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# Sustainable design of pervious concrete using waste glass and recycled concrete aggregate

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ABSTRACT

This study designed an eco-friendly pervious concrete (PC) product using waste glass cullet (WGC) and recycled concrete aggregate (RCA) by dry-mixed compaction technique. The mechanical properties, water permeability behavior and related pore structure characteristics, thermal conductivity of the PCs were determined. The experimental results showed that the use of silica fume in the cement paste was effective to compensate for the low compressive strength of the PCs due to the use of narrowed graded aggregates without the incorporation of fine particles (less than 2.36 mm). Although the incorporation of recycled aggregates (i.e. WGC and RCA) into the PCs led to reductions in compressive strength, the water permeability of the PCs was improved, especially for the PCs prepared with WGC, as the use of WGC was conducive to improving the water permeability due to the negligible water absorption nature and smooth surface of glass cullet. Another encouraging result indicated that the PCs comprising 50% WGC as the fine aggregate and 50% RCA as the coarse aggregates could achieve satisfactory strength and permeability, which could largely meet the requirement of the standard (JIS A 5371) for permeable pedestrian pavers. The appropriate blending of the selected size of WGC (2.36–5 mm) and RCA (5–10 mm) to produce a desirable pore structure in the PCs were responsible for the good performance. In addition, the low thermal conductivity of the produced PCs provided an opportunity to use the PC as partition block materials for saving energy consumption of buildings.



## 1. Introduction

### 1.1. Pervious concrete

The use of pervious concrete (PC) is a unique and effective means to address several important environmental issues, including improving the recharge of groundwater, reducing stormwater runoff, promoting tree survival by providing air and water, improving water quality and reducing the heat island effect, etc. (Tennis et al., 2004). Especially, in Hong Kong, heavy rainfall could happen commonly (about 2400 mm per annum of rainfall are recorded on average) (DSD, 2018). How to manage the heavy rainfall becomes a crucial issue for Hong Kong due to the densely built up urban areas and the mountainous terrain which further exacerbates the risk of flooding. Hence, it is necessary to undertake flood and waterlogging mitigation measures to improve the flow capacity. The U.S. Environmental Protection Agency identified PC pavement as one of the effective Best Management Practices for stormwater management as PC has sufficient void space to allow rapid percolation of water through the pavement (Tennis et al., 2004; DEP, 2006). Therefore, PC pavement has been extensively applied in the parking lots, drainage layers in exterior areas, residential street parking lanes, walkways/sidewalks, bike paths and pavements with minimal heavy truck traffic. Usually, PC consists of Portland cement (supplementary cementitious materials sometimes are used), aggregates and water. The difference from conventional concrete is that PC contains no fine aggregates and a lesser amount of cement paste is used to fill the voids between the aggregate particles. As a result, open cells (pores) are formed and the induced high porosity of PC leads to good internal drainage and infiltration. The common properties of normal PC are shown in Table 1 according to the American Concrete Institute (ACI 522R-10, 2010). Obviously, the requirement for compressive strength of PC is relatively low as compared to conventional concrete. This provides an opportunity to reuse waste materials in the production of PC.

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**Table 1**
Properties of common pervious concrete (ACI 522R-10, 2010).

| Properties | Compressive strength (MPa) | Drainage rate (L/min/m$^2$) | Porosity |
|---|---|---|---|
| Value range | 2.8–28 | 81–730 | 15–35% |

### 1.2. Recycled concrete aggregate and waste glass

In Hong Kong, about 66,000 tonnes/day of construction & demolition (C&D) wastes (including waste concrete) were disposed of at public fills and landfills according to the statistics of the Environmental and Protection Department (EPD) in 2016 (EPD, 2016). The large amount of C&D wastes poses challenges to the construction waste handling facilities. Therefore, the EPD implemented a Construction Waste Disposal Charging Scheme to charge for the disposal of C&D wastes under the polluter-pays principle. Given the high charge (200 dollars per tonne for landfill disposal) and the need to conserve landfilling space, there is a strong interest for industry and the Government to recycle C&D wastes. Waste concrete is an important component of the C&D waste stream. It can be crushed into recycled concrete aggregate (RCA) and be used in cement mortar (Li et al., 2019), road sub-base (Poon and Chan, 2006), pre-cast concrete blocks (Poon et al., 2009), asphalt (Paranavithana and Mohajerani, 2006) and minor concrete structures (Xiao et al., 2012) production. Also, the RCA has been used as a virgin aggregate replacement in concrete pavement slab (Shi et al., 2019a, 2019b), it was found that the pavement prepared with RCA was more environmentally friendly as compared to the pavement produced with natural aggregates.

Recently, some studies have been conducted to utilize RCA in the production of PC (Sata et al., 2013; Sriravindrarajah et al., 2012; Bhutta et al., 2013; Zaetang et al., 2016). Sata et al. (2013) used two types of recycled aggregates to produce pervious geopolymer concrete. The results indicated that the use of RCA and crushed clay brick resulted in significant losses in strength of the pervious geopolymer concrete as compared to natural aggregates. Similar results were also obtained by Sriravindrarajah et al. (2012) and Bhutta et al. (2013), who also found that the compressive strength of the PC was adversely affected by the incorporation of RCA. On the contrary, the study of Zaetang et al. (2016) showed that the replacement level of RCA up to 60% resulted in better compressive strength and surface abrasion resistance than the control PC prepared only with natural aggregates. In addition, the incorporation of RCA was found to have little effect on the void matrix of PC and the water permeability coefficient tended to increase slightly as the RCA replacement level increased. However, Sriravindrarajah et al. (2012) concluded that the water permeability of PC was primarily influenced by the porosity rather than the replacement level of RCA. Based on the above findings, the influence of the RCA on the properties of PC is still not clear. Further studies should be conducted to better understand the influence of RCA on the mechanical and water permeability performance of PC.

Except the RCA, the recycle and management of waste glass is also an imminent issue in Hong Kong due to the lack of a glass manufacture industry for its reuse (Lu and Poon, 2019). Based on the statistics of the Hong Kong EPD, about 300 tonnes of waste glass were generated per day in 2016, but only 7.7% of the waste glass was recycled (EPD, 2016). Previous studies (Du and Tan, 2013, 2014; Lu et al., 2017a; Lu and Poon, 2018) on the utilization of waste glass in cement mortars and conventional concrete mixtures showed that the use of glass cullet as fine aggregates was an effective solution to produce cement-based construction products. Although the replacement of river sand by the glass cullet might lower the compressive strength (Topçu and Canbaz, 2004; Park et al., 2004; Tan and Du, 2013a), the inclusion of glass cullet could effectively improve the durability of the mortar or concrete against sulfate attack (Wang, 2009) and acid corrosion (Ling et al., 2011). Furthermore, the chloride ion penetrability and drying shrinkage of the glass concrete decreased when the glass aggregate content was increased (Kou and Poon, 2009). One concern of recycling waste glass into cement mortars and concrete is the potential expansion due to the alkali-silica-reaction (ASR) of glass particles. To mitigate the ASR effect, replacing a portion of cement by supplementary cementitious materials (e.g. silica fume, fly ash, metakaolin, glass powder) was found to be an effective method (Du and Tan, 2013; Lu et al., 2017b, 2017c). Also, our recent studies showed that ASR in porous concrete blocks prepared with glass cullet as aggregates was not a problem because the presence of large pores could accommodate the expansive ASR gel (Yang et al., 2018). Therefore, based on the extensive investigations on using waste glass cullet (WGC) in mortars and concrete, it is believed that replacing fine aggregates by WGC has potentials to produce a sustainable PC. In addition, it is anticipated that the water permeability of the PC would be improved due to the negligible water absorption and smooth surface of the glass particles.

The purpose of this research is to design and develop a sustainable PC for mitigating excessive run-off during heavy rainfalls. The study focuses on entirely replacing natural aggregates with recycled materials including RCA and WGC to produce eco-PC. Physical properties (density, porosity), mechanical property (compressive strength), hydrological behavior (water permeability), thermal conductivity of the developed PC were determined and the related pore characteristics of the PC were also measured by an image analysis technique to reveal the underlying mechanisms governing the PC performance.

### 1.3. Research significance

Due to the over-exploitation of natural aggregates for construction development over the recent decades, Hong Kong and even the whole China are facing dwindling natural aggregates resources (especially for natural river sand) and severe environmental problems. In addition, the huge amounts of municipal solid wastes and construction wastes in Hong Kong are putting enormous pressure on the landfills (existing landfills will be full by about 2020 if not extended (EPD, 2013). Since crushed WGC can possibly be used to replace river sand and RCA can be a source of coarse aggregates, recycling these two recycled materials cooperatively into PC for stormwater management would be promising. Another motivation leading to renewed interest in PC produced with recycled aggregates is an increasing emphasis on sustainable construction. In this study, a preliminary research was conducted to quantify the effects of the incorporation of WGC and RCA on some of the fundamental properties of PC, which would provide a direction for future research on PC prepared with these two types of solid wastes. Previously, limited studies (Batayneh et al., 2007; Poon and Lam, 2008) were conducted on the performance of concrete prepared with RCA and WGC simultaneously. No investigations were carried out to jointly use RCA and WGC in the production of PC.

**Table 2**
Chemical compositions of cementitious materials.

| Chemical composition, % | OPC | SF |
|---|---|---|
| $SiO_2$ | 19.61 | 91 |
| $Al_2O_3$ | 7.32 | 0.4 |
| $Fe_2O_3$ | 3.32 | 1.8 |
| CaO | 63.15 | 1.0 |
| MgO | 2.14 | 0.9 |
| $Na_2O$ | 0.13 | 0.3 |
| $K_2O$ | 0.32 | 1.7 |
| $SO_3$ | 2.03 | 0.18 |
| Specific gravity | 3.15 | 2.52 |
| Specific surface ($cm^2/g$) | 3960 | 25000 |

## 2. Experimental design

### 2.1. Materials

The materials used to fabricate PCs were ASTM type I ordinary Portland cement (OPC, 52.5), natural aggregate (NA), WGC and RCA. The OPC was supplied by a local cement manufacturer in Hong Kong. Besides, a powdered form of silica fume (SF) sourced from Mainland China was adopted to partially replace OPC in order to enhance the strength of the binder. The chemical compositions and physical properties of OPC and SF are shown in Table 2.

Crushed granites including fine aggregates (2.36–5 mm) and coarse aggregates (5–10 mm) were used as NA, sourcing from a local aggregate supplier. WGC (2.36–5 mm) used in this study was crushed from post-consumer beverage bottles and RCA (5–10 mm) was sourced from a construction and demolition waste. Both of them were obtained from a recycling facility in Hong Kong. Fig. 1 shows the aggregates used in this study and their physical properties are shown in Table 3.

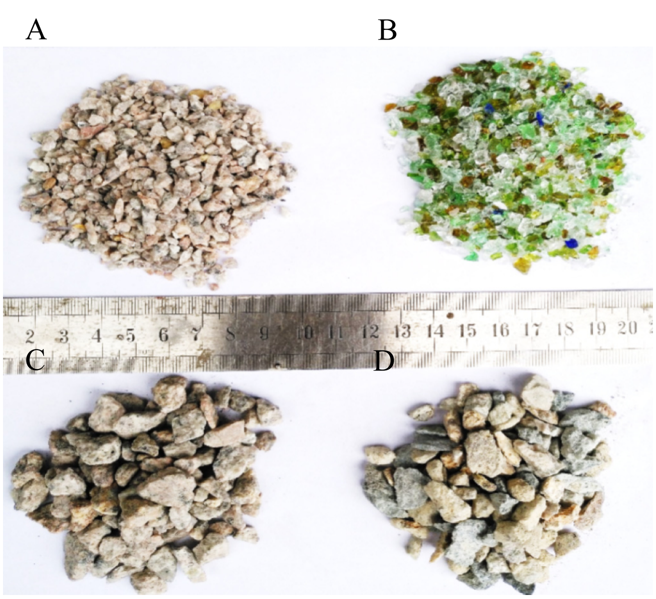


**Fig. 1.** Appearance of aggregates A: NA (2.36–5 mm), B: WGC (2.36–5 mm), C: NA (5–10 mm), D: RCA (5–10 mm).

### 2.2. Proportion of mix

In order to produce PCs with a good water permeability, single size aggregates were employed. In this study, two series of PCs were prepared by using two size ranges of aggregates. The first series of PCs were produced with only fine aggregates (2.36–5 mm) but without the size range of 0–2.36 mm. The same size of WGC (2.36–5 mm) was used to replace the natural fine aggregates at replacement levels of 25%, 50%, 75%, and 100% by weight, respectively (labelled as 0G, 25G, 50G, 75G and 100G).

The second series of PCs were prepared with only the coarse aggregates (5–10 mm). The RCA with the same size range (5–10 mm) was introduced in the PCs to replace the natural coarse aggregates at 25%, 50%, 75%, and 100% by weight, respectively (labelled as 0R, 25R, 50R, 75R and 100R). To improve the properties of PCs and maximize the use of waste materials as aggregates in PCs, the PCs using 100% recycled aggregates comprising 50% WGC as fine aggregates and 50% RCA as coarse aggregates were also produced (50G50R). As compared to the reference mixture, SF was used to replace 10% OPC to produce a strong binder to achieve the desired PC properties. The aggregate-to-binder ratio was fixed at 5, and the water-to-cement ratio ($w/c$) was adjusted based on the aggregate characteristics. It should be noted that no superplasticizer was used in this study since non-slump mixture was needed to prepare the PCs by dry-mixed compaction technique. Table 4 shows the proportions of 13 different PCs mixes. The reference mixtures were prepared with only natural fine or coarse aggregates, named as 100F and 100C, respectively.

### 2.3. Preparation of PCs

One intended use of the PC products could be precast pervious blocks for pedestrian pavers. Thus, the preparation of the PC specimens was based on a dry-mixed process normally used for concrete block production (Lu and Poon, 2019) to simulate the actual industrial production practices. The OPC and SF (if any) were initially dry mixed for 2 min in the mechanical mixer to obtain a homogeneous powder. Then, the aggregates were added and mixed for another 2 min followed by adding the required amount of water to produce a cohesive mix with no slump value. The amount of water used was determined by trial tests so that the mixtures condition could be agglomerated into a ball shape by hand without the falling off of the aggregates (CTT, 2004).

The freshly prepared mixtures were cast into the rectangular molds (200 × 100 × 60 mm) and cylindrical molds (Φ75 × H60 mm) for mechanical properties test and permeability test, respectively. The compaction method for fabricating the dry-mixed specimens had been described in our previous studies (Poon et al., 2009; Yang et al., 2018; Poon and Lam, 2008). The fabricated specimens were demolded after 24 h and then cured in a steam chamber at 60 °C for 7 days.

**Table 3**
Physical properties of the aggregates.

| Aggregates | 2.36–5 mm NA (f) | 2.36–5 mm WGC | 5–10 mm NA (c) | 5–10 mm RCA |
|---|---|---|---|---|
| Loose Bulk Density ($g/cm^3$) | 1.33 | 1.36 | 1.36 | 1.31 |
| Specific Gravity | 2.54 | 2.45 | 2.53 | 2.36 |
| Water Absorption (%) | 2.63 | 0.36 | 3.04 | 6.13 |

**Table 4**
Mix design of PCs (kg/m$^3$).

| Mix | Binder | | Aggregates | | | | w/b |
|---|---|---|---|---|---|---|---|
| | OPC | SF | 2.36–5 mm NA | 2.36–5 mm WGC | 5–10 mm NA | 5–10 mm RCA | |
| 100F | 302 | 0 | 1510 | 0 | 0 | 0 | 0.29 |
| 100C | 302 | 0 | 0 | 0 | 1510 | 0 | 0.32 |
| 0G | 272 | 30 | 1510 | 0 | 0 | 0 | 0.29 |
| 25G | 272 | 30 | 1132.5 | 377.5 | 0 | 0 | 0.29 |
| 50G | 272 | 30 | 755 | 755 | 0 | 0 | 0.30 |
| 75G | 272 | 30 | 377.5 | 1132.5 | 0 | 0 | 0.31 |
| 100G | 272 | 30 | 0 | 1510 | 0 | 0 | 0.32 |
| 0R | 272 | 30 | 0 | 0 | 1510 | 0 | 0.32 |
| 25R | 272 | 30 | 0 | 0 | 1132.5 | 377.5 | 0.35 |
| 50R | 272 | 30 | 0 | 0 | 755 | 755 | 0.39 |
| 75R | 272 | 30 | 0 | 0 | 377.5 | 1132.5 | 0.42 |
| 100R | 272 | 30 | 0 | 0 | 0 | 1510 | 0.45 |
| 50G50R | 272 | 30 | 0 | 755 | 0 | 755 | 0.40 |

### 2.4. Properties of PCs

#### 2.4.1. Density

The hardened densities of the PCs were determined using the methods described in ASTM C1754 (2012) specified for hardened pervious concrete. The specimens were placed in the oven at a temperature of 105 °C until the weight was constant. Then the dry weight ($W_{dry}$) was measured and the specimen volume ($V$) was calculated. The reported results were the average values of two PC specimens. The density of PCs can be calculated following the equation:

$$D = \frac{Wdry}{V} \tag{1}$$

where:

$D$ represents the density of specimen, g/cm$^3$;
$W_{dry}$ represents the oven dry mass of specimen, g;
$V$ represents the volume of specimen, cm$^3$.

#### 2.4.2. Porosity

The porosity (void content) of the PCs was also evaluated in accordance with ASTM C1754 (2012). First, the specimens were completely immerged in water for 30 min, and then the mass of specimens in water was measured and the value was named as $M_1$. Afterward, the specimens were dried in the oven at 105 °C for 24 h, and the dried mass of specimens in air were measured and named as $M_2$. For each batch of PC, two specimens were used for porosity determination and the average values were reported. The porosity ($P_v$) can be calculated as follows:

$$P_v = \left(1 - \frac{M_2 - M_1}{\rho_w \cdot V}\right) \times 100\% \tag{2}$$

where:

$P_v$ represents the volumetric porosity of specimen;
$M_2$ represents the dry mass of specimen, g;
$M_1$ represents the submerged mass of specimen, g;
$V$ represents the volume of specimen, cm$^3$;
$\rho_w$ represents the apparent density of water, g/cm$^3$.

#### 2.4.3. Compressive strength

The compressive strength tests according to the ASTM C39 (2018) were carried out to investigate the mechanical behavior of the PCs. It was determined by using a compression machine with a maximum loading capacity of 3000 kN. The PCs were loaded at rate of 0.6 MPa/s with 200 × 100 mm$^2$ surface upward until failure. The maximum load ($W$) was measured, and the compressive strength ($f_c$) was calculated using the following equation. The average compressive strength of two specimens were reported.

$$f_c = \frac{W}{A} \tag{3}$$

where:

$f_c$ represents compressive strength, MPa;
$W$ represents maximum load, N;
$A$ represents compression area, cm$^2$.

#### 2.4.4. Permeability

Water permeability is one of the important properties for pervious concrete as it is critical for storm water management in applications. The test method complying with JIS A 5371 (2016) was used to measure the permeability coefficient. Fig. 2 shows the set-up for testing the permeability coefficient. The average permeable coefficients of two cylinders were reported. Cylindrical specimens were sealed by silicon sealant to avoid the water spilling from the lateral surfaces of the specimens. Before measurement, the specimens were immersed into water for 24 h to ensure that the

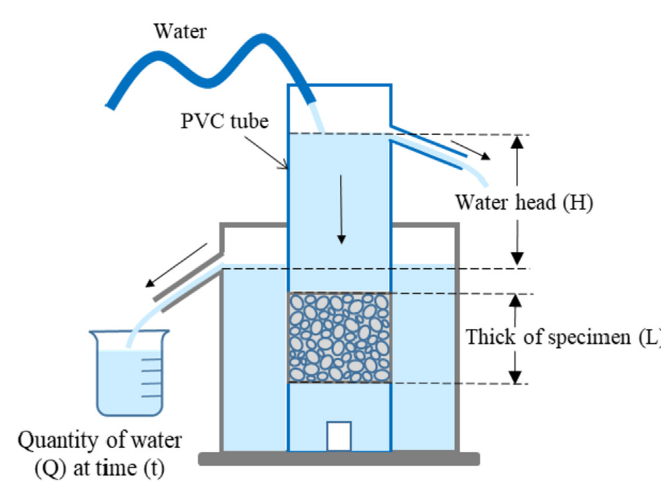


**Fig. 2.** Test set-up of permeable coefficient for the PCs.

specimens were fully saturated. The permeable coefficient of the PCs was calculated as follows:

$$k_t = \frac{QL}{AHt} \tag{4}$$

where:

$k_t$ represents the permeable coefficient, cm/s;
$L$ represents the thick of specimens, cm;
$Q$ represents the water content, mL;
$A$ represents the surface area of specimen, $cm^2$;
$H$ represents the difference height of water, cm;

*2.4.5. Thermal conductivity*

The thermal conductivity of PCs was measured using a quick thermal conductivity meter (QTM-500) based on ASTM C1113-90 (2013) Hot Wire Method. Measurement range of QTM-500 device was 0.0116–6 W/mK. Measurement precision was ±5% of record value per reference specimen and testing time was 100–120 s. Before measurement, the rectangular specimens were oven-dried at 60 °C for 48 h to remove the moisture. In this measurement, it was assumed that the development of hydration heat of specimens was small enough to be ignored. The results were averaged from three measurements on the loading surfaces of each specimen.

*2.4.6. Image analysis technique*

An image analysis technique was employed on the two-dimensional images to extract the pore structure features of PCs. In this study, cylindrical specimens were sectioned into Φ75 × H30 mm slices for the image analysis. The images of the cross sectional surfaces were captured using a SLR camera at a resolution of 300 dpi. Six images were obtained from each set of cylindrical specimens. The color images were cropped to obtain gray binary images (2200 diameter pixels) and then analyzed by a Photoshop software. The binary images were further processed to remove the noise using Image-Pro Plus 6.0. Square images with 900 pixel × 900 pixel were extracted and used to obtain the pore structure parameters. Fig. 3 shows the steps in the image processing and feature acquisition.

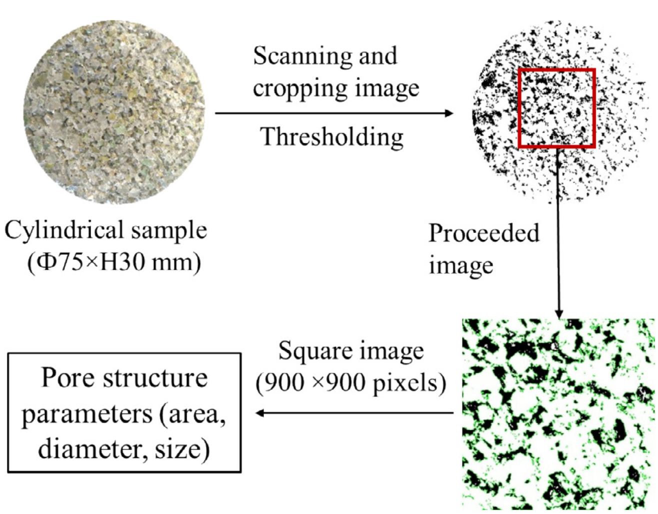


**Fig. 3.** Illustration of image analysis procedure employed.

## 3. Results and discussion

### *3.1. Effect of aggregate size and silica fume on the properties of PCs*

Generally, the PC consists of cement paste (binder) and single-size aggregates. Hence, an understanding of the effect of the binder and aggregate characteristics on the properties of the PCs is necessary. As indicated in Fig. 4a, the PCs prepared with only coarse aggregates had a lower compressive strength than those prepared with 100% fine aggregates. It is expected that the use of fine aggregates alone could produce a much denser matrix than the coarse aggregates, moreover, the relatively lower *w*/*b* of 100F (0.29) than that of 100C (0.32) might also result in a higher strength. This explanation is verified by the results of higher density and lower porosity in the following section. However, an opposite trend is observed in permeability as shown Fig. 4b. The permeable coefficient was much higher in the PCs with 100% coarse aggregates as compared to that of PCs prepared with the 100% smaller-size aggregates. This result indicated that the use of coarse aggregates in the PCs was conductive to improving the water permeability although the strength would be reduced correspondingly.

Based on the above results, SF was introduced into the PCs with a view to mitigating the reduced compressive strength. Fig. 4a also presents the influence of using 10% SF as a replacement of OPC on the properties of PCs. With SF incorporation, the compressive strengths of PCs prepared with the fine aggregate and the coarse aggregate were increased by 23.5% and 59.5%, respectively. This was because the SF had extremely fine particle size, the

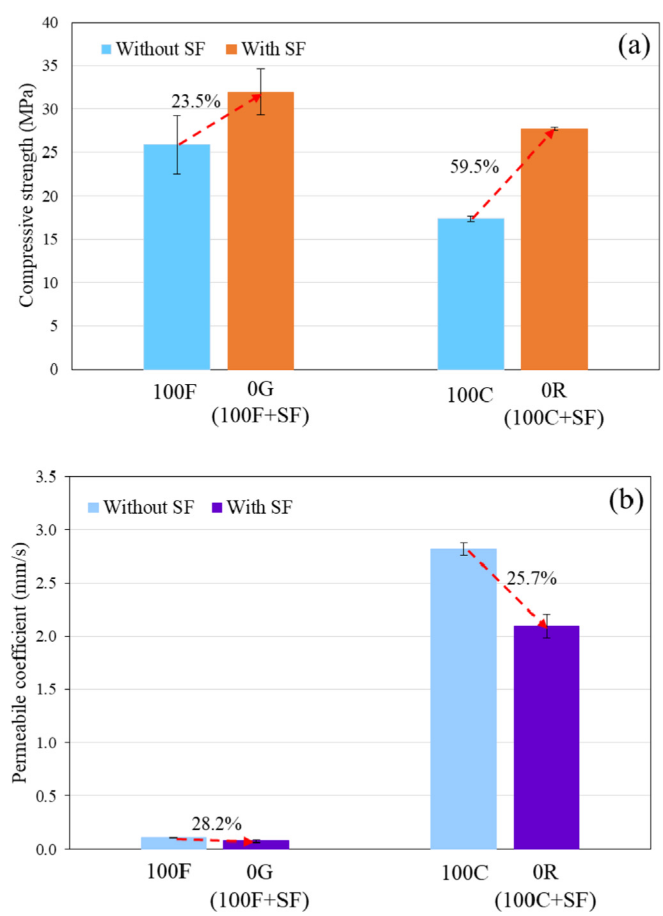


**Fig. 4.** Influence of aggregate sizes and SF on the compressive strength (a) and the permeability (b) of PCs.

replacement of OPC by the SF was beneficial to the strength enhancement of the cement paste (Cong et al., 1992; Zhang et al., 2016). Furthermore, the addition of the SF improved the viscosity of the cement paste that benefited the bonding between the aggregate particles (Marolf et al., 2004) and the interfacial transition zone (ITZ) between aggregate and cement paste might be improved by reducing the localized bleeding around the aggregates. As the ITZ area of coarse aggregates was smaller than that of fine aggregates, thus the benefit of SF in strength improvement was more significant for coarse aggregates compared to fine aggregates. Predictably, when the SF was added into the PCs, the permeable coefficients decrease by 28.2% and 25.7% in the PCs prepared with the single-size of fine aggregates and coarse aggregates, respectively. A similar conclusion was also drawn by Yang and Jiang (2003). The reason can be explained by the fact that the replacement of cement by the same weight of SF increased the volume of binder due to the lower density of SF, thus resulting in localized paste clogging the mixture and as a result its pore connectivity was lowered.

### 3.2. Compressive strength and density

The compressive strengths of PCs incorporating WGC and RCA are shown in Fig. 5a. It can be seen that the compressive strengths of PCs containing WGC or RCA were gradually reduced with increasing contents of WGC or RCA. For the case of WGC, the replacement of natural fine aggregates by the WGC resulted in weaker bonding between the cement paste and the aggregate due to the inherent smooth surface of glass. This may be the reason for the strength loss in the WGC-based PCs. Similar phenomenon was found in using WGC in concrete (Kou and Poon, 2009; Ali and Al-Tersawy, 2012; Tan and Du, 2013b). For the PCs using RCA to replace natural granite as coarse aggregates, the decrease in compressive strength was mainly attributed to the inhomogeneous, weaker, less dense and more porous of RCA, weakening the overall strength of the PCs (Poon et al., 2004; Shi et al., 2019a). In these two systems, the increased *w/b* of the mixtures with the increasing amount of recycled aggregates (i.e. WGC and RCA) could also lead to reductions in the compressive strength.

Although the compressive strengths of PCs decreased by 23% and 31% when the NAs were fully replaced by the WGC and RCA, respectively, all the strength values of PCs could still meet the requirement of permeable concrete blocks for pedestrian pavement according to JIS A 5371 specification with a limit of 17 MPa (JIS A 5371, 2016). This provided useful data for allowing the use of WGC and RCA for the production of pervious concrete blocks. Compared to the strength of PCs prepared with the coarse RCA, the strengths of PCs prepared with the fine WGC were higher, regardless of the replacement ratios of NA. The reason is that the fine aggregates could be compacted to produce concrete blocks with higher density. Fig. 6a shows the influence of WGC and RCA incorporation on the density of the PCs prepared with single-size aggregate. It can be obviously seen that the densities of WGC-based PCs were always higher than those of RCA-based PCs although the density decreased with the increase of replacement ratios. This reduction in the density corresponded well with the

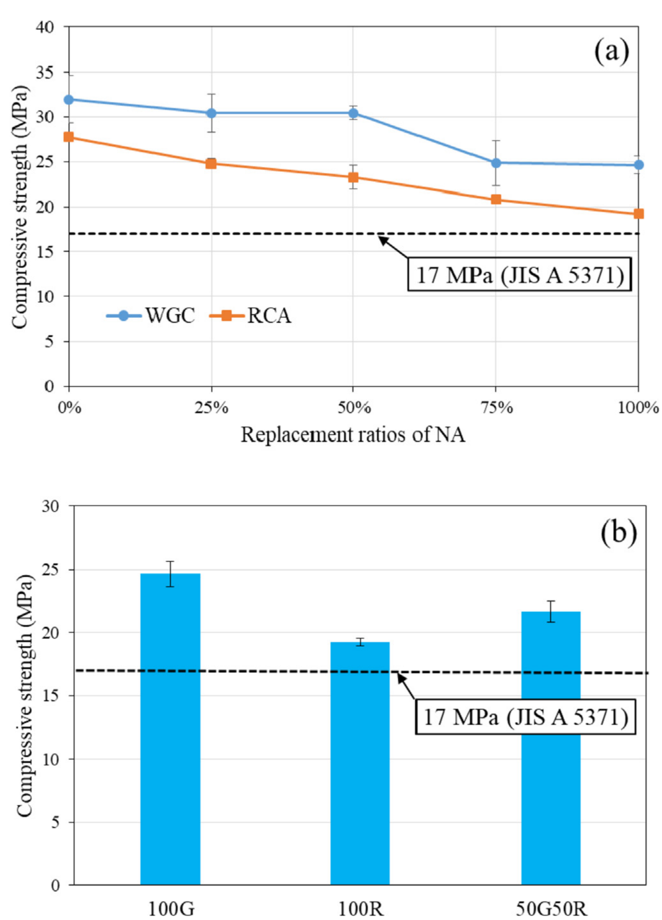


**Fig. 5.** Compressive strength of PCs prepared with WGC and RCA.

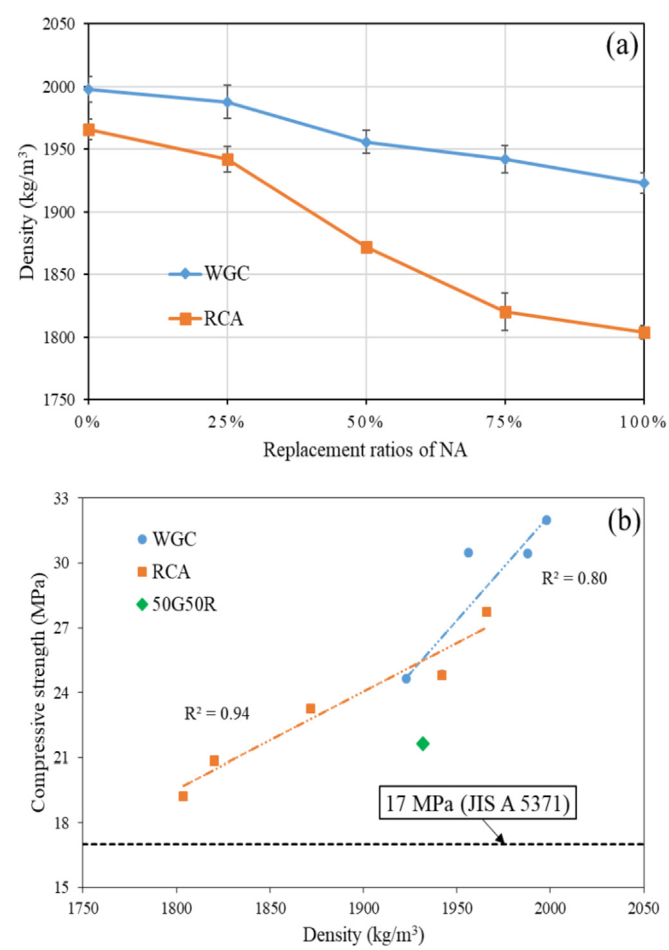


**Fig. 6.** Density of PCs prepared with WGC or RCA (a) and the correlation between compressive strength and density (b).

results of the compressive strength.

As for the permeability, a dense concrete matrix is not conducive to improving the water permeability of the PC. Therefore, the PCs (50G50R) were prepared to balance the strength and the water permeability requirements. Fig. 5b shows the compressive strength of 50G50R when compared with the cases of 100G and 100R. The compressive strength of 50G50R was 22 MPa, which was lower than that of 100G but higher than that of 100R. This result indicated that the addition of WGC as fine aggregates in PCs was helpful to enhance the compressive strength as compared to that of PCs prepared with only coarse RCA. This behavior was mainly attributed to the fact that the presence of WGC could fill in the intergranular voids between the coarse aggregates (RCA) and this interlocking would contribute to the compressive strength.

The relationships between the compressive strength and the density of PCs are shown in Fig. 6b. As seen, the density of PCs were ranged from 1800 to 2000 kg/m$^3$, which was less than normal concrete (approximately 2400 kg/m$^3$) due to the high void content of PC (Tennis et al., 2004). In addition, for both cases of WGC-based and RCA-based PCs, the compressive strength tended to increase linearly with the increase of density, which indicated that the density played a key role in affecting the compressive strength of the PCs. The density of 50G50R with blended aggregates is 1932 kg/m$^3$, which lies in between the PCs prepared with single-size aggregates. This result also corresponded well with the compressive strength of 50G50R locating in between that of 100G and that of 100R.

### 3.3. Permeability and porosity

The hydrological behavior is a key parameter in decisions to use this material for storm water management, so the water permeability of the PC was assessed. Fig. 7a shows the effect of WGC and RCA replacement on the permeability of PCs. It is obvious that the PCs prepared with coarse aggregates had much higher water permeability than the PCs prepared with fine aggregates. This can be explained by the denser matrix of PCs prepared with fine aggregates. For the PCs with RCA, the water permeability stayed relatively stable with increasing replacement level of RCA. The reason might be due to the similar gradation and characteristics of the coarse NA and the RCA. When the fine NA was replaced by up to 50% WGC, the permeable coefficient of the PCs was not affected. However, the permeability was improved significantly to 0.3 mm/s when 100% NA was replaced by WGC. The non-absorbing nature of glass particles is believed to benefit the water to permeate through the concrete. It also should be noted that the permeability requirement of JIS A 5371 specification for the pervious concrete is 0.1 mm/s. Therefore, the PCs proportioned with 100% WGC as fine aggregates is feasible from the point views of permeability and compressive strength.

As regards the PC 50G50R, the coefficient of permeability was 1.2 mm/s, which was 12 times of that the standard requirement. In terms of the permeability performance and strength value, the combined use of WGC as fine aggregates and RCA as coarse aggregates is attractive and promising to produce pervious concrete with good strength and permeability.

However, as expected, the WGC-based PCs with a dense matrix indeed had much lower permeability than the RCA-based PCs. Fig. 7b shows the relation between the porosity and the permeable coefficient of the PCs. As recommended by American Concrete Institute (ACI), the porosity range of pervious concrete should lie within 15%–35% (ACI 522R-10, 2010), thereby all the prepared specimens in this study can be classified as pervious concrete. Generally, the PCs prepared with the WGC had lower porosity than the PCs prepared with the RCA coarse aggregates due to the higher

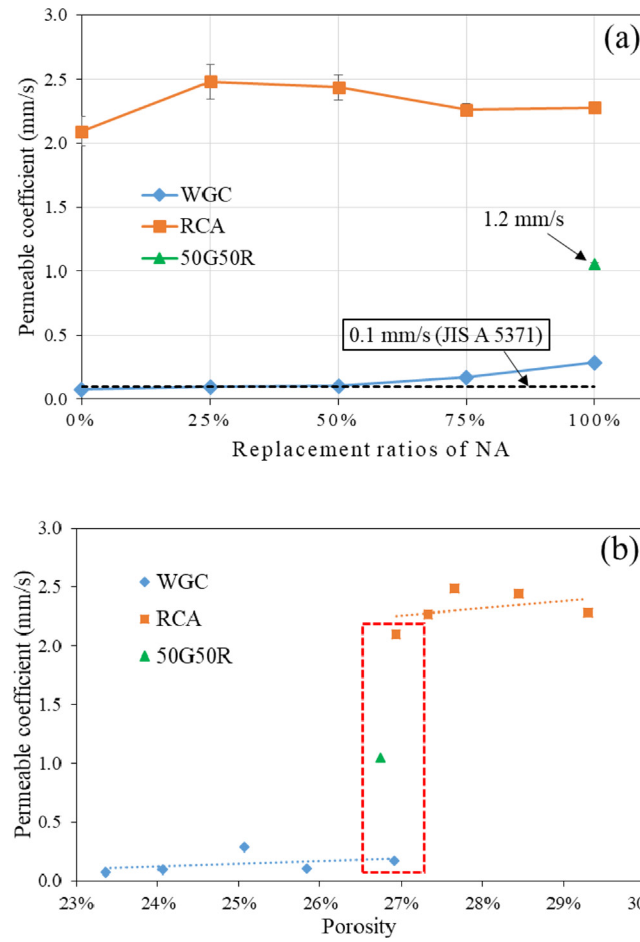


**Fig. 7.** Permeability of PCs (a) and its relation with porosity (b).

packing density. In addition, the permeability generally overall increased with an increase in porosity, but there was no definitive relationship between the permeability and the porosity. It can be noted that the three specimens including WGC-based, RCA-based and 50G50R had a similar porosity (red frame) while they had considerably different permeability coefficients. This indicates that the porosity is not the most principal factor in controlling the permeability. The result obtained is consistent with those of Neithalath et al. (2010), who also found that pervious concretes with similar porosities had very different permeability. The reason is attributable to the fact that porosity is a volumetric property of the material, whereas permeability is a parameter that defines the transport property through the material that not only depends on the volume of the pores but also on the distribution of the pore size and its connectivity (Neithalath et al., 2006). Therefore, it is also required to explore other pore structure characteristics in order to adequately understand the permeability behavior.

### 3.4. Pore structure characteristics

The pore structure features of PCs were characterized using image analysis. Fig. 8 illustrates the images of the diametrical cross sections of the PCs prepared with three different sizes of aggregates (i.e. 100G, 50G50R and 100R). As can be noticed in Fig. 8, the pore shapes in the three PCs are irregular and the pores tend to be more irregular with increasing aggregate sizes. A general trend of increasing pore sizes and connectivity (black areas) with the increasing aggregate sizes can be easily observed. This finding is in

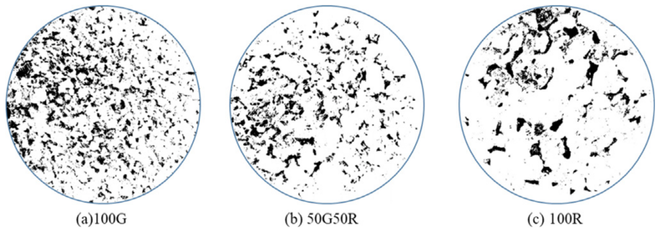


**Fig. 8.** Two-dimensional images of planar sections of PCs prepared with 100% WGC (a), 50% WGC+50% RCA (b), 100% RCA (c).

agreement with that of Marolf et al. (2004), who also found that an increase in aggregate size resulted in an increase of pore size.

Fig. 9 shows the pore size distribution histograms and the cumulative frequency curve of pore size for PCs containing 100% WGC, blended aggregates of 50% WGC and 50% RCA, and 100% RCA. The PCs prepared with 100% WGC had larger number of fine pores and the distribution of pore sizes was narrow. Approximate 90% of pores were smaller than 4 mm. By contrast, the specimens of 100R had a broader pore size distribution and more large pores (17% > 6 mm) were present in the mixtures. For the 50G50R, nearly 80% of the pores in the specimens lied within the 0–3 mm range and no pores were larger than 6 mm.

Compared to the PCs prepared with only the coarse-sized aggregates (100R), the PCs prepared with the blended aggregates contained a larger proportion of smaller pores. The above results indicated that the increase in aggregate size led to an increase in pore size of the mixture. The results also explain the phenomenon that the porosity of the PC with smaller-sized aggregates was approximately the same as the one prepared with the larger-sized aggregates; in other words, the porosity of the mixture with smaller aggregate size consisted of a greater number of fine pores while the similar porosity of the mixture prepared by coarse-sized aggregate contained more coarse pores but less fine pores. According to the study of Sumanasooriya and Neithalath (2011), for the same porosity, larger aggregate size or pore size could increase the pore connectivity factor, which is pivotal to determine the hydraulic transport properties of pervious concrete. Therefore, the PCs prepared with 100% RCA or the blended aggregates exhibited higher hydraulic conductivity because of the larger pore size and higher pore connectivity.

The equivalent pore diameter corresponding to the 50% cumulative frequency is taken as the effective pore size ($d_{50}$) (Neithalath and Sumanasooriya, 2010), which can be representatively used as the characteristic pore size in pervious concrete. It can be observed from Fig. 8 that the $d_{50}$ of PC mixture made with small-sized aggregates (100G) was much smaller than those for the mixture produced with coarse-sized aggregates (100R) (1.794 mm V 2.959 mm). The $d_{50}$ value for the blended-aggregate PC (50G50R) was 2.066 mm which lied between those of the two single-sized aggregate PCs. The reason is because the smaller aggregates could fill the pore spaces between the larger aggregates. Based on above results, it can be concluded that the $d_{50}$ value of PCs increased with the increase of aggregate sizes. As reported in previous studies (Neithalath and Sumanasooriya, 2010; Sumanasooriya and Neithalath, 2009), the $d_{50}$ value was linearly related to the critical pore size and an increase of the critical pore size led to an increase of the permeability. Therefore, the increase in the $d_{50}$ because of the increased aggregate sizes was expected to increase the permeability. In this study, the PCs prepared with a blend of aggregate sizes had a moderate $d_{50}$ value so that a desired permeability could be achieved.

### 3.5. Thermal conductivity

The effects of WGC and RCA on the thermal conductivity of PCs are shown in Fig. 10. The WGC and RCA were used to replace the NA

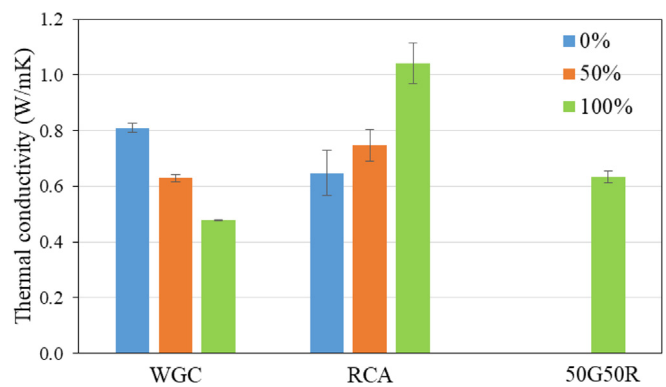


**Fig. 10.** Thermal conductivity of PCs prepared with different aggregates.

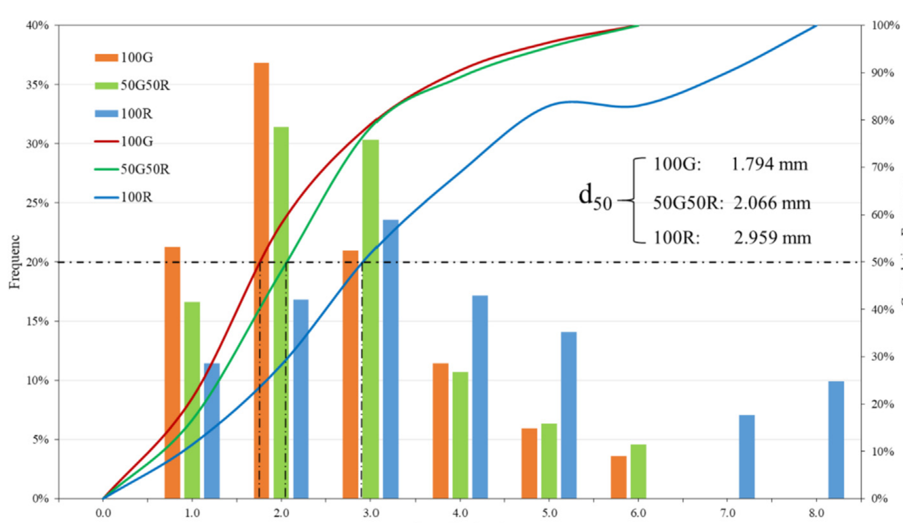


**Fig. 9.** Pore size distributions of PCs prepared with different aggregates.

by 0%, 50% and 100% in the PCs, respectively. As comparison, the thermal conductivity of PCs with 50% WGC and 50% RCA as aggregates was also measured. First, it can be seen that the PCs with the fine NA had a relatively higher thermal conductivity than the PCs prepare with the coarse NA. The reason for this behavior is that the higher density and relatively lower porosity of the former increased the contact points of the aggregate particles, which enhanced the heat transfer capability of the specimen. For the PCs containing WGC, the thermal conductivity tended to decrease as the WGC replacement level increased. This trend was mainly due to the lower thermal conductivity of glass (0.93 W/mK (Poutos et al., 2008)) in comparison with the natural granite aggregate (2.12–3.62 W/mK (Cho et al., 2009)). On the contrary, the thermal conductivity of the PCs increased when the content of RCA increased. The use of 100% RCA in the PCs rendered a higher thermal conductivity of 1.04 W/mK, which was more than twice than the PCs prepared with 100% WGC. This could be interpreted as the presence of the residual mortars in the RCA which contained quartz sand (with thermal conductivity of 7.69 W/mK (Zhao et al., 2016)) leading to the higher thermal conductivity of the RCA (Zega and Maio, 2009). Zaetang et al. (2016) also indicated that the thermal conductivity coefficients of PCs prepared with RCA were higher than those of PCs prepared with NA. Additionally, the incorporation of RCA with a high water absorption value (6.13%) could further increase the thermal conductivity because of the high moisture content. The replacement of the air with a lower thermal conductivity (0.026 W/mK) in the void of the RCA by water with a higher thermal conductivity (0.606 W/mK) would result in an increase of the thermal conductivity.

It is clearly evident that the combined use of the WGC and the RCA as aggregates for the production of PCs leads to a relatively low thermal conductivity (0.63 W/mK). This is partly attributed to the incorporation of the WGC with a lower thermal conductivity. Another possible reason is the presence of larger numbers of fine pores in the 50G50R specimens as compared to the specimen prepared with 100% RCA. The air with very low thermal conductivity (0.026 W/mK) present in the pores is expected to hinder the thermal conduction and thus reduce the overall thermal conductivity.

## 4. Discussion

One of the findings from the experimental investigations in the PCs is that the aggregate sizes and the SF addition have a significant influence on the compressive strength and the permeability behavior, which are two primary considerations for the potential application of PCs. The use of coarse aggregate (5–10 mm) in the PCs greatly improved the hydraulic conductivity but caused a relatively low compressive strength as compared to the use of smaller-sized aggregates (2.36–5 mm). Therefore, proper amount of SF (10%) was introduced into the PCs to enhance the low compressive strength although the addition of SF would reduce the permeability correspondingly. The increase of paste volume due to the addition of low density SF would increase the thickness of the paste layer adhered on the surface of aggregates, which caused a better bonding and increased strength. This improvement in strength further provided an opportunity to reuse recycled aggregates (i.e. WGC and RCA) in the production of sustainable PCs. It is encouraging to note that when 100% WGC or 100% RCA was used to replace natural granite aggregates, the compressive strength and the percolation rate of the produced PCs could meet the requirement of pedestrian concrete block in JIS A 5371 specification. This results showed that the use of WGC or RCA to totally replace natural aggregates in the PCs incorporating SF was feasible.

However, the 100% RCA-based PCs exhibited much higher permeable coefficient but relatively lower strength due to the fact that the PCs with single larger-sized aggregates contained a larger proportion of coarser pores and larger characteristic pore size. On the contrary, the 100% WGC-based PCs had a very lower permeability coefficient but relatively higher strength because the large pore were replaced by fine pores. These results indicated that aggregate sizes used have a considerable effect on the permeability behavior of PCs. Increasing the pore sizes or using large-sized aggregates was conducive to improving the water permeability and the use of fine aggregates was found to reduce the permeability. This reduction can be described by the fact that the fine particles blocked access to the pores, resulting in a hindrance to water path. In this study, except porosity, the other pore structure features including pore size distributions, characteristic pore sizes and the related pore connectivity were found to play dominant roles in affecting the water permeability and the mechanical properties. Specifically, the increase in the effective pore size (i.e. $d_{50}$) value due to the increase of aggregate sizes resulted in an increase of the permeability and a decrease of the strength. This suggests the possibility of employing the information of the features of pore structures to guide the design of the PCs with both good strength and high permeability.

As such, the aggregates in the PCs were designed as a combination of 50% WGC as fine aggregates and 50% RCA as coarse aggregates. The results showed that the combined use of WGC and RCA in the production of PCs could achieve an acceptable compressive strength of 22 MPa (as shown in Section 3.2) and a satisfied permeability value of 1.2 mm/s (as presented in Section 3.3), which was 12 times of that required by JIS A 5371 specification. The high permeability would ensure that the developed PCs can be capable in a heavy rainfall event. The desired performance was attributed to the fact that the produced PCs had appropriate proportions of small pores (1–3 mm), no very large pores (>6 mm) and suitably effective pore size distribution. In addition, the use of the WGC which had about zero water absorption value was further beneficial to enhance the permeability of the PCs. Hence, appropriate mix design based on aggregate sizes and types is needed to develop a PC with good strength and permeability.

Since the produced PCs had a high void content so that it had potential to be used as a thermal insulating material. Generally, the thermal conductivities of the PCs developed in this study varied between 0.48 and 1.04 W/mK, which were relatively lower in comparison with those of conventional concretes (0.95–1.46 W/mK) (Demirboğa, 2007). Also, the density values of the eco-PCs ranging from 1800–2000 kg/m$^3$ in this study were 20% lower than those of normal weight concrete. When 100% WGC was used as aggregates, the PC attained the lowest thermal conductivity of 0.48 W/mK, which was comparable to the thermal conductivity of lightweight concrete with thermal conductivities ranging from 0.40 to 0.69 W/mK (Alengaram et al., 2013; Blanco et al., 2000) and the compressive strengths of PCs were generally higher than 20 MPa, which was sufficient to meet the strength requirement of at least 17 MPa for structural lightweight concrete specified by ASTM C330 (2017). These findings suggest that the PCs produced with WGC and RCA could have potentials for another application, namely, as partition walls or blocks in buildings to reduce the amount of heat transfer and energy consumption.

## 5. Conclusions

From the compressive strength and the water permeability points of view, it appears that there is a potential use of WGC and RCA for the production of sustainable PCs. The effects of WGC and RCA as aggregates on the properties of pervious concrete were evaluated in this study, and the following conclusions can be drawn:

- Compared to the PCs prepared with single small-sized aggregates, the PCs with single coarse-sized aggregates exhibited much higher permeable coefficient but had lower compressive strength. However, introduction of 10% silica fume as cementitious materials could significantly improve the compressive strength although decrease the permeability of the PCs correspondingly.
- The use of WGC or RCA to replace the natural single-sized aggregates resulted in reductions of compressive strength due to the decrease in the density and weak bonding between the paste and the aggregates. Although 100% WGC or 100% RCA was incorporated as aggregates, the strength and the permeability obtained could still satisfy the requirement of JIS A 5371 specification for permeable concrete blocks.
- By using the image analysis technique, the water permeability of the PCs was found to be mainly controlled by the pore structure features (i.e. pore size distribution, effective/critical pore size) rather than only the porosity. Hence, to develop a PC with good strength and permeability, appropriate mix design based on aggregate sizes and types is needed.
- The PC proportioned with 50% WGC as fine aggregates and 50% RCA as coarse aggregates is practical for the production of permeable pedestrian paving blocks.
- The overall thermal conductivity of the PCs decreased with the increase of the WGC content. The proposed PCs with low thermal conductivity (0.48 W/mK) offer an alternative option to serve as thermal insulating partition walls/blocks.
- Considering the superior permeability and thermal insulating properties, this eco-friendly PCs with waste glass and recycled aggregate seem to be promising for use on building construction.

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