcı (2007) also prepared building blocks with a low content of cement (5%) and coal combustion wastes (90%) and the compressive strength of blocks could reach up to 22 MPa at the age of 28 days. However, severe expansion cracks were found when the blocks were cured in water as the wastes contained high amount of sulfate and CaO. Investigation by Al-Jabri et al. (2009) showed that replacing cement by cement kiln dust up to 15% in lightweight concrete blocks could produce comparable strength to conventional concrete blocks. A recent study (Xuan et al., 2016) was conducted on combining the use of concrete slurry waste (CSW) as a cementitious paste and fine recycled concrete aggregate to produce cementless partition wall blocks. The process was also able to sequestrate CO_2 owing to the rich calcium oxide content of CSW. Hence, this CSW-based partition block was regarded as a carbon neutral eco-product and was shown to have high environmental sustainability by life cycle assessment (Hossain et al., 2017).

Given that ISSA has been proven to possess a moderate pozzolanic activity (Cyr, et al., 2007; Garcés et al., 2008;), it is therefore worth to explore the feasibility of using ISSA as a replacement of cement in producing partition blocks. In addition, previous works have demonstrated that it is feasible to use waste glass in concrete or mortars by utilization glass sand as aggregates and glass powder as a partial replacement of cement due to their high intrinsic strength and pozzolanic reactivity respectively (Du and Tan, 2014a; Du and Tan, 2014b; Du and Tan, 2015; Du and Tan, 2017; Kamali and Ghahremaninezhad, 2015; Lu et al., 2017a; Lu et al., 2017b). Hence, combining the use of ISSA as a partial substitution of cement and waste glass as a replacement of fine aggregate may be a promising approach for producing concrete partition blocks.

1.3 Objectives and significance

The use of partition wall blocks as a thermal insulating material is of great importance in energy saving, especially in Hong Kong as high temperature weather conditions hover most of the year. Therefore, how to produce partition blocks with a low thermal conductivity and high thermal resistance is the objective of this investigation. Considering cost and environment pollution, turning waste materials to resources by manufacturing better quality of partition blocks is an attractive option. In Hong Kong, the large amount of waste glass and ISSA generation has become a serious concern due to the lack of landfill disposal sites. Hence, this study was carried out not only to find innovative recycling methods for waste glass and ISSA but also to develop a well-functioned and durable construction product. Previously, no investigation has been conducted on improving the functional and durability performance of partition wall blocks using waste glass aggregate (WGA) and ISSA simultaneously.

2. Experimental design

2.1 Materials

The materials used to produce the concrete partition blocks were ASTM type I ordinary Portland cement (OPC, 52.5), natural coarse aggregates (NCA, 5~10 mm), recycled fine aggregates (RFA, 0~5 mm), waste glass aggregate (WGA, 0~5 mm) and incinerated sewage sludge ash (ISSA). The OPC was supplied by Green Island Cement in Hong Kong. The granite NCA and waste RFA were sourced from a local aggregate supplier and a construction and demolition sorting facility, respectively. The WGA used in this study was crushed from post-consumer beverage bottles and collected from a recycling facility in Hong Kong.

The appearances of RFA and WGA are presented in Fig. 1. It can be seen that the waste RFA contained a certain amount of soil and the un-washed WGA contained impurities such as paper. The gradation curves of RFA and WGA are shown in Fig. 2(a), which indicates that the obtained RFA and WGA could meet the requirement of BS882. The ISSA used was collected from the local sewage sludge incinerator (T-park). Before use, the RFA, WGA and ISSA were oven dried at 105°C for 24 hours. Fig. 2(b) shows the particle size distributions of OPC and ISSA, indicating that the mean size of ISSA (109.0 μm) was much larger than that of OPC (29.7 μm). The chemical compositions of OPC, ISSA and the waste glass are listed in Table 1.

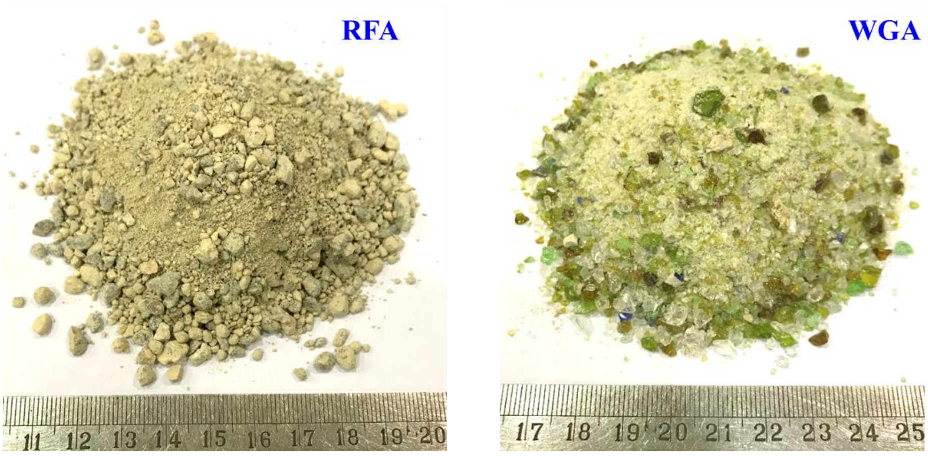

Fig. 1 Appearances of RFA and WGA

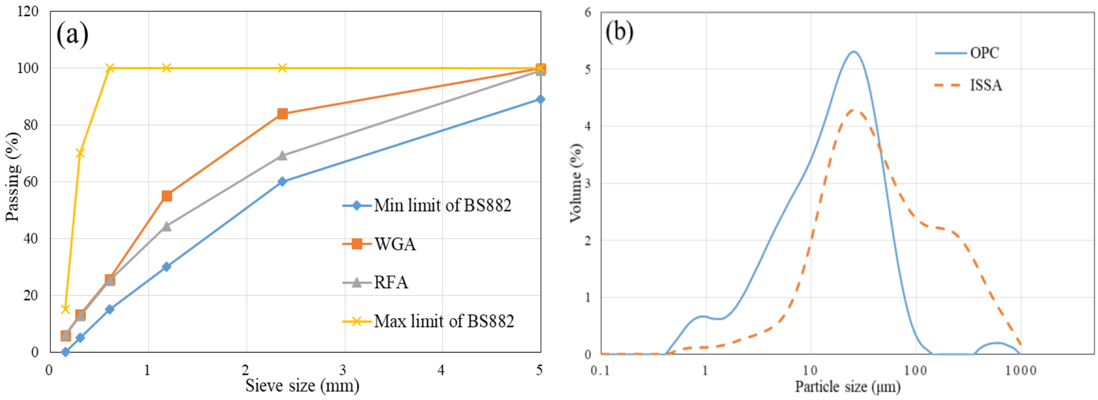

Fig. 2 Gradation curves of fine aggregates (a), particle size distributions of OPC and ISSA (b)

Table 1 Chemical compositions and physical properties of OPC, ISSA and glass

Chemical composition, %	OPC	ISSA	Glass
SiO_2	20.33	37.04	73.50
Al_2O_3	5.21	15.24	0.73
Fe_2O_3	3.13	14.03	0.38
CaO	64.00	6.91	10.45
MgO	1.62	2.80	1.25
Na_2O	/	7.11	12.74
K_2O	0.63	2.77	0.69
SO_3	4.17	3.66	/
TiO_2	0.27	0.38	0.09
MnO	0.06	/	0.01
P_2O_5	0.20	9.12	/
Cr_2O_3	/	/	0.12
Specific gravity	3.15	2.33	2.45
Mean diameter (μm)	29.7	109.0	/

2.2 Mix design

Three series of mix proportion of concrete were designed for evaluating the feasibility of using waste glass as aggregates and ISSA as binder in the production of concrete partition blocks. According to our pervious study (Poon and Lam, 2008), for pre-cast concrete blocks, an aggregate-to-binder (*a*/*b*) ratio of 10 could achieve concrete strength of 29.7 MPa and a *a*/*b* ratio of 13 would produce a concrete strength of 12.6 MPa. Considering the WGA contained some impurities and ISSA with a large particle size might have adverse effects on the properties of the concrete blocks, the *a*/*b* ratio was initially set at 10. The fine aggregate to coarse aggregate ratio was fixed at 2.

In Series I, to produce partition blocks with a maximum content of waste glass, the WGA was used as 0%, 25%, 50%, 75% and 100% by weight replacements of RFA (labelled as 0G, 25G, 50G, 75G and 100G). Only OPC was used as the binder. As the dry-mixed precast method was used (Kou et al., 2012; Xiao et al., 2011), the actual water-to-binder ratio (*w*/*b*) was determined based on the cohesion of the mixture. Only a sufficient amount of water was added to produce a cohesive mix but with no slump, with *w*/*b* ratios as 0.48~0.66.

In Series II, 20% ISSA was used as a supplementary cementitious material to replace OPC and the increasing amounts of WGA were used. The *a*/*b* ratio and the *w*/*b* ratios were the same with those of Series I.

Based on the results of Series II, the *a*/*b* ratio was increased from 10 to 12 in Series III in order to reduce the OPC dosage. The combined use of 100% WGA and 20% ISSA in the concrete block was adopted to compare with blocks prepared with 100% WGA and without WGA. The mix proportions of the three series of mixes are listed in Table 2. The mass of each material (except water) used was based on the oven dry condition.

Table 2 Mix proportions of concrete partition blocks (kg/m^3)

	Mix	OPC	ISSA	RFA	WGA	NCA	Water	*w*/*b*
Series I	0G	206	0	1372	0	686	136	0.66
	25G	206	0	1030	343	687	134	0.65
	50G	206	0	687	687	687	134	0.65
	75G	207	0	345	1036	690	122	0.59
	100G	209	0	0	1394	697	100	0.48
Series II	I-0G	165	41	1372	0	686	136	0.66
	I-25G	165	41	1030	343	687	134	0.65
	I-50G	165	41	687	687	687	134	0.65
	I-75G	166	41	345	1036	690	122	0.59
	I-100G	167	42	0	1394	697	100	0.48
Series III	12-0G	176	0	1405	0	703	116	0.66
	12-100G	178	0	0	1424	712	85	0.48
	12-I-100G	142	36	0	1424	712	85	0.48

Note: The WGA was only used to replace the fine aggregates due to their similar particle sizes.

Based on practical experience in the industry, recycled aggregates were commonly used in the production of concrete blocks (ETWBTC, 2004). *However, the variation of recycled aggregates is a concern to ensure consistent quality. Therefore, in this study, the WGA with a relatively consistent quality was used to replace the RFA for producing concrete partition blocks.*

2.3 Preparation of partition blocks

All the dry materials including OPC, RFA, WGA, NCA and ISSA (if any) were weighted in accordance with Table 1 and then were blended homogeneously in a concrete mixer. Subsequently, appropriate amounts of water were added to the dry mix until forming a desired mixture with sufficient cohesiveness, which could be agglomerated into a ball shape by hand without collapsing. The required amounts of water for producing the mixes were adjusted according to the characteristics of the aggregates. Due to the negligible water absorption characteristic of WGA, the *a*/*b* ratio was reduced with the increasing amount of WGA incorporation. After mixing, the fresh mixture was fabricated in steel moulds with size of 100W×200L×60H mm. The fabrication procedure of the partition blocks simulated the production process of industrial setting. A two-layer compaction process was applied to produce the blocks similar to the method used in previous studies (Lu et al., 2019; Yang et al., 2019). The first layer of the blocks was compacted manually by hammering by a wooden plank to ensure even distribution of compaction. After filling the second layer, the moulds were transferred to a compaction equipment for further compaction. Then, mechanical loading with a maximum force of 60 kN was applied for one minute to compact the mixture within the moulds. The fabricated blocks were demoulded after 24 h and subjected to steam curing at 60 °C for 7 days.

2.4 Properties of partition blocks

2.4.1 Density and Porosity

The density and porosity were measured based on the water saturation method, which measured the mass difference after the dry samples were totally saturated by water. The accuracy of this method depended on whether the water could fully occupy the permeable voids in the concrete samples. Therefore, in this study, the permeable porosity and density were determined by the vacuum water saturation method complying with ASTM C1202-12 (2019) and ASTM C642-13 (2013).

After steam curing for 7 days, the blocks were oven dried at 60°C for 4 days to achieve constant dry masses (M_{Dry}). Then, the samples were moved into a desiccator with a drying agent to cool down for 12 h. Afterward, the blocks were transferred to a vacuum desiccator for 3 h. With the vacuum pump still running, the water stopcock was opened and sufficient water was drained into the container to cover the specimens. After immersing the block samples with water, the vacuum pump was allowed to run for another hour. Then, air was allowed to re-enter desiccator. After soaking the specimens under water for 24 h, the saturated-surface-dry (SSD) and immersed weights were measured to calculate the density and the porosity of the blocks:

$$d = \frac{M_{Dry}}{M_{SSD} - M_{Water}}$$

$$\rho = \frac{M_{SSD} - M_{Dry}}{M_{SSD} - M_{Water}}$$

where:

d means the bulk density of the sample after immersion (g/cm^3);

ρ represents the permeable porosity of the sample (%);

M_{Dry} means the mass of oven-dried sample in air (g);

M_{SSD} stands for the mass of surface-dry sample in air after immersion (g);

M_{Water} represents the mass of sample in water after immersion (g).

2.4.2 Compressive strength

The compressive strength of concrete blocks was determined by a compaction machine with a maximum capacity of 3000 kN. The blocks with size of 100W×200L×60H mm were placed between two capping steel plates and then the load was applied with a loading rate of 0.6 MPa/s until the specimens failed. The calculation equation for compressive strength was based on the Hong Kong General Specification (DEVB TCW, 2006), the reported strength values were the averages of the measurements of two specimens.

$$C = \frac{W}{A} \times \frac{2.5}{1.5 + \frac{L}{H}}$$

where:

C is the compressive strength (MPa);
W 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).

2.4.3 Drying shrinkage

The blocks in Series I and II were prepared for dry shrinkage measurement according to BS ISO 1920-8 (2009) method. Blocks with size of 25W×25H×285L mm were fabricated in steel moulds. After demoulding, the block bars were stored in a water bath at 27±2°C until 28 days. The block bars were then taken out from the water bath and wiped with a wet towel, then the lengths of the block specimens were immediately recorded as the initial length. The specimens were then transferred to a drying chamber (25°C, 50% relative humidity) until further measurement at 1st, 2nd, 4th, 8th, 11th, 14th, 18th, 22nd, 25th and 28th day.

2.4.4 Thermal conductivity

A quick thermal conductivity meter (QTM-500) was used to test the thermal insulating property of the concrete blocks. The hot wire method was adopted according to ASTM C 1113-90 (2013). The measurement range of thermal conductivity meter was from 0.0116 to 6 W/mK. After the blocks were oven dried at 60°C for 4 days after the steam curing, six measurements were conducted on the loading surfaces of each specimen and the average values were reported.

2.4.5 High temperature resistance

In order to determine the resistance of the blocks against high temperature exposure, the specimens with 100W×200L×60H mm were casted according to the Series III proportions in Table 2. After demoulding, the block specimens were cured in laboratorial conditions at room temperature (23±2 °C, 75±5% relative humidity) for 28 days. Then, the blocks were transferred to an oven chamber at 105°C for 24 h followed by subjecting them to high temperature exposures using an electric furnace. The temperature of the furnace was increased at a rate of 5°C /min up to 800°C. After 2 h holding at 800°C, the blocks were cooled down to ambient temperature in the furnace before the residual compressive strength was determined. Based on the compressive strength values of the blocks with and without subjecting to 800°C, the residual strength index (RSI) was calculated by the following equation (Lu and Poon, 2018). The RSI was employed to evaluate the fire resistance of the blocks. A higher RSI value means a higher resistance to high temperature exposure, and vice versa.

$$RSI = \frac{S_r}{S_i} \times 100\%$$

where:

S_r is the residual compressive strength of sample after exposure to 800°C;

S_i is the initial compressive strength of sample without exposure to 800°C.

2.4.6 Pore structure

Mercury Intrusion Porosimetry (MIP, Micromeritics AutoPore IV 9500 Series) was employed to understand the influence of WGA and ISSA incorporation on the pore structure of cement mortar in the partition blocks and explore the underlying mechanism of WGA and ISSA on affecting the shrinkage property. After completing the compressive strength test, the block samples were broken into pieces and the cement mortars (without the coarse aggregates) were collected for MIP test. The prepared mortar pieces were first immersed into ethanol to stop further hydration for one week, followed by drying in a vacuum chamber at 60°C for two days to remove the residual ethanol. The pore sizes measured were ranged from 150 μm down to 7 nm with a maximum mercury intrusion pressure of 207 MPa. It should be noted that due to the ink bottle effect, most of pores reported by MIP are smaller than they actually are (Scrivener, 2016). However, although the MIP method may not exactly reflect the actual pore sizes of the cement-based materials, MIP is still thought to be a simple and reliable technique for quantitatively and qualitatively comparing pore structures between different cementitious materials (Scrivener, 2016).

3. Experimental results

3.1 Density and porosity

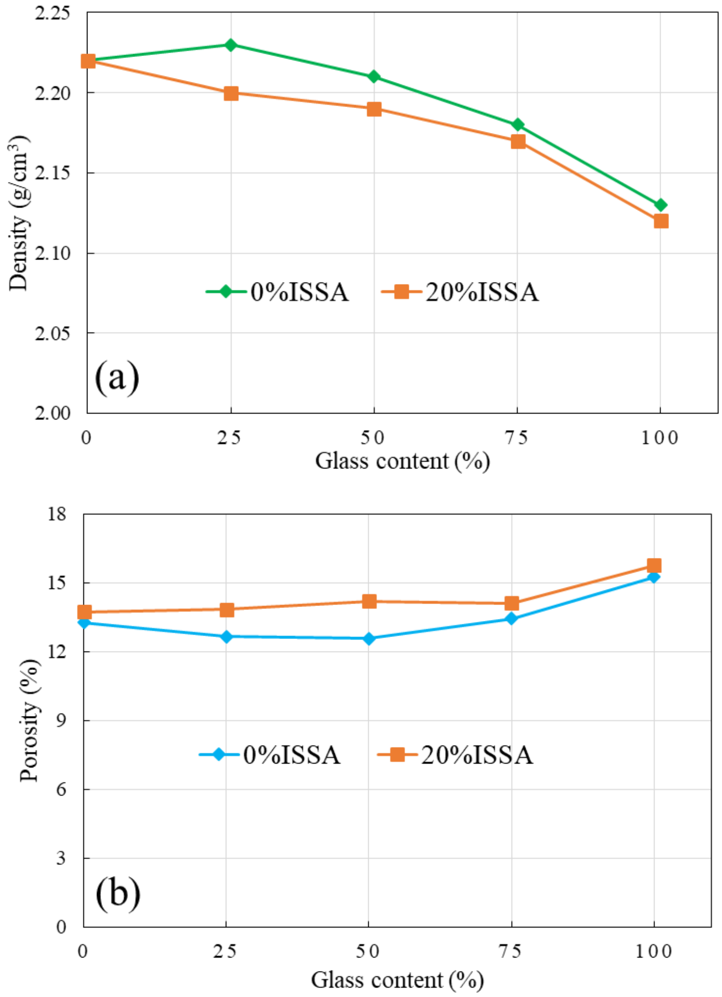

Fig. 3 Effect of WGA and ISSA on the density and porosity of blocks,
(a) density; (b) porosity

Fig. 3 shows the influence of waste glass aggregate (WGA) content and incinerated sewage sludge ash (ISSA) contents on the density and porosity results of the concrete blocks. Fig. 3a indicates that the density decreased with increasing WGA contents. The lower specify gravity of glass aggregates as compared to that of recycled aggregates was responsible for the reduced density of the blocks. Another reason may be attributed to the irregular and angular grain shape of WGA, which resulted in a poorer compacted concrete mixture. Park et al. (2004) also found that a decrease in the compacting factor of the concrete containing WGA as compared to the plain concrete without glass. Overall, the reduction in density due to the replacements of WGA was beneficial to the use of the concrete partition blocks because of the reduced weight. Furthermore, the replacement of cement by ISSA could continuously decrease the hardened density of the partition blocks. This can also be explained by the lower specific density of ISSA as compared to that of cement (as shown in Table 1) and the poor packing due to the larger size of ISSA particles (see Fig. 2b). Similar results were reported by a previous study (Li et al., 2017), which found that the density of cement mortar containing ISSA as a cement replacement was lower than that of the mortar prepared without ISSA.

For the porosity results (Fig. 3b), it can be observed that the porosity was relatively stable when the WGA content was increased up to 75%, whereas it showed some increase as the WGA content reached 100% of the fine aggregates. Two factors played important roles in determining the porosity of the glass-based blocks. One was the incorporation of WGA with negligible water absorption led to the use of a low *w*/*b* ratio, which resulted in a denser structure and lower porosity. On the other hand, the irregular and angular shape of the glass aggregates as compared to the relatively round shape of RFA (see Fig. 1) could result in poor packing of the aggregates. In addition, the weak bonding between the glass particles and the cement paste due to the smooth surface of the glass cullet could lead to more interface pores as compared to RFA with a rough surface. Therefore, when considering these two factors together, the porosity of the blocks did not change much as the content of WGA was less than 75%. However, when the fine aggregates were fully replaced by the WGA, the latter factor might exert a more vital role in controlling the porosity of the concrete blocks.

It also can be seen that the replacement of 20% cement by ISSA generally increased the porosity of the blocks regardless of the glass cullet content. The trend of ISSA-based blocks closely matched with that of the blocks prepared with increasing amounts of WGA, which also confirmed the porosity results of the glass-based blocks prepared without ISSA incorporation. The increase of porosity was partly due to the low pozzolanic reactivity of ISSA in the cement-based material (Chen and Poon, 2017a), leading to a lower degree of overall hydration, and the inherent porous nature of ISSA (Chen and Poon, 2017a) might also increase the porosity.

3.2 Compressive strength

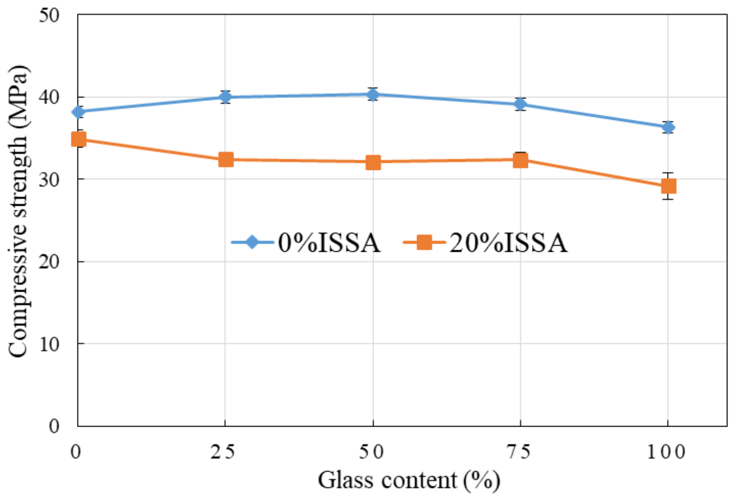

Fig. 4 Effect of WGA and ISSA on the compressive strength of blocks

Fig. 4 shows the influence of varying WGA contents and ISSA incorporation on the compressive strength of the blocks. It can be observed that the compressive strength was relatively stable when the GC content was increased from 0% to 75%. Subsequently, the strength was slightly reduced as the WGA content was increased to 100% for both of the blocks prepared with and without ISSA replacement. Unlike the significant reduction of strength in conventional wet-mixed glass-based concrete (Topçu and Canbaz, 2004; Mardani-Aghabaglou et al., 2015), the increasing content of glass aggregates seemed to have little influence on the compressive strength in the case of the dry-mixed concrete blocks. The reason for such a discrepancy is thought to be due to the different nature of the concrete mixtures. The wet-mixed concrete generally has a good workability and thus a dense structure, and therefore the bonding strength between the cement paste and the aggregate particles is the primary factor governing the overall strength development. Therefore, the incorporation of WGA with a smooth surface would cause a significant decrease in strength. However, the concrete blocks prepared by the dry-mixed method had a low workability (no slump) and thus a very porous structure was resulted. Hence, the packing condition of the mixture might play a more important role in determining the strength. Due to the similar gradations of WGA and RFA, the packing efficiencies of the mixtures produced were expected to be similar, thus resulting in comparable strengths. In addition, the lesser amount of water required for producing the blocks with the increase of WGA content could also counteract the adverse effect induced by the weak bonding between the WGA and the cement paste. However, incorporating an excessive amount of WGA would increase the porosity of the blocks due to the irregular and angular shape of the glass cullet (see porosity results). Therefore, it is found that the blocks prepared with 100% WGA had slightly lower compressive strength as compared to those prepared with lesser amounts of WGA.

Meanwhile, regardless of the WGA content, all the compressive strength values of the ISSA-based blocks were lower than those of the blocks prepared without ISSA addition. This was attributed to the low pozzolanic activity of ISSA. The result was consistent with the study of Chen and Poon (2017b), who indicated that replacement of cement by 20% ISSA in the cement mortar led to strength loss at the early age (within 28 days). Therefore, in this study, the dilution effect of ISSA had a more dominant influence on the strength of the ISSA-containing concrete partition blocks.

In Series II, the trend of strength development was similar to that of the blocks prepared without ISSA, which was also consistent with the porosity results. It is worth to point out that, although there were some reductions in the strength caused by the use ISSA, the partition blocks of Series I and II could easily meet the minimum compressive strength requirement for partition blocks according to the BS 6073-1 (2008) (>7.0 MPa), which provided a strong support for the combined use of waste glass and ISSA for the production of the concrete partition blocks.

3.3 Drying shrinkage

The influence of the different WGA contents on the drying shrinkage of the partition blocks are presented in Fig. 5a. It can be easily observed that the control block prepared with 100% RFA suffered from a high drying shrinkage value of 900 microstrains. When 25% WGA was introduced to replace the RFA in the blocks, the drying shrinkage was reduced effectively and the shrinkage values of the blocks decreased with the increasing contents of WGA. This is due to the replacement of recycled aggregates with high water absorption characteristics by the non-hydroscopic of WGA was conducive to reducing the drying shrinkage of the blocks. Another possible explanation is that RFA contained a certain amount of contaminant such as fine soil (see Fig. 1) which was less stiff than WGA, resulting in a lower restraint in the drying condition. The reduction in the drying shrinkage with the incorporation of WGA was also reported by Kou and Poon (2009) and Tan and Du (2013) in the conventional wet mixed cement mortar/concrete prepared with WGA.

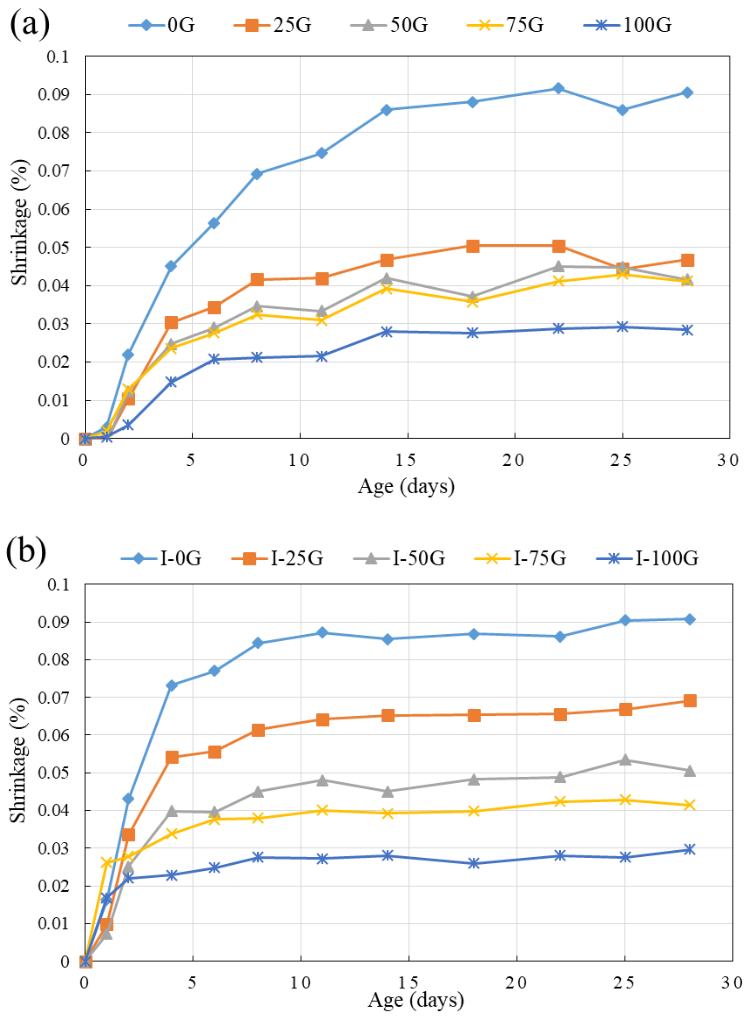

Fig. 5 Effect of WGA and ISSA on the drying shrinkage of blocks,
(a) 0% ISSA; (b) 20%ISSA

Fig. 5b shows the effect of combined use of WGA and ISSA on the drying shrinkage of the blocks. In the blocks containing WGA and ISSA, the reducing trend of drying shrinkage was consistent with that of Series I blocks prepared with WGA. However, the replacement of cement by ISSA seemed to have little influence on the ultimate drying shrinkage values of the blocks. This can be explained by the lesser volume of binder and hydrated cement paste (*a*/*b* ratio=10) in these two series of blocks, so that only 20% substitution of cement by ISSA did not have influence on the drying shrinkage. However, it can be noticed that the addition of ISSA increased the dry shrinkage at the early age (within 7 days of drying). This might be related to the porous structure of the unreacted ISSA (Chen and Poon, 2017a), which absorbed more water that would then be evaporated during early-aged drying.

Overall, the introduction of WGA and ISSA was useful to reduce the drying shrinkage of the partition blocks. The drying shrinkage of the blocks incorporating with 100% WGA (and 20% ISSA) was only one-third of that of the blocks prepared with RFA alone. According to the Australian Standard 1012.13 (2015), the drying shrinkage of concrete should be within 1000 microstrains. Therefore, the combined use of WGA as 100% fine aggregates and ISSA as 20% binder could successfully render the shrinkage of the partition blocks within the permitted limit.

3.4 Thermal insulation

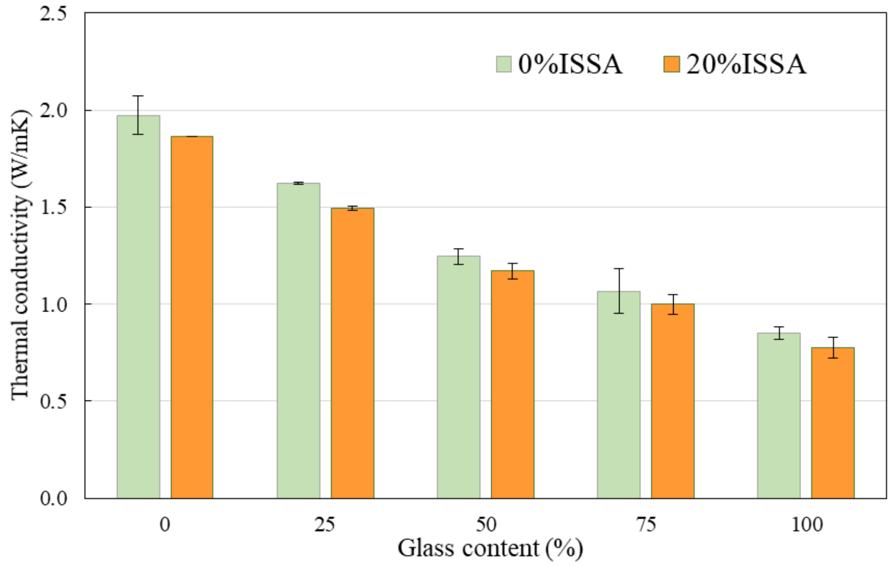

Fig. 6 Effect of WGA and ISSA on the thermal conductivity of blocks

Fig. 6 presents the influence of WGA contents and ISSA addition on the thermal conductivity of the blocks. Apparently, the thermal conductivity of the blocks decreased significantly with the increase of the WGA content. The replacement of WGA as 100% fine aggregates led to a 57% reduction in the thermal conductivity as compared to the blocks prepared with 100% RFA. This is because the inherent thermal conductivity of RFA containing granite (2.12~3.62 W/mK (Cho et al., 2009)) was much higher than that of glass (0.93 W/mK (Poutos et al., 2008)). Furthermore, the incorporation of RFA with a high water absorption capacity (6.2~11.3% (Li et al., 2019)) could increase the thermal conductivity of the blocks due to the higher water demand for producing the mixture. The substitution of water with a higher thermal conductivity (0.606 W/mK) for air with a lower thermal conductivity (0.026 W/mK) in the void of the RFA would result in an increase of the thermal conductivity.

For the blocks containing ISSA, the thermal conductivities were always lower than those of the blocks prepared without ISSA regardless of the WGA replacement levels. This was attributed to the lower density and the higher porosity of the ISSA-containing blocks. The lower density and higher porosity reduced the compactness of the mixture, which lowered the heat transfer capability of the blocks. Additionally, the inherent thermal conductivity of ISSA was also much lower than the pure cement paste due to its porous structure (Wang et al., 2005). Consequently, the incorporation of WGA and ISSA together was beneficial in producing partition blocks with a low thermal conductivity, which would considerably reduce the demand of electrical energy for cooling and heating purposes.

3.5 High temperature resistance

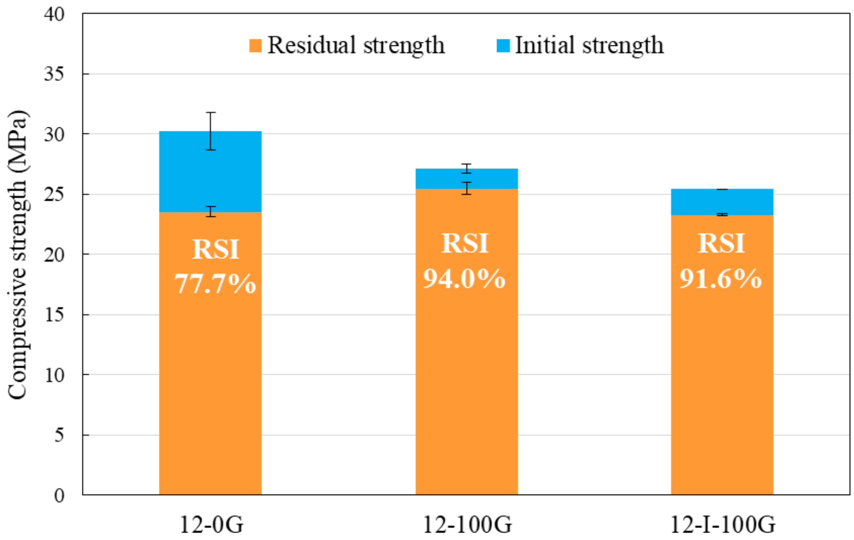

Fig. 7 Effect of WGA and ISSA on the high temperature resistance of blocks

The influence of WGA and ISSA on the fire resistance of the partition blocks is illustrated in Fig. 7. For the blocks prepared with RFA only, there was a large reduction in the compressive strength after exposure to 800°C. Even so, the residual strength of the RFA block could still meet the requirement of BS 6073-1 with a residual strength index (RSI) of 77.7%, which was much higher than the RSI of conventional wet-mixed concrete after being heated to 800°C, which is typically at 10~40% (Xu et al., 2001;

Poon et al., 2003; Poon et al., 2004). This result means that the dry-mixed partition blocks had a better resistance to high temperature as compared to conventional wet-mixed concrete. Two effects were responsible for this behavior. One was related to the high *a*/*b* ratio in the partition blocks, resulting in the lesser amount of binder in the concrete block that would be subjected to thermal decomposition. The other was associated with the porous structure of the partition blocks, which mitigated the thermal stresses due to the vapor pressure built up when the blocks were subjected to the high temperature.

As indicated in Fig. 7, the initial compressive strength of the blocks decreased when the fine aggregates were fully replaced by the WGA. However, the residual strength of the blocks incorporating 100% WGA was higher than that of the blocks prepared without WGA after subjected to the elevated temperature (RSI: 94.0% vs. 77.7%). This indicates that the introduction of WGA further improved the fire resistance of the partition blocks. It can be explained by the improved interfacial transition zone between the cement paste and the WGA after exposure to high temperature. This explanation was validated in our previous study (Yang et al., 2019), which found that the partially melted glass could adhere to the decomposed binder to re-form a good bonding. In addition, due to the presence of a large amount of WGA in the blocks, the partially melted glass aggregates could bond together and re-solidified to form bonded glass particles after cooling, resulting in providing a strong support for the block structure. On this basis, when the ISSA was used to replace 20% of cement, the residual strength of the blocks was reduced slightly due to the reduced initial strength, however the RSI could still reach above 90%. Therefore, as compared to the RFA-based blocks, it can be concluded that the combined use of WGA and ISSA contributed to the better fire resistance of the partition blocks.

3.6 Porosity analyses by MIP

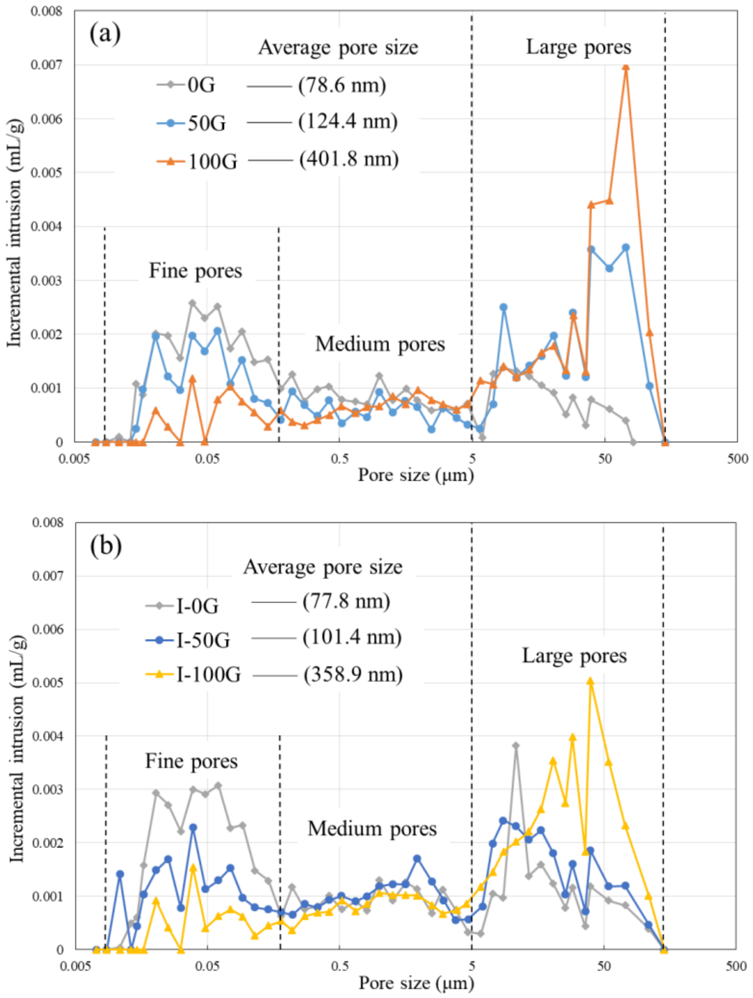

Fig. 8 Effect of WGA and ISSA on the pore structure of blocks,
(a) 0% ISSA; (b) 20%ISSA

In order to better understand the underlying mechanism of the WGA and ISSA incorporation on the properties of partition blocks, MIP test was used to analyze the pore structure. Fig. 8 presents the pore size distributions of the cement mortar in the partition blocks. For the blocks prepared without ISSA shown in Fig. 8(a), with the increase of WGA content, the number of fine pores (<0.18 μm) decreased while the amount of large pores (>5 μm) increased significantly. As a result, the average pore diameter was increased as the content of WGA increased in the blocks. Especially for the block prepared with 100% WGA, the average pore diameter was about five times of that of the block prepared without WGA. The poor packing of the mixture due to the irregular geometry of the glass particles could be responsible for the coarser pore size. This result also explained the higher porosity of the 100% WGA block (see Section 3.1).

For the blocks containing both the ISSA and WGA (see Fig. 8b), a similar trend of pore size distribution was observed in comparison with those prepared with WGA only, that is the increasing amount of WGA caused an increase of average pore size. However, it can be seen that when the ISSA was introduced into the blocks, all the average pore sizes were smaller than those of the blocks prepared without the ISSA. The reason was considered to be due to the pozzolanic effect of the ISSA, which formed secondary hydration products filling the large pores. Therefore, as indicated in Fig. 8b, the number of large pores was greatly reduced with the ISSA incorporation. On the other hand, the number of medium and fine pores was increased in the ISSA-based samples. It is well known that the pore size distribution has a critical influence on the drying shrinkage (Collinsa and Sanjayan, 2000). In particular, the mesopores (2.5–50 nm) and macropores (50 nm – 10 μm) are primary factors in determining the shrinkage (Young, 1988). Therefore, the presence of larger number of capillary pores (mesopores plus macropores) in the ISSA-block might contribute to the increase of the drying shrinkage at early age. Similarly, the introduction of WGA tended to reduce the number of fine pores in the two series of blocks, which was conducive to reducing the drying shrinkage (as shown in Section 3.3).

4. Conclusions

The lack of landfill spaces for waste disposal brings interests in investigating the recycling of waste materials for the production of construction products. This work helps shed light on the reuse of waste glass aggregates (WGA) and incinerated sewage sludge ash (ISSA) concurrently for producing concrete partition blocks. The conclusion of the experimental results obtained can be drawn as follows:

- The density of the partition blocks decreased with the increasing contents of WGA and ISSA incorporation due to the poorer packing of the mixture and the lower inherent density of WGA and ISSA. The porosity showed a relatively stable trend when the WGA content was increased. The addition of ISSA further increased the porosity of the blocks due to its low pozzolanic reactivity.

- Regardless of the WGA replacement levels, the compressive strength of the partition blocks was relatively stable due to the use of the dry-mixed method as a lesser amount of water was required for fabricating the blocks. Further replacing 20% of the cement by ISSA in the blocks resulted in a lower strength because of the low pozzolanic reactivity of ISSA. Even so, the strength of the eco-partition blocks could satisfy the minimum requirement of BS 6073-1.

- The combined use of the WGA and the ISSA was beneficial to reducing the drying shrinkage of the partition blocks. The thermal conductivity of the blocks decreased considerably when incorporating the WGA and ISSA together owing to their inherent lower thermal conductivities. Also, the combined use of WGA and ISSA significantly improved the fire resistance of the partition blocks.

- The WGA-ISSA concrete block exhibited improvements of functional and durability performances and it can be considered as a promising alternative option for internal walls and partitions blocks applications.

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