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Laboratory Evaluation of Load-Bearing Behavior and Drainage Ability of Pervious Concrete Pavement

LAM Tri-Khang[1,a], NGUYEN Dinh-Thang[2,b], NGO Van-Anh[3,c], NINH Hoai Phuong Duy[4,d] and HUYNH Trong-Phuoc[1,e,*]

[1]Faculty of Civil Engineering, College of Engineering, Can Tho University, Campus II, 3/2 Street, Ninh Kieu District, Can Tho City 94000, Vietnam

[2]Faculty of Automotive Engineering Technology, Vinh Long University of Technology Education, No. 73, Nguyen Hue Street, Vinh Long City 85000, Vinh Long Province, Vietnam

[3]Faculty of Transportation Engineering, College of Engineering, Can Tho University, Campus II, 3/2 Street, Ninh Kieu District, Can Tho City 94000, Vietnam

[4]ODA Project Management Unit, Can Tho University, Campus II, 3/2 Street, Ninh Kieu District, Can Tho City 94000, Vietnam

[a]ltkhang.ts@gmail.com, [b]thangnd@vlute.edu.vn, [c]vananh@ctu.edu.vn, [d]nhpduy@ctu.edu.vn, [e]htphuoc@ctu.edu.vn (*Corresponding author)

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Abstract. This study presents an experimental investigation of the load-bearing behavior and drainage ability of pervious concrete (PC) produced using local materials in Vietnam with differently designed porosities of 15% (R15), 20% (R20), and 25% (R25). The PC samples were cast at the laboratory and cured in open air before being tested for drainage ability, flexural and compressive strengths, and dry density. The relationship between load and displacement of the PC was also analyzed in this study. Results showed that the designed porosity significantly affected the mechanical strength, density, and infiltration rate of the PC. In detail, the compressive strength of PC ranged from 1 to 5 MPa while the flexural strength values were 0.86, 0.99, and 1.71 MPa for samples designed at the respective porosities of 25%, 20%, and 15%. In addition, the dry density of PC specimens (1560-1688 kg/m^3) decreased with an increase in the designed porosity. The infiltration rate values were measured at 19.4, 38.3, and 1215 cm/min corresponding to the R15, R20, and R25 specimens. Besides, the load-displacement curves under flexure and compression revealed a significant impact of void contents on the strength-bearing capacity of PC as the R15 specimen exhibited the highest slope, indicating the higher brittle behavior and lower deformation. Overall, the experimental results further demonstrated the high applicability of the PC for various construction applications in real practice.

Introduction

Urbanization and modernization are growing faster in the modern days. Cities nowadays have grown considerably and have a greater potential to continue expanding. As a result, there are now many structures and concrete roads, which creates many problems related to drainage. So far, conventional pavement has inhibited water permeability. This leads to rising temperatures, reduced traffic safety, escalation of the urban heat island effect, and an increased risk of sudden floods [1,2]. This creates many problems for infrastructure and citizens. It is important to note that uncontrolled runoff water can transform into sewage, putting groundwater resources at risk of contamination. Therefore, in response to these challenges, pervious concrete (PC) has become an essential component of modern civil engineering, providing innovative solutions for urban infrastructure and environmental sustainability.

Pervious concrete, also known as porous concrete, permeable concrete, gap-graded concrete, no-fine concrete, and enhance-porosity concrete [3]. It is a special concrete that refers to an almost zero-slump, with a high interconnected pore structure and large pore sizes (2-8 mm typically). In the PC mixture, fine aggregate is non-existent or present in very small amounts [4]. Thus, the porosity in

PC is significantly higher than that of normal concrete, which is typically designed within a range of 15% to 35% [3–6]. The void and pore structure are important properties that influence the performance of PC. Because of its high porosity and permeability, PC can control stormwater runoff, restoring groundwater supplies as well as the urban enthalpy and heat island effects [6]. Besides, PC is also commonly used for building materials because of its high permeability and acceptable strength. In the past, the PC was first used in 1852 in Europe due to a lack of sand and other fine aggregates [3]. Over time, PC has demonstrated its great application potential. Currently, this type of concrete is widely used in road surface pavement, parking areas, sidewalks, pathways, residential roads, driveways, drainage materials, structural walls, floors for greenhouses and zoos, and swimming pool decks [4,5,7].

With high applicability, several studies have utilized various mineral additives to manufacture PC such as fly ash, metakaolin, and slag [1,8,9]. Additionally, the influences of different particle sizes, artificial aggregates, aggregate-to-binder ratio, and water-to-binder ratio have been investigated using different methods and different sample sizes [10–13]. Some key findings drawn from previous studies indicated that the water-to-binder ratio commonly fell within the range of 0.26 to 0.4 [1,4,14], aggregate sizes ranged from 2.36 to 30 mm [1,4], aggregate contents ranged from 15% to 33% [1,15], and the paste volumes ranged from 20% to 25% [15]. Besides, PCs with mineral additives exhibited higher performance in engineering properties, cost savings, and energy efficiency [8,9]. In terms of strength and durability of PC, the crucial factors impacting its technical characteristics significantly include the porosity, pore sizes, cementitious contents, paste volume, water-to-binder ratios, compaction level, and aggregates gradation and quality [4,6,7,16]. Particularly, the variation of permeability of PC may be in the ranges of 81-730 L/min/m^2, and the typical compressive strength is between 2.8 to 28 MPa, depending on compaction, void content, materials, and sub-base infiltration rates [4,14]. The compressive strength and flexural strength had a similar trend [12].

As presented, most of the previous research concentrated on the mechanical strength while not much research has been carried out to evaluate the load-displacement behavior of PC. Besides, the challenge in PC mixture proportioning is achieving a balance between an acceptable percolation rate and an acceptable compressive strength [4]. Thus, both the load-displacement behavior and drainage ability of PC produced using locally sourced materials in Southern Vietnam were evaluated. The potential applications of such concrete in real practice were also considered in the present study.

Experimental Details

Materials and mixture proportions. Grade-40 Portland cement in compliance with TCVN 2862:2020 standard [17] was used as binder material and No. 8 natural crushed sand (ranges size of 2.36-9.5 mm, density of 2612 kg/m^3, and water absorption of 2.32%) as per ASTM C33 was used as fine aggregate for the preparation of PC samples. Using a lower aggregate diameter resulted in a greater strength and durability value for a given paste volume due to the higher packing density [4,5]. Therefore, the No. 8 classified aggregate was commonly used in the manufacturing of PC samples [4].

Table 1. Mixture proportions of 1 m^3 of pervious concrete

Mix designature	Designed porosity (%)	Cement (kg)	Aggregate (kg)	Water (kg)
R15	15	497.1	1824.9	185.3
R20	20	429.4	1935.1	167.2
R25	25	369.2	2033.3	151.0

The design of PC used in this experiment was primarily based on ACI 522R-10 [4] with the designed porosities of 15%, 20%, and 25% and the water-to-cement ratio in the ranges of 0.37-0.41 to ensure a good aggregate coating and paste stability. Note that the porosity in the PC should be from 15% to 35% [4] because, in this range, the water could percolate through the PC. At a porosity level of below 15%, there was insufficient interconnectivity between the porosities to allow for quick percolation, leading to insignificant percolation [3,4]. In addition, porosities of 15% to 35% are necessary to ensure the strength capacity of the PC as a porosity of higher than 35% could cause a decrease in mechanical strength in the PC. By following the designed procedures of ACI 522R-10 [4], the material proportions of PC with different porosities are calculated as shown in Table 1.

Sample preparation and test methods. To prepare the PC samples, cement and aggregate were first prepared. All of the materials were then dry-mixed in a laboratory mixer for 2 mins. After that, water was gradually added and mixed until a homogeneous mixture. The fresh mixture was poured into a steel mold with dimensions of 400×400×100 mm (Fig. 1, left). The samples were compressed under 1.5 MPa and then covered with a thin plastic to maintain the moisture [1]. After 24 hours, the samples were de-molded and cured in the open air until testing days (Fig. 1, right).

Fig. 1 Casting of pervious concrete samples

After 28 days of curing, the casted samples were cut for testing of dry density, flexural and compressive strengths, and infiltration rate. The density of PC was determined on 100×100×100 mm specimens following ASTM C642. The flexural strength (Fig. 2a) and compressive strength (Fig. 2b) of PC were tested using the 100×100×400 mm and the 70×70×70 mm specimens following ASTM C78 and ASTM C39, respectively. Besides, the infiltration rate (Fig. 2c) was measured according to the ASTM C1701. The load-displacement curves of the PC under flexure and compression were also recorded to clarify the relationship between the load and deformation behavior of the PC under loading. Finally, the potential applications of PC were suggested based on the experimental results.

(a) (b) (c)

Fig. 2 Setup for testing of (a) flexural strength, (b) compressive strength, and (c) infiltration rate

Results and Discussion

Dry density. Table 2 illustrates the variation in dry density values of PC specimens. Particularly, the density of all PC specimens was below 2000 kg/m^3, which is much lower than that of conventional concrete because of the significantly higher porosity in the PC system [14]. Results also found that there was an around 8% difference between the minimum and the maximum dry density values of the PC, which is primarily due to the change in the designed porosity. Previous studies proved an inverse correlation between porosity and density of concrete [5,12,13]. Thus, the R15 specimen with the lowest designed porosity (15%) exhibited a denser structure and the highest dry density (1560 kg/m^3).

Table 2. Dry density measurements of pervious concretes

Mix designation	Dry density (kg/m^3)		Infiltration rate (cm/min.)
	Value	Standard deviation	
R15	1688	36.429	19.4
R20	1620	32.182	38.3
R25	1560	22.948	1215

Infiltration rate. The infiltration rate (permeability) is a critical engineering characteristic of PC, indicating the rate at which water can pass through the material. The speed of infiltration in PC with different porosity is shown in Table 2. As a result, the infiltration rate of PC specimens ranged from 19.4 to 1215 cm/min. The lowest infiltration rate of 19.4 cm/min was observed at the designed porosity of 15%. However, the infiltration rate increased to 97% in the R20 specimen. The highest infiltration rate of 1215 cm/min was recorded in the R25 specimen. These results proved that porosity was the most important feature of PC, significantly affecting its permeability. Furthermore, the relationships among infiltration rate, dry density, porosity, and strength of PCs were observed in previous studies as higher density was associated with lower porosity, lower permeability, and higher strength [5,13,14].

Flexural strength. PC's flexural strength is defined as its capacity to bear bending or flexing forces without cracking our serious deformation. PC is typically used for applications such as sidewalks, parking lots, and low-traffic pavements, where it is subjected to loads that can cause bending stresses. Test results showed that the flexural strength values of PC were in the ranges of 0.86-1.71 MPa (Table 3). In which, the R15 specimen exhibited the highest flexural strength of 1.71 MPa. This value was decreased by approximately 42% and 50% when the designed porosity increased to 20% and 25%, respectively. Hence, the porosity played an important role in controlling the flexural strength of the PC as the higher the porosity, the lower the flexural strength [16]. This trend was also observed in previous studies [15,16]. As presented in previous sections, the R15 specimen had lower porosity, resulting in higher flexural strength. Furthermore, the results also demonstrated a correlation between compressive strength and flexural strength as higher compressive strength was associated with higher flexural strength. This trend was in good agreement with a previous study [12].

Table 3. Flexural and compressive strengths of pervious concretes

Mix designation	Flexural strength (MPa)		Compressive strength (MPa)	
	Value	Standard deviation	Value	Standard deviation
R15	1.71	0.048	5.08	0.391
R20	0.99	0.045	2.76	0.048
R25	0.86	0.089	1.09	0.264

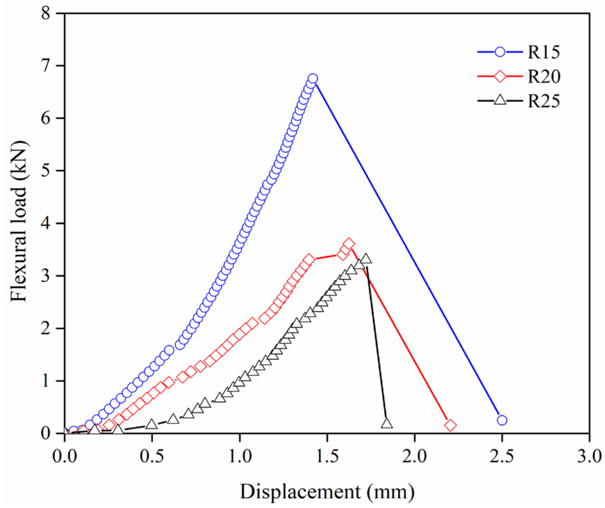

Fig. 3. Flexural load-displacement curves

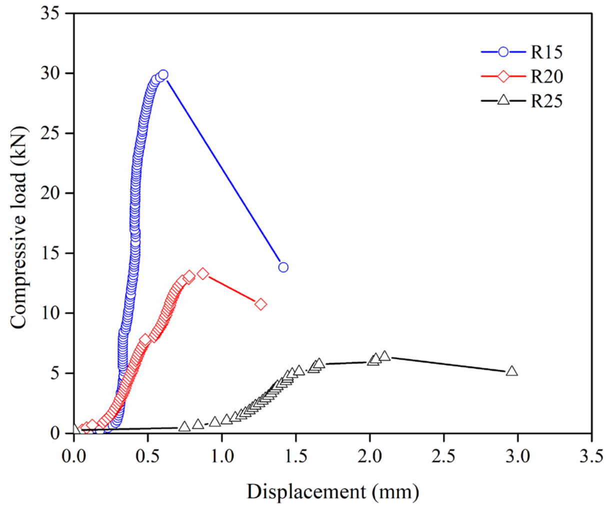

Fig. 4. Compressive load-displacement curves

Besides, Fig. 3 depicts flexural load-displacement relationships for the PC proportioned for 15%, 20%, and 25% porosities. As a result, the R15 specimen exhibited the highest displacement at the point of failure, demonstrating that R15 was stiffer and more brittle than others. The more porosity in R20 and R25 specimens caused a reduction of flexural strength and strain-carrying capacity [15].

Compressive strength. The compressive strength of a PC refers to its ability to withstand axial loads or forces applied along its axis without failing or breaking. PC is designed to allow water to pass through, but it still needs to have enough compressive strength to support the intended loads in applications such as sidewalks, parking lots, and low-traffic pavements. The 28-day compressive strength of PCs is presented in Table 3. As a result, the compressive strength value reached 5.08 MPa for the PC specimen with designed porosity of 15%. Increasing the designed porosity to 20% and 25% reduced the compressive strength values by about 45% and 78%, respectively. This trend was in line with previous studies [6,16,18].

Fig. 4 shows the compressive load-displacement curves recorded from the compressive strength test of PC specimens. This figure provided a comprehensive reflection of the compressive behavior of the PC as the greater porosity caused a faster decrease in the compressive strength. The consistent decline in peak compressive strength was found with rising porosity, aligning with expectations for porous materials. Notably, different pore structure aspects (i.e., pore sizes, spacing, and connectivity) in the PC may significantly influence the compressive response. Besides, the slopes of the ascending portions of the curves were different [7,19]. The R15 specimen exhibited the highest slope, followed by the R20 and R25 specimens. This might be attributed to the compactness of the specimens. As aforementioned, the R15 had a higher density, making it more compact with lower deformation than the others. The compressive load-displacement curves also revealed the brittleness of the specimens. A previous study proved that the PC samples with lower porosity exhibited higher brittle behavior, which was indicated by a sudden fall in post-peak load [7].

Potential applications of pervious concrete. PC is increasingly used due to rapid urbanization and has been used widely across various climatic, structural, and environmental conditions. Specifically, PC should be applied in certain cases such as pervious pavement [20], bridges [21], parking lots (with a thickness of 125-300 mm), pathways, low-volume roads (with a thickness of 150-300 mm) [22], permeable bases and edge drains (with a strength of ≤7 MPa), shoulders (with compressive strength ≤14 MPa), drains, greenhouses, tennis courts, noise barriers, and building walls [4]. Moreover, the sound restriction of PC is proved when it was applied in transportation [23,24]. Besides, PC can be applied to residential streets for typical design [25] and other constructions, especially in the USA, Japan, Europe, and China [26]. However, PC cannot be used for reinforcement, high-speed roads, and heavy-load traffic roads due to its mechanical properties and the open pore in the structure. This study aims to understand the mechanical characteristics and behavior of PC under loading. The results showed that PC can be used in many constructions, proving the potential of using PC. With relatively low strength, the PC produced in this study may be suitable for applications in drainage layer and pathway construction.

Conclusions

This study experimentally investigated the load-bearing behavior and drainage ability of PC produced using local materials in Vietnam with differently designed porosities (i.e., 15, 20, and 25%). Based on the experimental results and the associated discussions, the following conclusions can be drawn:

1. PC specimens registered dry density values in the ranges of 1560-1688 kg/m^3, which were significantly lower than conventional concrete. This study also found that higher dry density values were strongly associated with lower porosity in the PC specimens.

2. The infiltration rate of PC specimens ranged from 19.4 cm/min to 1215 cm/min. The infiltration rate increased up to 97% when increasing the designed porosity from 15% to 20%. Further increasing the designed porosity to 25% resulted in a remarkable infiltration rate of 1215 cm/min.

3. The 28-day flexural and compressive strengths of PC were distributed from 0.86 MPa to 1.71 MPa and 1.09 MPa to 5.08 MPa, respectively. Generally, the lower the designed porosity of the PC, the higher the mechanical strength. The load-displacement curves of the R15 specimen were steeper and dropped suddenly after reaching the peak point, indicating that R15 was more brittle than that of the R20 and R25 specimens.

4. Literature reviews showed that PC can be applied for many construction purposes, proving the high potential of using PC. The results of this study suggested that the produced PC was suitable for applications in drainage layer and pathway construction.

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