4

5 Sustainable design of pervious concrete using waste glass

6 and recycled concrete aggregate

7 Jian-Xin Lu [a], Xin Yan [a,b], Pingping He [a], Chi Sun Poon [a,*]

8

9 [a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic
10 University, Hung Hom, Kowloon, Hong Kong
11 [b] China Academy of Building Research, North Third Ring Road East, Bei Jing, China
12 * Corresponding author: cecspoon@polyu.edu.hk (C.S. Poon)

13

14 Abstract

15 This study designed an eco-friendly pervious concrete (PC) product using waste glass
16 cullet (WGC) and recycled concrete aggregate (RCA) by dry-mixed compaction
17 technique. The mechanical properties, water permeability behavior and related pore
18 structure characteristics, thermal conductivity of the PCs were determined. The
19 experimental results showed that the use of silica fume in the cement paste was effective
20 to compensate for the low compressive strength of the PCs due to the use of narrowed
21 graded aggregates without the incorporation of fine particles (less than 2.36 mm).
22 Although the incorporation of recycled aggregates (i.e. WGC and RCA) into the PCs
23 led to reductions in compressive strength, the water permeability of the PCs was
24 improved, especially for the PCs prepared with WGC, as the use of WGC was
25 conducive to improving the water permeability due to the negligible water absorption
26 nature and smooth surface of glass cullet. Another encouraging result indicated that the
27 PCs comprising 50% WGC as the fine aggregate and 50% RCA as the coarse aggregates
28 could achieve satisfactory strength and permeability, which could largely meet the
29 requirement of the standard (JIS A 5371) for permeable pedestrian pavers. The
30 appropriate blending of the selected size of WGC (2.36-5mm) and RCA (5-10mm) to
31 produce a desirable pore structure in the PCs were responsible for the good performance.
32 In addition, the low thermal conductivity of the produced PCs provided an opportunity
33 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 2,400 millimetres 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.

67

68

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%

70

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, Shi et al., 2019b), it was found that the pavement prepared with RCA was more environmentally friendly as compared to the pavement produced with natural aggregates.

88

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 and co-workers (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

96   the PC was adversely affected by the incorporation of RCA. On the contrary, the study
97   of Zaetang et al. (2016) showed that the replacement level of RCA up to 60% resulted
98   in better compressive strength and surface abrasion resistance than the control PC
99   prepared only with natural aggregates. In addition, the incorporation of RCA was found
100   to have little effect on the void matrix of PC and the water permeability coefficient
101   tended to increase slightly as the RCA replacement level increased. However,
102   Sriravindrarajah et al. (2012) concluded that the water permeability of PC was primarily
103   influenced by the porosity rather than the replacement level of RCA. Based on the
104   above findings, the influence of the RCA on the properties of PC is still not clear.
105   Further studies should be conducted to better understand the influence of RCA on the
106   mechanical and water permeability performance of PC.

107

108   Except the RCA, the recycle and management of waste glass is also an imminent issue
109   in Hong Kong due to the lack of a glass manufacture industry for its reuse (Lu and Poon,
110   2019). Based on the statistics of the Hong Kong EPD, about 300 tonnes of waste glass
111   were generated per day in 2016, but only 7.7% of the waste glass was recycled (EPD,
112   2016). Previous studies (Du and Tan, 2014; Du and Tan, 2013; Lu et al., 2017a; Lu and
113   Poon, 2018) on the utilization of waste glass in cement mortars and conventional
114   concrete mixtures showed that the use of glass cullet as fine aggregates was an effective
115   solution to produce cement-based construction products. Although the replacement of
116   river sand by the glass cullet might lower the compressive strength (Topçu and Canbaz,
117   2004; Park et al., 2004; Tan and Du, 2013a), the inclusion of glass cullet could
118   effectively improve the durability of the mortar or concrete against sulfate attack (Wang,
119   2009) and acid corrosion (Ling et al., 2011). Furthermore, the chloride ion penetrability
120   and drying shrinkage of the glass concrete decreased when the glass aggregate content
121   was increased (Kou and Poon, 2009). One concern of recycling waste glass into cement
122   mortars and concrete is the potential expansion due to the alkali-silica-reaction (ASR)
123   of glass particles. To mitigate the ASR effect, replacing a portion of cement by
124   supplementary cementitious materials (e.g. silica fume, fly ash, metakaolin, glass
125   powder) was found to be an effective method (Du and Tan, 2013; Lu et al., 2017b; Lu
126   et al., 2017c). Also, our recent studies showed that ASR in porous concrete blocks
127   prepared with glass cullet as aggregates was not a problem because the presence of
128   large pores could accommodate the expansive ASR gel (Yang et al., 2018). Therefore,
129   based on the extensive investigations on using waste glass cullet (WGC) in mortars and
130   concrete, it is believed that replacing fine aggregates by WGC has potentials to produce

131 a sustainable PC. In addition, it is anticipated that the water permeability of the PC

132 would be improved due to the negligible water absorption and smooth surface of the

133 glass particles.

134

135 The purpose of this research is to design and develop a sustainable PC for mitigating

136 excessive run-off during heavy rainfalls. The study focuses on entirely replacing natural

137 aggregates with recycled materials including RCA and WGC to produce eco-PC.

138 Physical properties (density, porosity), mechanical property (compressive strength),

139 hydrological behavior (water permeability), thermal conductivity of the developed PC

140 were determined and the related pore characteristics of the PC were also measured by

141 an image analysis technique to reveal the underlying mechanisms governing the PC

142 performance.

143

144 **1.3 Research significance**

145 Due to the over-exploitation of natural aggregates for construction development over

146 the recent decades, Hong Kong and even the whole China are facing dwindling natural

147 aggregates resources (especially for natural river sand) and severe environmental

148 problems. In addition, the huge amounts of municipal solid wastes and construction

149 wastes in Hong Kong are putting enormous pressure on the landfills (existing landfills

150 will be full by about 2020 if not extended (EPD, 2013). Since crushed WGC can

151 possibly be used to replace river sand and RCA can be a source of coarse aggregates,

152 recycling these two recycled materials cooperatively into PC for stormwater

153 management would be promising. Another motivation leading to renewed interest in

154 PC produced with recycled aggregates is an increasing emphasis on sustainable

155 construction. In this study, a preliminary research was conducted to quantify the effects

156 of the incorporation of WGC and RCA on some of the fundamental properties of PC,

157 which would provide a direction for future research on PC prepared with these two

158 types of solid wastes. Previously, limited studies (Batayneh et al., 2007; Poon and Lam,

159 2008) were conducted on the performance of concrete prepared with RCA and WGC

160 simultaneously. No investigations were carried out to jointly use RCA and WGC in the

161 production of PC.

162

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.

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

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.
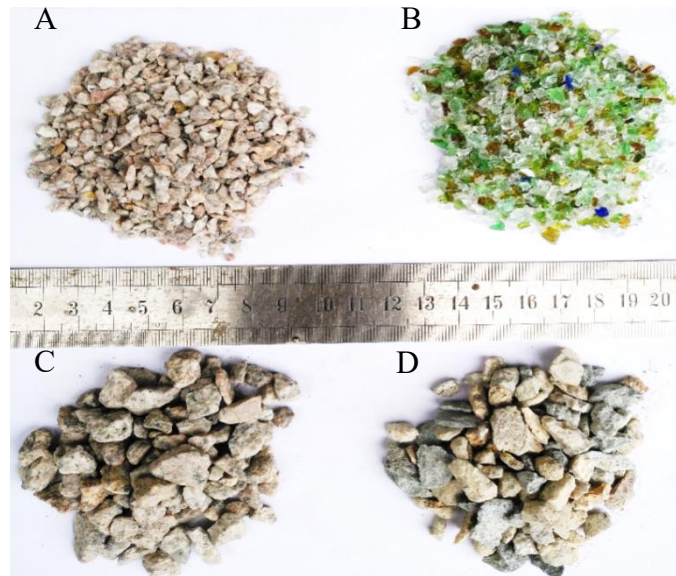
Fig. 1 Appearance of aggregates

A: NA (2.36~5 mm), B: WGC (2.36~5 mm), C: NA (5~10 mm), D: RCA (5~10 mm)

181

182

183   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

184

185   **2.2 Proportion of mix**

186   In order to produce PCs with a good water permeability, single size aggregates were

187   employed. In this study, two series of PCs were prepared by using two size ranges of

188   aggregates. The first series of PCs were produced with only fine aggregates (2.36~5

189   mm) but without the size range of 0-2.36mm. The same size of WGC (2.36~5 mm) was

190   used to replace the natural fine aggregates at replacement levels of 25%, 50%, 75%,

191   and 100% by weight, respectively (labelled as 0G, 25G, 50G, 75G and 100G).

192

193   The second series of PCs were prepared with only the coarse aggregates (5~10 mm).

194 The RCA with the same size range (5~10 mm) was introduced in the PCs to replace the

195 natural coarse aggregates at 25%, 50%, 75%, and 100% by weight, respectively

196 (labelled as 0R, 25R, 50R, 75R and 100R). To improve the properties of PCs and

197 maximize the use of waste materials as aggregates in PCs, the PCs using 100% recycled

198 aggregates comprising 50% WGC as fine aggregates and 50% RCA as coarse

199 aggregates were also produced (50G50R). As compared to the reference mixture, SF

200 was used to replace 10% OPC to produce a strong binder to achieve the desired PC

201 properties. The aggregate-to-binder ratio was fixed at 5, and the water-to-cement ratio

202 (w/c) was adjusted based on the aggregate characteristics. It should be noted that no

203 superplasticizer was used in this study since non-slump mixture was needed to prepare

204 the PCs by dry-mixed compaction technique. Table 4 shows the proportions of 13

205 different PCs mixes. The reference mixtures were prepared with only natural fine or

206 coarse aggregates, named as 100F and 100C, respectively.

207

208 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

209

2.3 Preparation of PCs

211 One intended use of the PC products could be precast pervious blocks for pedestrian

212 pavers. Thus, the preparation of the PC specimens was based on a dry-mixed process

213 normally used for concrete block production (Lu and Poon, 2019) to simulate the actual

214 industrial production practices. The OPC and SF (if any) were initially dry mixed for 2

215 minutes in the mechanical mixer to obtain a homogeneous powder. Then, the aggregates

216 were added and mixed for another 2 minutes followed by adding the required amount

217 of water to produce a cohesive mix with no slump value. The amount of water used was

218 determined by trial tests so that the mixtures condition could be agglomerated into a

219 ball shape by hand without the falling off of the aggregates (CTT, 2004).

220

221 The freshly prepared mixtures were cast into the rectangular molds (200×100×60 mm)

222 and cylindrical molds (Φ75×H60 mm) for mechanical properties test and permeability

223 test, respectively. The compaction method for fabricating the dry-mixed specimens had

224 been described in our previous studies (Poon et al., 2009; Yang et al., 2018; Poon and

225 Lam, 2008). The fabricated specimens were demolded after 24 h and then cured in a

226 steam chamber at 60°C for 7 days.

227

228 **2.4 Properties of PCs**

229 **2.4.1 Density**

230 The hardened densities of the PCs were determined using the methods described in

231 ASTM C1754 (2012) specified for hardened pervious concrete. The specimens were

232 placed in the oven at a temperature of 105°C until the weight was constant. Then the

233 dry weight (W_{dry}) was measured and the specimen volume (V) was calculated. The

234 reported results were the average values of two PC specimens. The density of PCs can

235 be calculated following the equation:

236
$$D = \frac{W_{dry}}{V} \tag{1}$$

237 Where:

238 D represents the density of specimen, g/cm^3;

239 W_{dry} represents the oven dry mass of specimen, g;

240 V represents the volume of specimen, cm^3.

241

242 **2.4.2 Porosity**

9

The porosity (void content) of the PCs was also evaluated in accordance with ASTM C1754 (2012). First, the specimens were completely immersed in water for 30 minutes, 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:

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

(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;

ρ_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.

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

(3)

Where:

f_c represents compressive strength, MPa;

W represents maximum load, N;

10

270   A represents compression area, cm^2.

271

2.4.4 Permeability

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

281
$$k_t = \frac{QL}{AHt} \tag{4}$$

282   Where:

283   k_t represents the permeable coefficient, cm/s;

284   L represents the thick of specimens, cm;

285   Q represents the water content, mL;

286   A represents the surface area of specimen, cm^2;

287   H represents the difference height of water, cm;
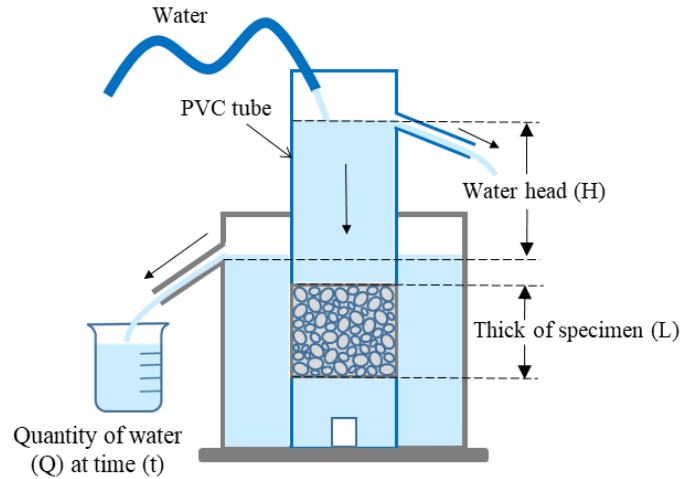
288   t represents the time, s.

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

289

290

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.
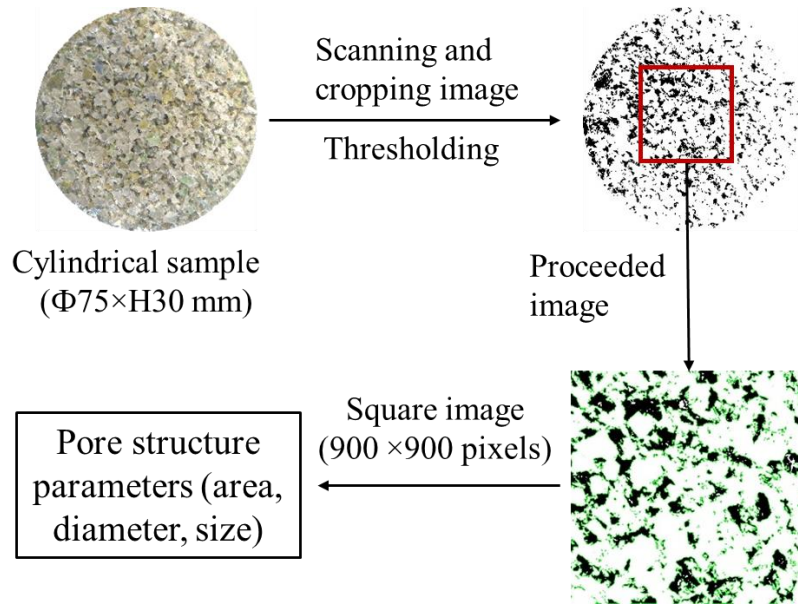
300

301 **2.4.6 Image analysis technique**

Fig. 3 Illustration of image analysis procedure employed

302
303

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

3. Results and discussion

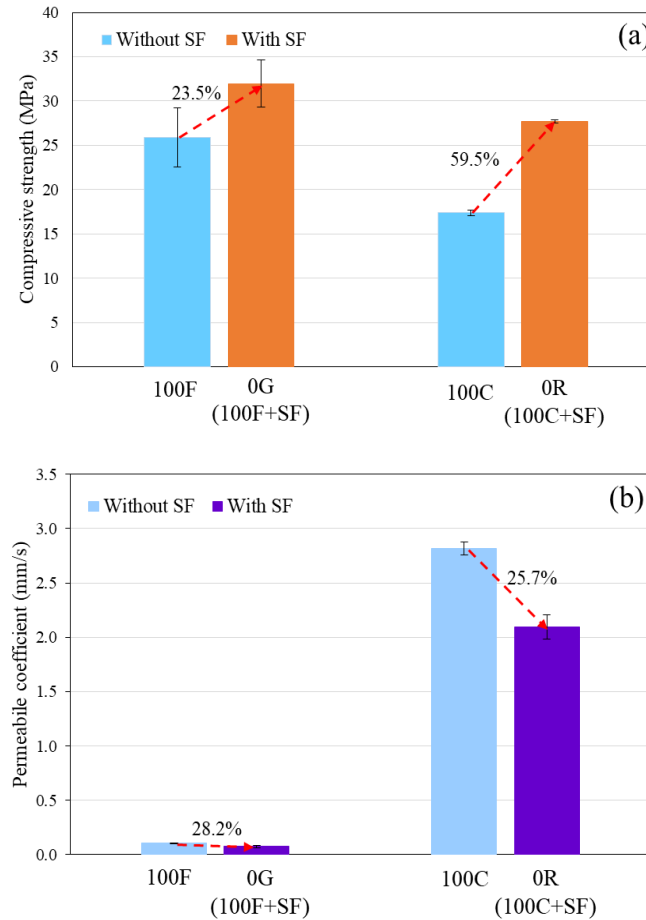### 3.1 Effect of aggregate size and silica fume on the properties of PCs

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

14

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 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;

361　Tan and Du, 2013b). For the PCs using RCA to replace natural granite as coarse
362　aggregates, the decrease in compressive strength was mainly attributed to the
363　inhomogeneous, weaker, less dense and more porous of RCA, weakening the overall
364　strength of the PCs (Poon et al., 2004; Shi et al., 2019a). In these two systems, the
365　increased w/b of the mixtures with the increasing amount of recycled aggregates (i.e.
366　WGC and RCA) could also lead to reductions in the compressive strength.
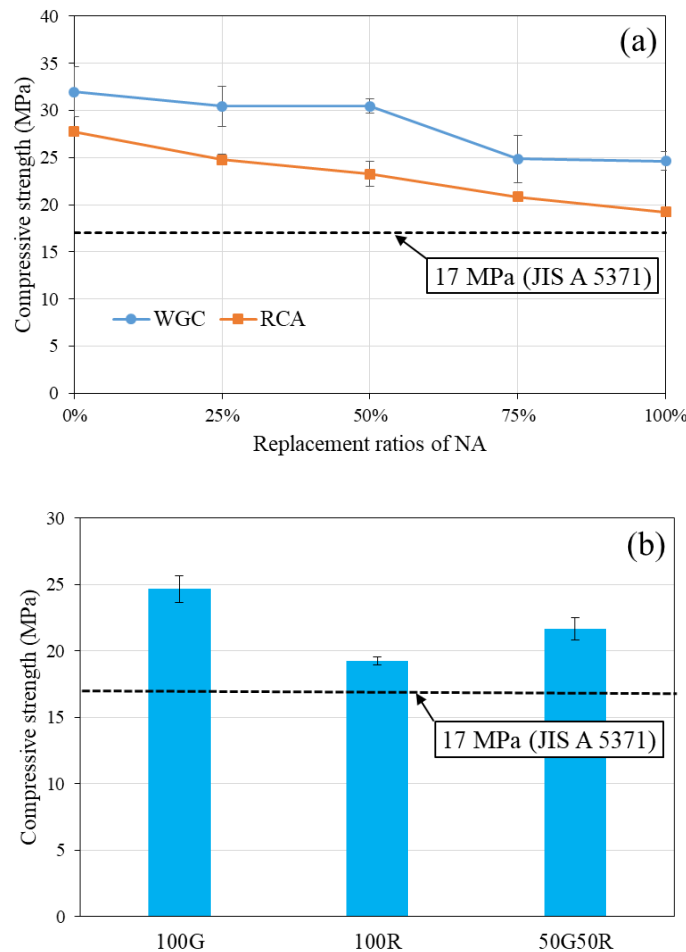
367

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

368

369

370　Although the compressive strengths of PCs decreased by 23% and 31% when the NAs
371　were fully replaced by the WGC and RCA, respectively, all the strength values of PCs
372　could still meet the requirement of permeable concrete blocks for pedestrian pavement
373　according to JIS A 5371 specification with a limit of 17 MPa (JIS A 5371, 2016). This
374　provided useful data for allowing the use of WGC and RCA for the production of
375　pervious concrete blocks. Compared to the strength of PCs prepared with the coarse

376   RCA, the strengths of PCs prepared with the fine WGC were higher, regardless of the

377   replacement ratios of NA. The reason is that the fine aggregates could be compacted to

378   produce concrete blocks with higher density. Fig. 6a shows the influence of WGC and

379   RCA incorporation on the density of the PCs prepared with single-size aggregate. It can

380   be obviously seen that the densities of WGC-based PCs were always higher than those

381   of RCA-based PCs although the density decreased with the increase of replacement

382   ratios. This reduction in the density corresponded well with the results of the

383   compressive strength.

384

385   As for the permeability, a dense concrete matrix is not conducive to improving the water

386   permeability of the PC. Therefore, the PCs (50G50R) were prepared to balance the

387   strength and the water permeability requirements. Fig. 5b shows the compressive

388   strength of 50G50R when compared with the cases of 100G and 100R. The compressive

389   strength of 50G50R was 22 MPa, which was lower than that of 100G but higher than

390   that of 100R. This result indicated that the addition of WGC as fine aggregates in PCs

391   was helpful to enhance the compressive strength as compared to that of PCs prepared

392   with only coarse RCA. This behavior was mainly attributed to the fact that the presence

393   of WGC could fill in the inter-granular voids between the coarse aggregates (RCA) and

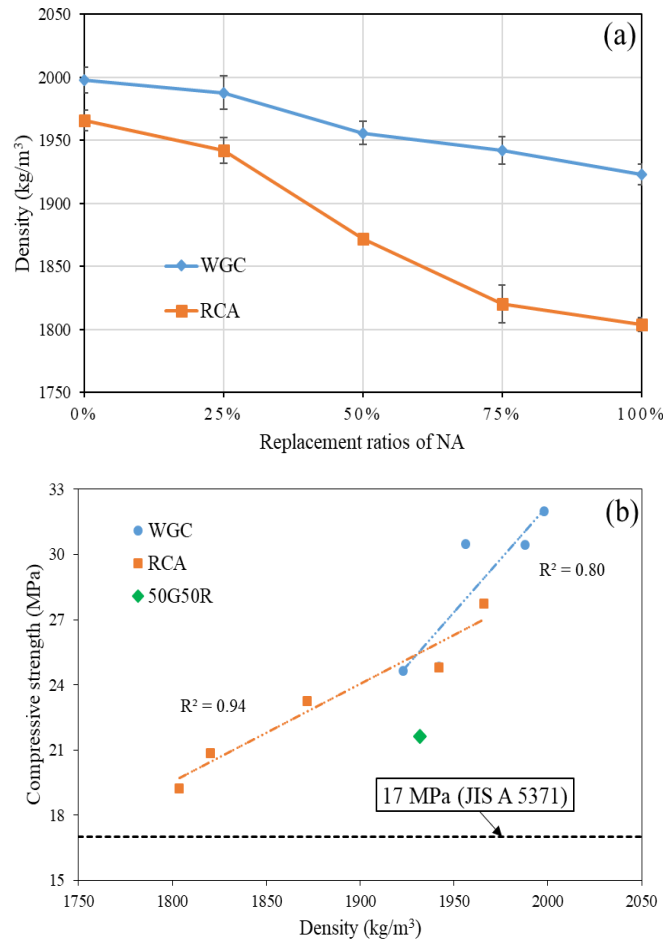394   this interlocking would contribute to the compressive strength.

395

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

396

397

398   The relationships between the compressive strength and the density of PCs are shown

399   in Fig. 6b. As seen, the density of PCs were ranged from 1800 to 2000 kg/m^3, which

400   was less than normal concrete (approximately 2400 kg/m^3) due to the high void content

401   of PC (Tennis et al., 2004). In addition, for both cases of WGC-based and RCA-based

402   PCs, the compressive strength tended to increase linearly with the increase of density,

403   which indicated that the density played a key role in affecting the compressive strength

404   of the PCs. The density of 50G50R with blended aggregates is 1932 kg/m^3, which lies

405   in between the PCs prepared with single-size aggregates. This result also corresponded

406   well with the compressive strength of 50G50R locating in between that of 100G and

407   that of 100R.

408

18

409 **3.3 Permeability and porosity**

410 The hydrological behavior is a key parameter in decisions to use this material for storm

411 water management, so the water permeability of the PC was assessed. Fig. 7a shows

412 the effect of WGC and RCA replacement on the permeability of PCs. It is obvious that

413 the PCs prepared with coarse aggregates had much higher water permeability than the

414 PCs prepared with fine aggregates. This can be explained by the denser matrix of PCs

415 prepared with fine aggregates. For the PCs with RCA, the water permeability stayed

416 relatively stable with increasing replacement level of RCA. The reason might be due to

417 the similar gradation and characteristics of the coarse NA and the RCA. When the fine

418 NA was replaced by up to 50% WGC, the permeable coefficient of the PCs was not

419 affected. However, the permeability was improved significantly to 0.3 mm/s when 100%

420 NA was replaced by WGC. The non-absorbing nature of glass particles is believed to

421 benefit the water to permeate through the concrete. It also should be noted that the

422 permeability requirement of JIS A 5371 specification for the pervious concrete is 0.1

423 mm/s. Therefore, the PCs proportioned with 100% WGC as fine aggregates is feasible

424 from the point views of permeability and compressive strength.

425

426 As regards the PC 50G50R, the coefficient of permeability was 1.2 mm/s, which was

427 12 times of that the standard requirement. In terms of the permeability performance and

428 strength value, the combined use of WGC as fine aggregates and RCA as coarse

429 aggregates is attractive and promising to produce pervious concrete with good strength
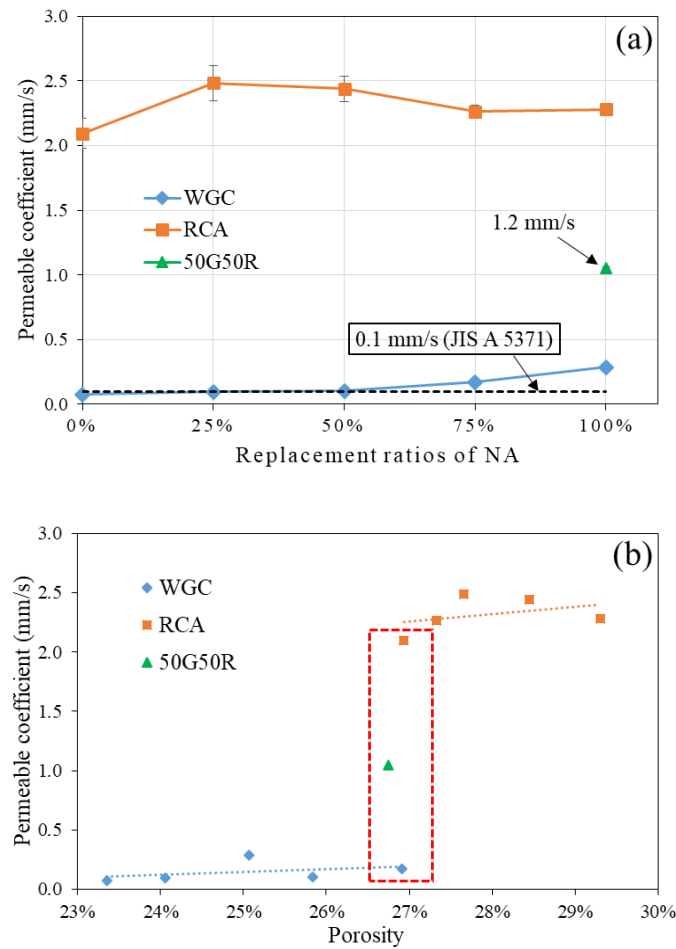
430 and permeability.

431

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

432

433

434   However, as expected, the WGC-based PCs with a dense matrix indeed had much lower

435   permeability than the RCA-based PCs. Fig. 7b shows the relation between the porosity

436   and the permeable coefficient of the PCs. As recommended by American Concrete

437   Institute (ACI), the porosity range of pervious concrete should lie within 15%~35%

438   (ACI 522R-10, 2010), thereby all the prepared specimens in this study can be classified

439   as pervious concrete. Generally, the PCs prepared with the WGC had lower porosity

440   than the PCs prepared with the RCA coarse aggregates due to the higher packing density.

441   In addition, the permeability generally overall increased with an increase in porosity,

442   but there was no definitive relationship between the permeability and the porosity. It

443   can be noted that the three specimens including WGC-based, RCA-based and 50G50R

444   had a similar porosity (red frame) while they had considerably different permeability

445   coefficients. This indicates that the porosity is not the most principal factor in

446   controlling the permeability. The result obtained is consistent with those of Neithalath

447 et al. (2010), who also found that pervious concretes with similar porosities had very
448 different permeability. The reason is attributable to the fact that porosity is a volumetric
449 property of the material, whereas permeability is a parameter that defines the transport
450 property through the material that not only depends on the volume of the pores but also
451 on the distribution of the pore size and its connectivity (Neithalath et al., 2006).
452 Therefore, it is also required to explore other pore structure characteristics in order to
453 adequately understand the permeability behavior.
454

455 **3.4 Pore structure characteristics**

456 The pore structure features of PCs were characterized using image analysis. Fig. 8
457 illustrates the images of the diametrical cross sections of the PCs prepared with three
458 different sizes of aggregates (i.e. 100G, 50G50R and 100R). As can be noticed in Fig.
459 8, the pore shapes in the three PCs are irregular and the pores tend to be more irregular
460 with increasing aggregate sizes. A general trend of increasing pore sizes and
461 connectivity (black areas) with the increasing aggregate sizes can be easily observed.
462 This finding is in agreement with that of Marolf et al. (2004), who also found that an
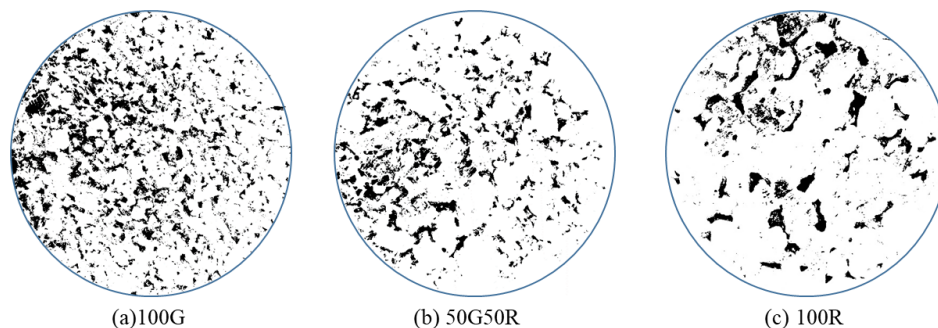463 increase in aggregate size resulted in an increase of pore size.

(a)100G   (b) 50G50R   (c) 100R

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

464
465

466 Fig. 9 shows the pore size distribution histograms and the cumulative frequency curve
467 of pore size for PCs containing 100% WGC, blended aggregates of 50% WGC and 50%
468 RCA, and 100% RCA. The PCs prepared with 100% WGC had larger number of fine
469 pores and the distribution of pore sizes was narrow. Approximate 90% of pores were
470 smaller than 4 mm. By contrast, the specimens of 100R had a broader pore size
471 distribution and more large pores (17%＞6 mm) were present in the mixtures. For the
472 50G50R, nearly 80% of the pores in the specimens lied within the 0~3 mm range and
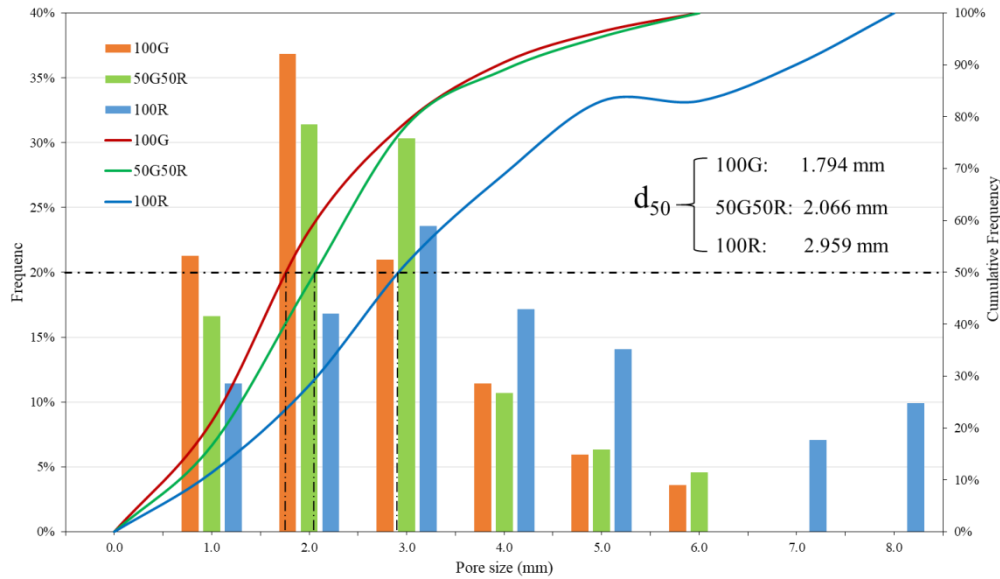
473   no pores were larger than 6 mm.

474

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

475

476

477   Compared to the PCs prepared with only the coarse-sized aggregates (100R), the PCs

478   prepared with the blended aggregates contained a larger proportion of smaller pores.

479   The above results indicated that the increase in aggregate size led to an increase in pore

480   size of the mixture. The results also explain the phenomenon that the porosity of the PC

481   with smaller-sized aggregates was approximately the same as the one prepared with the

482   larger-sized aggregates; in other words, the porosity of the mixture with smaller

483   aggregate size consisted of a greater number of fine pores while the similar porosity of

484   the mixture prepared by coarse-sized aggregate contained more coarse pores but less

485   fine pores. According to the study of Sumanasooriya and Neithalath (2011), for the

486   same porosity, larger aggregate size or pore size could increase the pore connectivity

487   factor, which is pivotal to determine the hydraulic transport properties of pervious

488   concrete. Therefore, the PCs prepared with 100% RCA or the blended aggregates

489   exhibited higher hydraulic conductivity because of the larger pore size and higher pore

490   connectivity.

491

492   The equivalent pore diameter corresponding to the 50% cumulative frequency is taken

493   as the effective pore size (d_{50}) (Neithalath and Sumanasooriya, 2010), which can be

494   representatively used as the characteristic pore size in pervious concrete. It can be

495   observed from Fig. 8 that the d_{50} of PC mixture made with small-sized aggregates (100G)

496   was much smaller than those for the mixture produced with coarse-sized aggregates

497   (100R) (1.794 mm Vs. 2.959 mm). The d_{50} value for the blended-aggregate PC

498   (50G50R) was 2.066 mm which lied between those of the two single-sized aggregate

499   PCs. The reason is because the smaller aggregates could fill the pore spaces between

500   the larger aggregates. Based on above results, it can be concluded that the d_{50} value of

501   PCs increased with the increase of aggregate sizes. As reported in previous studies

502   (Neithalath and Sumanasooriya, 2010; Sumanasooriya and Neithalath, 2009), the d_{50}

503   value was linearly related to the critical pore size and an increase of the critical pore

504   size led to an increase of the permeability. Therefore, the increase in the d_{50} because of

505   the increased aggregate sizes was expected to increase the permeability. In this study,

506   the PCs prepared with a blend of aggregate sizes had a moderate d_{50} value so that a

507   desired permeability could be achieved.

508

509   **3.5 Thermal conductivity**

510   The effects of WGC and RCA on the thermal conductivity of PCs are shown in Fig. 10.

511   The WGC and RCA were used to replace the NA by 0%, 50% and 100% in the PCs,

512   respectively. As comparison, the thermal conductivity of PCs with 50% WGC and 50%

513   RCA as aggregates was also measured. First, it can be seen that the PCs with the fine

514   NA had a relatively higher thermal conductivity than the PCs prepare with the coarse

515   NA. The reason for this behavior is that the higher density and relatively lower porosity

516   of the former increased the contact points of the aggregate particles, which enhanced

517   the heat transfer capability of the specimen. For the PCs containing WGC, the thermal

518   conductivity tended to decrease as the WGC replacement level increased. This trend

519   was mainly due to the lower thermal conductivity of glass (0.93 W/mK (Poutos et al.,

520   2008)) in comparison with the natural granite aggregate (2.12~3.62 W/mK (Cho et al.,

521   2009)). On the contrary, the thermal conductivity of the PCs increased when the content

522   of RCA increased. The use of 100% RCA in the PCs rendered a higher thermal

523   conductivity of 1.04 W/mK, which was more than twice than the PCs prepared with

524   100% WGC. This could be interpreted as the presence of the residual mortars in the

525   RCA which contained quartz sand (with thermal conductivity of 7.69 W/mK (Zhao et

526   al., 2016)) leading to the higher thermal conductivity of the RCA (Zega and Maio, 2009).

527   Zaetang et al. (2016) also indicated that the thermal conductivity coefficients of PCs

528   prepared with RCA were higher than those of PCs prepared with NA. Additionally, the

529 incorporation of RCA with a high water absorption value (6.13%) could further increase
530 the thermal conductivity because of the high moisture content. The replacement of the
531 air with a lower thermal conductivity (0.026 W/mK) in the void of the RCA by water
532 with a higher thermal conductivity (0.606 W/mK) would result in an increase of the
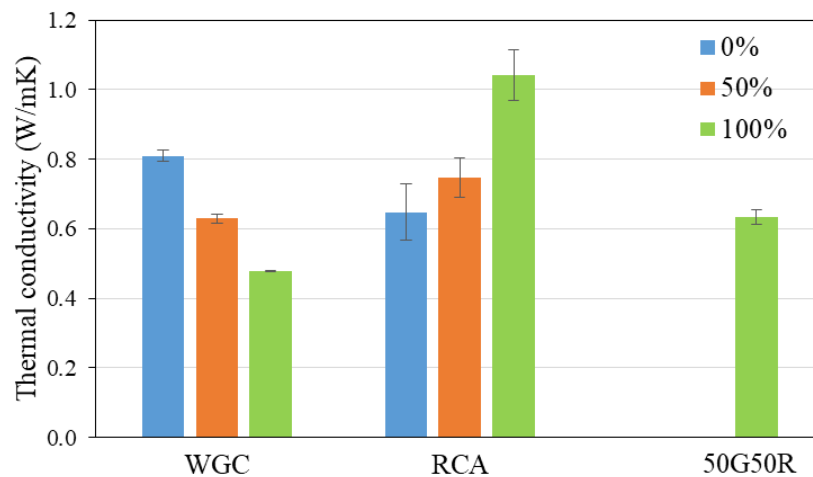533 thermal conductivity.
534

Fig. 10 Thermal conductivity of PCs prepared with different aggregates
535
536

537 It is clearly evident that the combined use of the WGC and the RCA as aggregates for
538 the production of PCs leads to a relatively low thermal conductivity (0.63 W/mK). This
539 is partly attributed to the incorporation of the WGC with a lower thermal conductivity.
540 Another possible reason is the presence of larger numbers of fine pores in the 50G50R
541 specimens as compared to the specimen prepared with 100% RCA. The air with very
542 low thermal conductivity (0.026 W/mK) present in the pores is expected to hinder the
543 thermal conduction and thus reduce the overall thermal conductivity.
544

545 **4. Discussion**

546 One of the findings from the experimental investigations in the PCs is that the aggregate
547 sizes and the SF addition have a significant influence on the compressive strength and
548 the permeability behavior, which are two primary considerations for the potential
549 application of PCs. The use of coarse aggregate (5~10 mm) in the PCs greatly improved
550 the hydraulic conductivity but caused a relatively low compressive strength as
551 compared to the use of smaller-sized aggregates (2.36~5 mm). Therefore, proper

552 amount of SF (10%) was introduced into the PCs to enhance the low compressive

553 strength although the addition of SF would reduce the permeability correspondingly.

554 The increase of paste volume due to the addition of low density SF would increase the

555 thickness of the paste layer adhered on the surface of aggregates, which caused a better

556 bonding and increased strength. This improvement in strength further provided an

557 opportunity to reuse recycled aggregates (i.e. WGC and RCA) in the production of

558 sustainable PCs. It is encouraging to note that when 100% WGC or 100% RCA was

559 used to replace natural granite aggregates, the compressive strength and the percolation

560 rate of the produced PCs could meet the requirement of pedestrian concrete block in

561 JIS A 5371 specification. This results showed that the use of WGC or RCA to totally

562 replace natural aggregates in the PCs incorporating SF was feasible.

563

564 However, the 100% RCA-based PCs exhibited much higher permeable coefficient but

565 relatively lower strength due to the fact that the PCs with single larger-sized aggregates

566 contained a larger proportion of coarser pores and larger characteristic pore size. On the

567 contrary, the 100% WGC-based PCs had a very lower permeability coefficient but

568 relatively higher strength because the large pore were replaced by fine pores. These

569 results indicated that aggregate sizes used have a considerable effect on the permeability

570 behavior of PCs. Increasing the pore sizes or using large-sized aggregates was

571 conducive to improving the water permeability and the use of fine aggregates was found

572 to reduce the permeability. This reduction can be described by the fact that the fine

573 particles blocked access to the pores, resulting in a hindrance to water path. In this study,

574 except porosity, the other pore structure features including pore size distributions,

575 characteristic pore sizes and the related pore connectivity were found to play dominant

576 roles in affecting the water permeability and the mechanical properties. Specifically,

577 the increase in the effective pore size (i.e. d_{50}) value due to the increase of aggregate

578 sizes resulted in an increase of the permeability and a decrease of the strength. This

579 suggests the possibility of employing the information of the features of pore structures

580 to guide the design of the PCs with both good strength and high permeability.

581

582 As such, the aggregates in the PCs were designed as a combination of 50% WGC as

583 fine aggregates and 50% RCA as coarse aggregates. The results showed that the

584 combined use of WGC and RCA in the production of PCs could achieve an acceptable

585 compressive strength of 22 MPa (as shown in Section 3.2) and a satisfied permeability

586 value of 1.2 mm/s (as presented in Section 3.3), which was 12 times of that required by

25

587 JIS A 5371 specification. The high permeability would ensure that the developed PCs
588 can be capable in a heavy rainfall event. The desired performance was attributed to the
589 fact that the produced PCs had appropriate proportions of small pores (1~3 mm), no
590 very large pores (＞6 mm) and suitably effective pore size distribution. In addition, the
591 use of the WGC which had about zero water absorption value was further beneficial to
592 enhance the permeability of the PCs. Hence, appropriate mix design based on aggregate
593 sizes and types is needed to develop a PC with good strength and permeability.

595 Since the produced PCs had a high void content so that it had potential to be used as a
596 thermal insulating material. Generally, the thermal conductivities of the PCs developed
597 in this study varied between 0.48 and 1.04 W/mK, which were relatively lower in
598 comparison with those of conventional concretes (0.95 to 1.46 W/mK) (Demirboğa,
599 2007). Also, the density values of the eco-PCs ranging from 1800~2000 kg/m^3 in this
600 study were 20% lower than those of normal weight concrete. When 100% WGC was
601 used as aggregates, the PC attained the lowest thermal conductivity of 0.48 W/mK,
602 which was comparable to the thermal conductivity of lightweight concrete with thermal
603 conductivities ranging from 0.40 to 0.69 W/mK (Alengaram et al., 2013; Blanco et al.,
604 2000) and the compressive strengths of PCs were generally higher than 20 MPa, which
605 was sufficient to meet the strength requirement of at least 17 MPa for structural
606 lightweight concrete specified by ASTM C330 (2017). These findings suggest that the
607 PCs produced with WGC and RCA could have potentials for another application,
608 namely, as partition walls or blocks in buildings to reduce the amount of heat transfer
609 and energy consumption.

611 ## 5. Conclusions

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

616 • Compared to the PCs prepared with single small-sized aggregates, the PCs with
617 single coarse-sized aggregates exhibited much higher permeable coefficient but had
618 lower compressive strength. However, introduction of 10% silica fume as cementitious
619 materials could significantly improve the compressive strength although decrease the
620 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.

Acknowledgements

Reference

ACI 522R-10, 2010. Report on pervious concrete. Farmington Hills, Michigan: American Concrete Institute.

Alengaram, U.J., Al Muhit, B.A., Jumaat, M.Z. bin, Jing, M.L.Y., 2013. A comparison of the thermal conductivity of oil palm shell foamed concrete with conventional materials. Mater. Des. 51, 522–529.

Ali, E.E., Al-Tersawy, S.H., 2012. Recycled glass as a partial replacement for fine aggregate in self compacting concrete. Constr. Build. Mater. 35, 785–791.

ASTM C1113-90, 2013. Test method for thermal conductivity of refractories by hot wire (Platinum Resistance Thermometer Technique), American Society for Testing

654   and Materials.

655   ASTM C330/C330M-17a, 2017. Standard specification for lightweight aggregates for
656   structural concrete, American Society for Testing and Materials.

657   ASTM C39, 2018. Standard test method for compressive strength of cylindrical
658   concrete specimens, American Society for Testing and Materials.

659   ASTM C1754, 2012. Standard test method for density and void content of hardened
660   pervious concrete, American Society for Testing and Materials.

661   Batayneh, M., Marie, I., Asi, I., 2007. Use of selected waste materials in concrete mixes.
662   Waste Manage. 27, 1870–1876.

663   Bhutta, M.A.R., Hasanah, N., Farhayu, N., Hussin, M.W., Tahir, M. bin Md, Mirza, J.,
664   2013. Properties of porous concrete from waste crushed concrete (recycled
665   aggregate). Constr. Build. Mater. 47, 1243–1248.

666   Blanco, F., García, P., Mateos, P., Ayala, J., 2000. Characteristics and properties of
667   lightweight concrete manufactured with cenospheres. Cem. Concr. Res. 30, 1715–
668   1722.

669   Cho, W.J., Kwon, S., Choi, J.W., 2009. The thermal conductivity for granite with
670   various water contents. Eng. Geol. 107, 167–171.

671   Concrete Technology Today (CTT), 2004. Pervious concrete mixtures and properties.
672   The Portland Cement Association, CT043, 25(3).

673   Cong, X., Gong, S., Darwin, D., McCabe, S.L., 1992. Role of silica fume in
674   compressive strength of cement paste, mortar and concrete. ACI Mater. J. 89(4),
675   375–387.

676   Demirboğa, R., 2007. Thermal conductivity and compressive strength of concrete
677   incorporation with mineral admixtures. Build. Environ. 42, 2467–2471.

678   Department of Environmental Protection (DEP), 2006. Pennsylvania stormwater best
679   management practices manual.

680   Drainage Services Department (DSD), 2018. Stormwater drainage manual: Planning,
681   design and management, the Hong Kong Special Administrative Region, Fifth
682   Edition.

683   Du, H.J., Tan, K.H., 2013. Use of waste glass as sand in mortar: part II–alkali–silica
684   reaction and mitigation methods. Cem. Concr. Compos. 35, 118–126.

685   Du, H.J., Tan, K.H., 2014. Concrete with recycled glass as fine aggregates. ACI Mater.
686   J. 47–57.

687   Environmental Protection Department (EPD), 2013. The Hong Kong waste problem,
688   https://www.legco.gov.hk/yr12-13/chinese/panels/ea/duty_v/eavp1304-4-ec.pdf.

689   Environmental and Protection Department (EPD), 2016. Monitoring of solid waste in
690   Hong Kong, Waste Statistics for 2016, the Hong Kong Special Administrative
691   Region, https://www.wastereduction.gov.hk/sites/default/files/msw2016.pdf.

692   JIS A 5371, 2016. Precast unreinforced concrete products, Japanese Standards
693   Association.

694   Kou, S.C., Poon, C.S., 2009. Properties of self-compacting concrete prepared with
695   recycled glass aggregate. Cem. Concr. Compos. 31, 107–113.

696 Li L., Zhan B.J., Lu J.X., Poon C.S., 2019. Systematic evaluation of the effect of
697   replacing river sand by different particle size ranges of fine recycled concrete
698   aggregates (FRCA) in cement mortars. Constr. Build. Mater. 209, 147–155.

699 Ling, T.C., Poon, C.S., Kou, S.C., 2011. Feasibility of using recycled glass in
700   architectural cement mortars. Cem. Concr. Compos. 33, 848–854.

701 Lu, J.X., Poon, C.S., 2019. Recycling of waste glass in construction materials (Chapter
702   6), New Trends in Eco-efficient and Recycled Concrete, 1st Edition, Woodhead
703   Publishing.

704 Lu, J.X., Duan, Z.H., Poon, C.S., 2017a. Combined use of waste glass powder and cullet
705   in architectural mortar. Cem. Concr. Compos. 82, 34–44.

706 Lu, J.X., Poon, C.S., 2018. Improvement of early-age properties for glass-cement
707   mortar by adding nanosilica. Cem. Concr. Compos. 89, 18–30.

708 Lu, J.X., Zhan, B.J., Duan, Z.H., Poon, C.S., 2017b. Improving the performance of
709   architectural mortar containing 100% recycled glass aggregates by using SCMs.
710   Constr. Build. Mater. 153, 975–985.

711 Lu, J.X., Zhan, B.J., Duan, Z.H., Poon, C.S., 2017c. Using glass powder to improve the
712   durability of architectural mortar prepared with glass aggregates. Mater. Des. 135,
713   102–111.

714 Marolf, A., Neithalath, N., Sell, E., Wegner, K., Weiss, J., Olek, J., 2004. Influence of
715   aggregate size and gradation on acoustic absorption of enhanced porosity concrete.
716   ACI Mater. J. 101(1), 82–91.

717 Neithalath, N., Sumanasooriya, M.S., Deo, O., 2010. Characterizing pore volume, sizes,
718   and connectivity in pervious concretes towards permeability prediction. Mater.
719   Charact. 61(8), 802–813.

720 Neithalath, N., Weiss, J., Olek, J., 2006. Characterizing enhanced porosity concrete
721   using electrical impedance to predict acoustic and hydraulic performance. Cem.
722   Concr. Res. 36, 2074–2085.

723 Paranavithana, S., Mohajerani, A., 2006. Effects of recycled concrete aggregates on
724   properties of asphalt concrete. Resour. Conserv. Recy. 48, 1–12.

725 Park, S.B., Lee, B.C., Kim, J.H., 2004. Studies on mechanical properties of concrete
726   containing waste glass aggregate. Cem. Concr. Res. 34, 2181–2189.

727 Poon, C.S., Chan, D., 2006. Feasible use of recycled concrete aggregates and crushed
728   clay brick as unbound road sub-base. Constr. Build. Mater. 20, 578–585.

729 Poon, C.S., Kou, S.C., Wan, H.W., Etxeberria, M., 2009. Properties of concrete blocks
730   prepared with low grade recycled aggregates. Waste Manage. 29, 2369–2377.

731 Poon, C.S., Lam, C.S., 2008. The effect of aggregate-to-cement ratio and types of
732   aggregates on the properties of pre-cast concrete blocks. Cem. Concr. Compos. 30,
733   283–289.

734 Poon, C.S., Shui, Z.H., Lam, L., 2004. Effect of microstructure of ITZ on compressive
735   strength of concrete prepared with recycled aggregates. Constr. Build. Mater. 18,
736   461–468.

737 Poutos, K.H., Alani, A.M., Walden, P.J., Sangha, C.M., 2008. Relative temperature

changes within concrete made with recycled glass aggregate. Constr. Build. Mater. 22, 557–565.

Sata, V., Wongsa, A., Chindaprasirt, P., 2013. Properties of pervious geopolymer concrete using recycled aggregates. Constr. Build. Mater. 42, 33–39.

Shi, X., Mukhopadhyay, A., Zollinger, D., 2019a. Long-term performance evaluation of concrete pavements containing recycled concrete aggregate in Oklahoma. Transportation Research Record: Journal of the Transportation Research Board, 1-14.

Shi, X., Mukhopadhyay, A., Zollinger, D., Grasley, Z., 2019b. Economic input-output life cycle assessment of concrete pavement containing recycled concrete aggregate. J. Clean. Prod. 225, 414-425.

Sriravindrarajah, R., Wang, N.D.H., Ervin, L.J.W., 2012. Mix design for pervious recycled aggregate concrete. Inter. J. Concr. Struct. Mater. 6(4), 239–246.

Sumanasooriya, M.S., Neithalath, N., 2009. Stereology- and morphology-based pore structure descriptors of enhanced porosity (pervious) concretes. ACI Mater. J, 106, 429–438.

Sumanasooriya, M.S., Neithalath, N., 2011. Pore structure features of pervious concretes proportioned for desired porosities and their performance prediction. Cem. Concr. Compos. 33, 778–787.

Tan K.H., Du H.J., 2013a. Sandless concrete with fly ash as supplementary cementing material, J. Sustain. Cement-based Mater. 2, 238-249.

Tan K.H., Du H.J., 2013b. Use of waste glass as sand in mortar: Part I-fresh, mechanical and durability properties, Cem. Concr. Compos. 35, 109-117.

Tennis, P.D., Leming, M.L., Akers, D.J., 2004. Pervious Concrete Pavements, EB302.02. Portland Cement Association, Skokie, Illinois, and National Ready Mixed Concrete Association, Silver Spring, MD, USA.

Topçu, İ.B., Canbaz, M., 2004. Properties of concrete containing waste glass. Cem. Concr. Res. 34, 267–274.

Wang, H.Y., 2009. A study of the effects of LCD glass sand on the properties of concrete. Waste Manage. 29, 335–341.

Xiao, J.Z., Li, W.G., Fan, Y.H., Huang, X., 2012. An overview of study on recycled aggregate concrete in China (1996–2011). Constr. Build. Mater. 31, 364–383.

Yang, J., Jiang, G.L., 2003. Experimental study on properties of pervious concrete pavement materials. Cem. Concr. Res. 33, 381–386.

Yang, S.Q., Cui, H.Z., Poon, C.S., 2018. Assessment of in-situ alkali-silica reaction (ASR) development of glass aggregate concrete prepared with dry-mix and conventional wet-mix methods by X-ray computed micro-tomography. Cem. Concr. Compos. 90, 266–276.

Zaetang, Y., Sata, V., Wongsa, A., Chindaprasirt, P., 2016. Properties of pervious concrete containing recycled concrete block aggregate and recycled concrete aggregate. Constr. Build. Mater. 111, 15–21.

Zega, C.J., Di Maio, A.A., 2009. Recycled concrete made with different natural coarse

780   aggregates exposed to high temperature. Constr. Build. Mater. 23, 2047–2052.

781   Zhang, Z.Q., Zhang, B., Yan, P.Y., 2016. Comparative study of effect of raw and

782   densified silica fume in the paste, mortar and concrete. Constr. Build. Mater. 105,

783   82–93.

784   Zhao, X.G., Wang, J., Chena, F., Li, P.F., Ma, L.K., Xie, J.L., Liu, Y.M., 2016.

785   Experimental investigations on the thermal conductivity characteristics of Beishan

786   granitic rocks for China's HLW disposal. Tectonophysics 683, 124–137.