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POROSITY AND PERMEABILITY OF PERVIOUS CONCRETE USING CONSTRUCTION AND DEMOLITION WASTE IN VIETNAM

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ABSTRACT: Using recycled aggregates (RA) from construction and demolition wastes to produce non-structural concrete is a sustainable solution with dual environmental benefits. There is potential to use RA to manufacture pervious concrete for permeable pavement systems. The ratio of concrete and clay brick aggregates, designed porosity, and the complete mix design has been evaluated for their contributions to making pervious concrete blocks. In this study, the porosity characteristics, hydraulic conductivity and mechanical properties of the pervious concrete made in Vietnam were investigated aiming to characterize the relationships among mechanical properties, total and effective porosities, and water permeability. Experimental results showed that the mechanical strengths decreased basically with increasing of the design porosity, in especial, the previous blocks made from clay brick aggregate led to the lowest of compressive and flexural strength. The ratio of mixed aggregates, on the other hand, gave a negligible influence on the effective porosity and permeability of pervious concrete blocks, and the water permeabilities were mainly controlled by the total porosities of tested pervious blocks.

Keywords: Pervious concrete, Recycled aggregate, Porosity, Water permeability

1. INTRODUCTION

Population growth, infrastructure, and housing construction activities generate large amounts of construction and demolition waste (CDW) and as a result, increase demand for recycling construction waste. In many countries, the proportion of recycled aggregate used is very small, while the land available for landfill becomes scarce and the world demand for aggregate reaches a massive 40 billion tons per year. Therefore, more solutions to this problem are needed [1].

According to official statistics of major cities in Vietnam, the total amount of CDW generated is about 1.46 to 1.92 million tons per year [2]. The amount of CDW has also increased very quickly, accounting for about 10–15% of urban solid waste. In special cities of Hanoi, Hochiminh, CDW accounts for 25% of urban solid waste [3]. Meanwhile, the recycling rate is as low as 1% to 2% [2], which goes unmanaged due to lack of legislation, awareness and technology and many other reasons.

In some countries, CDW is classified as inert materials (bricks, masonry, concrete and soil) that are reused at construction sites and the remaining waste is disposed of at other landfill sites [4]. Japan and other developed countries are leading the way in recycling CDW, achieving 98% recycling, and the recycled CDW is used in many applications thanks to high taxes on natural aggregate and development of techniques [5, 6].

Recycled aggregate (RA) is commonly used as bulk backfill, as sub-base, base, or surface materials in road construction, sidewalks, and hydraulically bound materials, and in the manufacture of new concrete structures as fresh concrete [1,7,8]. Due to the weak mechanical characteristics and the high variability in quality, the use of recycled aggregates should be carefully considered in terms of applicability in proportion to the mechanical strength achieved. Therefor, pervious concrete, which has a typical porosity of 0.15 – 0.3 and median pore diameter of 2 – 4 mm [9], has a high potential application of recycled materials.

Pervious concrete displays better water permeability characteristics due to its connected pore structure [10,11]. Futhermore, pervious concrete is an environmentally friendly material that improves skid resistance and sound absorption characteristics, reduces the ‘‘heat island” effect and for the natural ecosystem [14-17]. Pervious concrete pavements are the most widely used in sustainable urban drainage systems due to their availability and ease of construction in urban areas and also coastal areas [13]. Applications that can be mentioned are pavement in parking lots, sidewalks, and internal roads due to their poor strength related to porosity.

Hydraulic conductivity or water permeability is the most valuable parameter of any porous materials, and a number of studies have already been carried out to relate the pore structure to permeability [14]. Experimental investigation has shown that the hydraulic conductivity of any porous materials is inherently dependent on the pore features such as pore size, specific surface area of pores, porosity, and the tortuous flow path [16,18,19]. However, the interconnected pore system (the main factor determining the drainage capacity) is most affected by the type of aggregate, not the size of the aggregate [17]. Pervious concrete using recycled aggregates with many angles often has a porosity greater than the desired porosity and higher than when using normal aggregates (from 2–3%) [19-22]. Another study showed that recycling of concrete did not affect the porosity but reduced its density and increased its water permeability [19]. The water permeability of pervious concrete achieved ranges from 0.1 to 3.3 cm/s. It is therefore suitable for the purpose of water drainage [18,22] .

The water permeability coefficient depends on the pore system, pore size, aggregate type, and proportions of mixes [24,25]. Using recycled aggregate increases the drainage rate of concrete compared to using natural aggregate (with the same cement paste ratio). Several studies have shown that the permeability coefficient is 24.8 mm/s and 37 mm/s, respectively, for pervious concrete using ceramic and recycled concrete aggregate, while the permeability of natural aggregate is 21mm/s [22,26]. Barnhouse [23] obtained permeability coefficients up to 55 and 80, mm/s when using recycled aggregates to make concrete with a hight porosity. The pore system is enlarged and the water permeability of porous concrete using recycled aggregate is increased due to the thinner cement paste covering the aggregate particles. This phenomenon occurs because the specific surface area of recycled aggregate is higher than that of natural aggregate [18,28,29]. In some cases, although the porosity is equivalent to that of natural aggregates, the drainage capacity is still increased [25]. However, some authors concluded that the drainage capacity depends only on the porosity and is not significantly affected by the use of recycled aggregate [26]. It has been demonstrated that combining 50% fine glass waste (2.36–5 mm) and 50% coarse aggregate from concrete creates a pervious concrete that meets both the strength and drainage requirements of the Japanese standards (JIS A 5371) for pedestrian roads [27]. In contrast, using 100% fine glass waste drastically reduced the water permeability to only 0.3 mm/s.

2. RESEARCH SIGNIFICANCE

The available research results also have different views and results on the effects of recycled aggregates on the porosity and drainage characteristics. Further, the effects of clay brick content in the recycled aggregate mix (brick and recycled concrete) on the porosity and permeability properties as well as the strength of permeable concrete have not been reported by many studies. In this paper, the relationship between the porosity, water permeability, and mechanical strength of pervious concrete blocks with different proportions of aggregate mixture of concrete and clay brick aggregates was investigated.

3. MATERIALS AND TESTING METHODS

3.1 Materials

Three main materials are used in the fabrication of pervious concrete: cement, coarse aggregates, and water. Ordinary Portland cement with a specific gravity and specific surface area of 3.1 and 3300 cm^2/g, respectively, was used for this investigation. The 28-day compressive strength of cement is 47 MPa. No plasticizer was used in this study. Two types of single-size coarse aggregates of 5–10 mm diameter were considered in this research. One was recycled aggregate comprised of crushed structural concrete (RC), and the other was crushed broken clay brick (RB). Both were obtained from local construction sites inVietnam.

Fig. 1 Coarse recycled aggregate: Concrete aggregate (upper), Clay brick aggregate (lower)

Table 1 Material properties of recycled aggregate from concrete and clay brick demolition waste

Parameter	Unit	This study		Quality standards/Coarse aggregate		
		RC	RB	Class H [(a)]	Class M [(b)]	Class L [(c)]
Specific gravity	–	2.60	2.55	–	–	–
Bulk density	kg/m^3	1620	1280	–	–	–
24h water absorption	%	5.5	14.6	≤ 3.0	≤ 3.5	≤ 7.0
Fine amount < 75μm	%	0	0	≤ 1.0	≤ 1.5	≤ 2.0
Los Angeles abrasion	%	38	46	≤ 35	–	–
Density of oven-dried	g/cm^3	2.27	1.62	≥ 2.5	≥ 2.3	–
Density in saturated surface-dry condition	g/cm^3	2.45	1.95	–	–	–

[(a)] JIS A 5021:2018 Recycled aggregate for concrete - Class H
[(b)] JIS A 5022:2012 Recycled concrete using recycled aggregate - Class M
[(c)] JIS A 5023:2012 Recycled concrete using recycled aggregate - Class L

Table 2 Mixture proportions of pervious concrete

	Design porosity (%)	Recycled concrete aggregate (RC) (kg/m^3)	Recycled brick aggregate (RB) (kg/m^3)	Cement (C) (kg/m^3)	Water (W) (kg/m^3)
100%RC	15 (RC15)	1519	0	414	138
	20 (RC20)	1519	0	337	112
	25 (RC25)	1519	0	270	89
100% RB	15 (RB15)	0	1121	414	137
	20 (RB20)	0	1121	337	112
	25 (RB25)	0	1121	268	88
50%RC + 50%RB	15 (M15)	754	565	414	137
	20 (M20)	754	565	337	111
	25 (M25)	754	565	268	88

The raw RA was initially large in size, and it was crushed using a crushing machine. The crushed RA was then sieved to obtain RA in the range of 5–10 mm. The aggregate size between 5 and 10 mm was chosen as it was reported that a relatively smaller amount of cement paste is sufficient to coat aggregates in this range [14]. No treatment was done to the RA to remove the adhering mortar in order to minimize the production cost of pervious concrete. Figure 1 shows the coarse aggregates used in this study, and their properties are detailed in Table 1. The higher water absorption and higher Los Angeles abrasion loss of RC and RB were due to the residues of cement mortar attached to the aggregate surface and the high porosity of the recycled aggregate.

3.2 Mixing Proportion

The mixture proportions for pervious concrete were in accordance with the ACI 522R–10 [28]. In general, the overarching philosophy of mixture proportioning for pervious concrete is to achieve a balance between voids, strength, paste content, and workability [28]. The coarse aggregate size No. 8, which meets the requirements for C33/C33M was used in this study. The water-cementitious material ratio (w/c) is an important consideration for obtaining the desired strength and void structure in pervious concrete. Experience has shown that w/cm in the range of 0.26 to 0.45 will provide the best aggregate coating and paste stability. The w/c was fixed at 0.33 in all mixtures. To ensure that water will percolate through pervious concrete, the void content, both in design of the mixture and measured as the percent air by ASTM C138/C138M (the gravimetric method), should be 15% or greater. The design porosity was in the range of 15%, 20%, and 25% in this research. The paste percentage was determined from void content and lightly compacted. The concrete mix design in this study is shown in Table 2. The mix proportions are matches the average proportions of the materials used in pervious concrete according to the literature reviewed [29].

3.3 Testing Methods

The compressive and flexural strengths of pervious concrete were determined after 28 days. The porosity and water permeability coefficients of pervious concrete were tested using rectangular specimens 210 x 100 x 60 mm, and the reported values are the average of three specimens. The pervious concrete porosity was calculated by taking the difference between the weight of specimens oven dried and saturated by submerging under water [30]. The total porosity, ϕ_T (m³/m³ in %) can be determined by two methods. Assuming no isolated pores in the sample, the ϕ_T was calculated using Eq. (1):

$$\phi_T = (1 - \frac{\rho_d}{G_s \rho_w}) \times 100 \quad (1)$$

where ρ_d is the dry density (kg/cm^3), G_s is the specific gravity, and ρ_w is the density of water (kg/cm^3).

If according to a water displacement method [34,35], the ϕ_T can be calculated using Eq. (2):

$$\phi_T = (1 - \frac{M_d - M_{sub}}{V_T \rho_w}) \times 100 \quad (2)$$

where M_d is the mass of a dry sample (kg), M_{sub} is the mass of a specimen under water (kg), and V_T is the volume of specimen (cm^3).

The effective porosity, ϕ_{eff} (m³/m³ in %), represents the open (connected) pores of the sample [36,37] and can be determined by using Eq. (3):

$$\phi_{eff} = (1 - \frac{M_{suf} - M_{sub}}{V_T \rho_w}) \times 100 \quad (3)$$

where M_{suf} is the saturated surface dried weight of a specimen (kg).

In addition, if it is assumed that the tested sample has a bimodal pore system consisting of inter-aggregate (outer aggregate) and intra-aggregate pores [34] and that the water absorbed in the water adsorption test fully fills intra-aggregate pores of aggregates and binders, the porosity of intra-aggregate pore, ϕ_{intra} (m³/m³ in %) can be calculated using measured water absorption, w_{abs} (%), and is given by Eq. (4):

$$\phi_{intra} = (1 - \frac{w_{abs} \rho_d}{100}) \times 100 \quad (4)$$

Water permeability (hydraulic conductivity; in mm/s) was calculated by the following equation in this study, and the experimental model is based on the principle of constant head method, according to Japanese standards, JIS A5371-2016 [35].

$$K = \frac{t}{\Delta h} \times \frac{Q}{A * 30} \times 10 \quad (4)$$

where t is the thickness of the sample (cm), Q is the quantity of water (cm^3), Δh is the water head deference (cm), A is the area of the sample (cm^2), 30 is the time (seconds), and 10 is the 1 cm equal to 10 mm.

4. RESULTS AND DISCUSSION

4.1 Density, Compressive and Flexural Strength

The results of density, compressive strength, and flexural strength tests of pervious concrete are shown in Table 2.

The density of pervious concrete depends on the type of aggregates and is directly related to the porosity of the sample specimen. The densities in this study were between 1394 and 1957 kg/m^3, which were lower than that of the conventional concrete (about 2400–2500 kg/m^3) due to the high voids of pervious concrete. The lowest density of a pervious concrete sample that used 100% clay brick aggregate (RB) and 25% design porosity was 1394 kg/m^3. The density of pervious concrete blocks decreased with increasing of the design porosity, and the highest density was 1957 kg/m^3 for the sample using 100% concrete aggregate (RC) and 15% design porosity. Similar findings were noticed by Ramezanianpour and Joshaghani, who reported the density of pervious concrete as 1723 to 1901 kg/m^3 depending on the mix proportions [32].

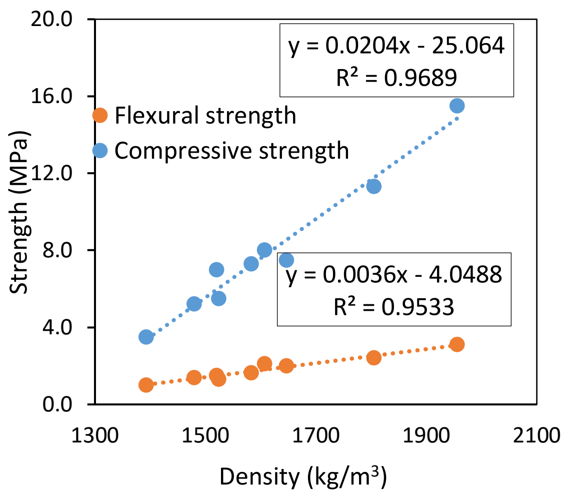

Fig. 2 Relationship between compressive strength, flexural strength, and density

For a given porosity, the compressive strength of pervious concrete using clay brick aggregate (RB) was lower than that using concrete aggregate

(RC). The compressive strength of pervious concrete using RC and RB varied from 7.5–15.5 MPa and 3.5–7 MPa, respectively, depending on the designed porosity (Fig. 2).

For example, at 20% designed porosity, the compressive strengths of concrete using 100% concrete aggregate and 100% clay brick aggregate were 11.3 MPa and 5.2 MPa, respectively. These results are also consistent with previous results [19,22,26]. The compressive strength of pervious mixes made with brick aggregate ranged from 2–10 MPa. Meanwhile, author Zhang et al [21] showed that the compressive strength of pervious concrete using RA was in the range of 5–24 MPa. Güneyisi et al. [38] used 100% RA, which had a compressive strength of 14 MPa, and flexural strength of only 1MPa.

The same trend was found at the other designed porosities. The highest compressive strength of 15.5 MPa was obtained with 15% designed porosity and using 100% RC, while the concrete sample using 100% RB and 25% designed porosity showed the lowest strength at 3.5 MPa. This result confirms that designed porosity is the most important factor affect in the compressive strength of pervious concrete [25,37,40]. Similar results were also observed in Hung's research, where the average void content for Mixes 1, 2, and 3 was measured at approximately 22.2%, 13.7%, and 11.6%, respectively, while the average compressive strengths were 11.0 MPa, 13.3 MPa, and 18.4 MPa [36].

The effect of design porosity on the compressive strength of concrete using brick aggregate was lower than when using concrete aggregate. Specifically, the design porosity increased from 15% to 25%, the compressive strength of concrete using RB decreased from 7 to 4.5 MPa, respectively, equivalent to 36%, while that of pervious concrete using RC decreased from 15.5 to 7.5 MPa, equivalent to 52%. This phenomenon occurs because the strength of concrete depends more on the aggregate strength and adhesion strength between aggregate and cement paste due to increasing porosity. With the low strength characteristics of RB, almost failures occur due to aggregate breakage.

Meanwhile, the pervious concrete using RC is stronger than that using RB, and it relies on the adhesion strength of the cement paste and recycled aggregate, which is affected by the design porosity and attached mortar in RC. The compressive strength of pervious concrete using 50% RB and 50% RC is higher than that of pervious concrete using 100% RB and lower than the case of using 100% RC. Thus, the strength of pervious concrete is directly related to the porosity and weakness of the attached mortar in recycled aggregate. Therefore, it reduces the strength of the pervious concrete.

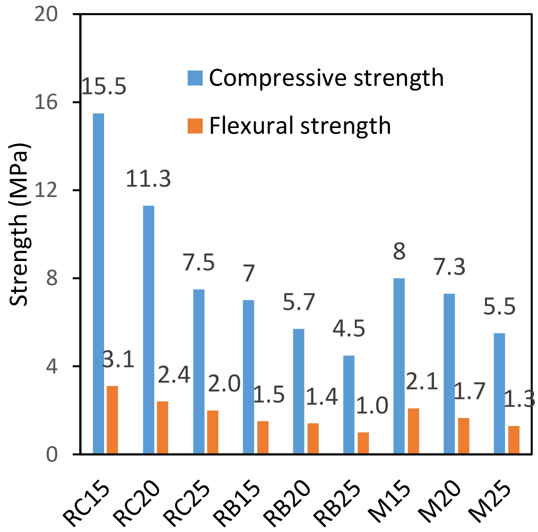

Fig. 3 Compressive and flexural strength of pervious concrete with different designed porosities

The relationship between density, compressive strength, and flexural strength of all specimens is shown in Fig. 2. An increase in density enhanced the strength development of all mixes. When we compared the effects of aggregate type and design porosity on the compressive strengths, flexural strengths within each mix design were quite similar. As shown in Fig. 3, as the porosity increases, the flexural strength of the pervious concrete decreases. For example, the flexural strengths of RC 15 and RB 15 were 3.1 MPa and 1.5 MPa, while those of RC 25 and RB 25 were 2.0 and 1.0 MPa, respectively (Table 3).

4.2 Porosity

The method for determining the porosity of pervious concrete in this research involves a volumetric procedure in which the mass of water in a sealed pervious concrete sample is converted to an equivalent volume of pores. As shown by the results in Fig. 4 three different porosities were present: total porosity, effective porosity, and the porosity of intra-aggregate pores. The relationship between designed porosity and measured porosity of all specimens is shown in Fig. 5.

Thereby, it can be concluded that the total porosity and effective porosity increase with the increase of designed porosity, while the intra-aggregate pores seem to be unaffected. Unlike smooth round aggregates, pervious concrete using RA often has a porosity value greater than the design porosity due to the shape and angles of the aggregate [21,22]. The results show that the measured effective porosity is higher than the designed porosity (15%, 20%, and 25%).

Table 3: Parameters of tested pervious concrete samples

Mixes	Density (kg/m^3)	Total porosity (1) ϕ_T (%)	Total porosity (2) ϕ_T (%)	Effective porosity ϕ_{eff} (%)	Intra-aggregate pores ϕ_{intra} (%)	Water permeability K (mm/s)	Compressive strength (MPa)	Flexural strength (MPa)
RC15	1957	18.0	17.0	15.0	2.00	4.5	15.5	3.1
RC20	1806	24.0	22.6	20.5	2.10	6.0	11.3	2.4
RC25	1648	28.0	27.2	25.3	1.90	7.6	7.5	2.0
RB15	1521	27.5	26.5	14.2	12.3	5.7	7	1.5
RB20	1481	34.0	32.1	20.0	12.1	7.5	5.7	1.4
RB25	1394	39.0	37.8	26.0	11.8	8.5	4.5	1
M15	1608	23.3	22.0	14.5	7.5	6.4	8	2.1
M20	1584	27.5	26.9	19.7	7.2	7.3	7.3	1.65
M25	1525	32.8	31.7	24.0	7.7	8.2	5.5	1.3

When using RB aggregates and mixing aggregate M, the total porosity is significantly higher than the effective porosity and the designed porosity. On the other hand, when using RC aggregates, the total porosity is slightly higher than the design porosity (from 1% to 1.2%). After 24 h of water immersion, the voids in the aggregate have been filled with water due to the water absorption properties of the RC aggregate. However, in the other research of Debnath and Sarkar [16] the pervious mix using brick aggregate showed somewhat lesser porosity value than the mix made with stone aggregate. During compaction, there is a tendency of brick aggregate to be crushed into finer particles, which fills the available void spaces. The voids are filled with water after 24 h immersion in water, contributing to the total porosity.

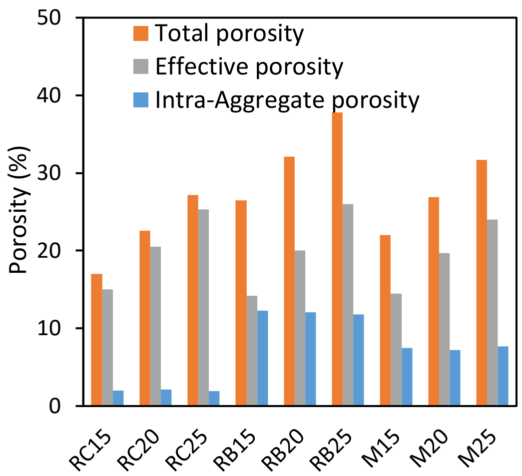

Fig. 4 Total porosity, effective porosity, and intra-aggregate porosity with different designed porosities

The intra-aggregate porosity, on the other hand, does not contribute to the water permeability properties [40]. Effective porosity excludes intra-aggregate pores and closed voids. The RB 25 mix had the highest total porosity of 39%, while the smallest total porosity was 16% for RC 15. Samples using blended aggregates (50% RC – 50% RB) had total porosities of 22%, 26.9%, and 31.7% corresponding to 15%, 20%, and 25% designed porosity. Figure 5 shows the total porosity calculated by two different equations bases on the experimental test results,. The total porosity determined by Eq. (1) was larger than that of Eq. (2).

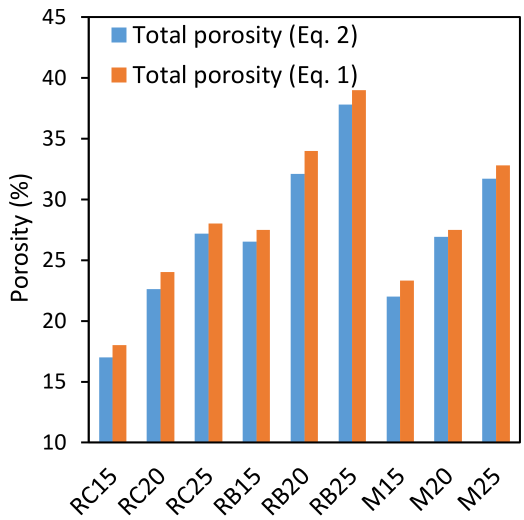

Fig. 5 Total porosity calculated by two different equations

For example, for a given design porosity of 20%, the total porosity of the pervious concrete samples using concrete aggregate, clay brick aggregate, and blended aggregate corresponding to Eq. (1) were 24%, 34%, and 27.5%, respectively, while these figures when applying Eq. (2) were 22.6%, 32.1%, and 26.9%, respectively. The difference in the two calculation formulas is because Eq. (2) calculates the total porosity only when those voids are filled with water. In fact, after 24 h immersion in the sample in water, there are still some isolated pores or small capillary tubes along with the air pressure in the pores preventing the water from filling them completely even when soaked longer than 24 h. With the increase in the porosity, the strength of pervious concrete is reduced. Figure 7 shows the correlation between compressive strength, porosity, and water permeability of pervious concrete. It displays the tendency of compressive strength to decrease when the void ratio increases.

4.3 Water Permeability

The pervious concrete block that were expected to have the highest permeability rates were those constructed from single-sized aggregates. The permeability of the pervious concrete mixtures is shown in Table 3 and illustrated in Figs. 6 and 7.

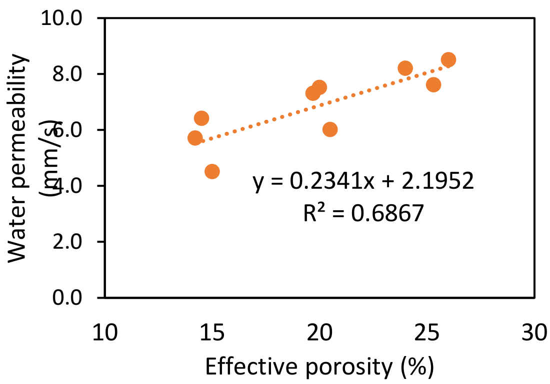

Fig. 6 Relationship between water permeability and effective porosity

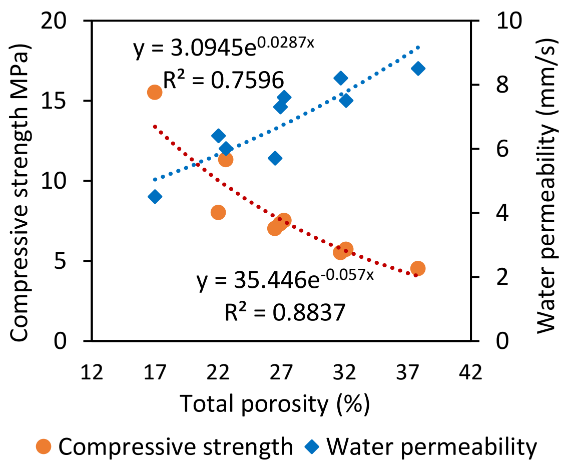

Fig. 7 Relationships of water permeability, compressvie strength, and total porosity

As with the effective porosity, the trends were opposite those of the concrete strength. The results confirm that the water permeability of pervious concrete rises with an increase in the void ratio. On other hand, with the increase of total porosity and effective porosity, the compressive, flexural strength decreases. The RC 15 mixture has significantly lower hydraulic conductivity than RC 25 at 4.5 mm/s and 7.6 mm/s, respectively. The high values of water permeability coefficients of 5.7–8.5 mm/s were achieved with pervious concretes using RB aggregate. The water permeability of RC aggregate was lower than that of RB aggregate with 4.5–7.6 mm/s. Similar results were also observed in Aliabdo et al [41]: the increase of recycled aggregate content increases water permeability, ranging from 5.2–6.2 mm/s.

In general, using RB aggregate for pervious concrete can increase the drainage capacity, although the porosity is equivalent to the other aggregates such as RC aggregate or mixed aggregate. This point was confirmed by Gaedicke et al. [25] and Hung et al. [36]: despite having the same porosity, there was a difference in the permeability coefficient. The explanation for such consequences is the fact that the angular shaped aggregates possess larger shortest paths, which has resulted in a higher water permeability coefficient.

The level of porosity and permeability at all designed porosities illustrates a slight decrease with the decrease in the percentage of clay brick content. Due to the light compaction, there was no tendency for brick aggregate to be crushed into finer particles, which would fill the available void spaces as well as providing better enveloping of aggregates [16]. For example, for a given designed porosity, the water permeability of pervious concrete was 7.5, 7.3, and 6.0, corresponding to when 100%, 50%, and 0% clay brick were used.

From the experimental test results, it is understood the relationships among porosity, strength, and permeability of pervious concrete are understood. It ca be used to estimate the void content needed for mixtures that satisfy the specification requirement for permeability and strength of concrete. By determining the void ratio, it is possible to obtain proper permeability and compressive strength.

5. CONCLUSIONS

Based on the experimental investigation of pervious recycled aggregate concrete, the effects of coarse aggregate types and designed porosity on pervious concrete properties were analysed. From the test results, the following conclusions could be drawn:

1) This study deals with the analysis of porosity and the permeability of pervious concrete using the

recycled aggregate from crushed concrete waste (RC) and crushed clay bricks waste (RB). It is clear from the test results that the porosity of pervious concrete with brick aggregate shows different phenomena from that of the recycled concrete aggregate and conventional aggregate.

2) The density of pervious concrete mixtures changed from 1394 kg/m^3 to 1957 kg/m^3 as total porosity decreased from 37.8% to 17% when the clay brick content in blended aggregate range from 100% to 0%. The density decreased with an increase in total porosity and decreasing strength of the pervious concrete. However, the obtained compressive strengths of 3.5 – 15.5 MPa were within the typical strength distributions reported [19,23,42]. Linearity can be used to describe the relationship among density, compressive strength and flexural strength, and the coefficient of determination reaches 0.97 and 0.95, respectively.

3) Porosity is the most important factor determining pervious concrete properties (permeability, compressive strength, flexural strength). Higher porosity improves permeability but decreases the mechanical properties of the samples. The total porosity not only affects the permeability of the mix, but also represents the characteristics of coarse aggregate. The clay brick aggregate and the attached mortar in recycled aggregate contributes significantly to total porosity thanks to an intra-aggregate porosity.

4) The water permeability, on the other hand, was affected by the intra-aggregate porosity. Effective porosity and shortest paths (connected pores) are crucial factor to permeability. The use of recycled aggregate had a slight effect on permeability depending on the compacting method and aggregate angularity. In this study, water permeability coefficients of 5.7–8.5 and 4.5–7.6 mm/s were achieved with pervious concretes using RB and RC aggregate, respectively.

6. ACKNOWLEDGEMENTS

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