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Experimental Study on Compressive and Flexural Strengths of High-Strength Pervious Concrete Using Various Binding Materials

Ridengaoqier E[1], Shigemitsu Hatanaka[2], Kei-ichi Imamoto[1], Chizuru Kiyohara[1], Tanakorn Phoo-ngernkham[3]
[1]Tokyo University of Science
6-3-1 Niijuku, Katsushika-ku, Tokyo, Japan
ochiru@rs.tus.ac.jp; imamoto@rs.tus.ac.jp; ckiyo@rs.tus.ac.jp
[2]Mie University
1577 Kurimamachiya-cho, Tsu City, Mie, Japan
hatanaka@arch.mie-u.ac.jp
[3]Rajamangala University of Technology Isan
Nakhon Ratchasima 30000, Thailand
Tanakorn.ph@rmuti.com

Abstract **-** This paper examined the properties of high-strength pervious concrete to investigate the applicability to highways. The properties included porosity, compressive strength, and flexural strength. The high-strength pervious concrete were produced using ordinary Portland cement, silica fume premixed cement, and geopolymer as binding materials. Consequently, the experiment confirmed that the relationship between the compressive strength and flexural strength of pervious concrete using high-strength binding materials (compressive strength of 150 N/mm² or higher) such as silica fume premixed cement (water–cement ratio = 0.15) and geopolymer (solution-powder ratio = 0.5). In addition, it confirmed that their porosity can be approximated by an exponential function, similar to that of pervious concrete using ordinary Portland cement as a binding material. Furthermore, it was observed that pervious concrete using silica fume premixed cement (water–cement ratio = 0.15) as a binder could achieve a compressive strength of 22.5 N/mm² and a flexural strength of 4.5N/mm² up to 20% porosity, emphasizing water permeability. In addition, it was established that pervious concrete using geopolymer as a binder could achieve a compressive strength of 22.5 N/mm² in the high-porosity range of 20–25% and partially meet the flexural strength requirement of 4.5 N/mm², also in the region emphasizing water permeability. These results demonstrate the potential of high-strength pervious concrete for use in highways.

Keywords**:** Pervious concrete, Porous concrete, Geopolymer, Silica fume premixed cement, Compressive strength, Flexural strength

1. Introduction

Pervious concrete (POC), also known as porous concrete, is a type of concrete with a high percentage of interconnected voids within its structure [1]. Given its uniquely porous nature, POC possesses numerous beneficial properties: permeability, sound absorption, water quality purification, gas adsorption, and humidity control [2]–[5]. These properties have resulted in its widespread utilization in practical applications including pedestrian walkways, light traffic roads such as parking lots and sidewalks, and environmentally friendly green embankments. However, in road applications that demand high strength, such as driveways, POC is often utilized by decreasing its porosity. Unfortunately, this approach may result in the loss of the benefits provided by POC, such as permeability and sound absorption, over extended periods of use. Consequently, the application of POC to roads or highways requiring even greater strength is currently restricted.

In addition, POC is prone to failure as a result of interfacial failure between the aggregate and binding material, in addition to failure of the binding material and the aggregate, as depicted in Figure 1 [6]. Thus, the strength of the binding material can determine the strength of POC. The strength of POC increases with an increase in the strength of the binding material. In addition, it is possible to enhance the strength of POC by decreasing the water-cement ratio (W/C) or the solution-powder ratio (W/P) of the binding material.

Hence, this experiment aimed to produce high-strength POC by utilizing ordinary Portland cement (OPC), silica fume premix cement (SFPC), and geopolymers (GP) as binding materials. The mechanical properties of the resulting POC were measured to evaluate its suitability for highway applications. SFPC enables workability even in regions with extremely low water–cement ratios, while GP has the potential to reduce CO2 emissions, making it an alternative material to cement. Both of the binding materials are capable of producing paste with compressive strength exceeding 100 N/mm². To utilize POC in a roadway, a flexural strength (Fb) of 4.5 N/mm² is necessary. Subsequently, this requires a compressive strength (Fa) of 22.5 N/mm², according to the relationship between Fa and Fb (Fa/Fb ≒ 5). Therefore, the porosity and strength properties of POC were examined within this compressive and flexural strength range to evaluate its suitability for highway applications.

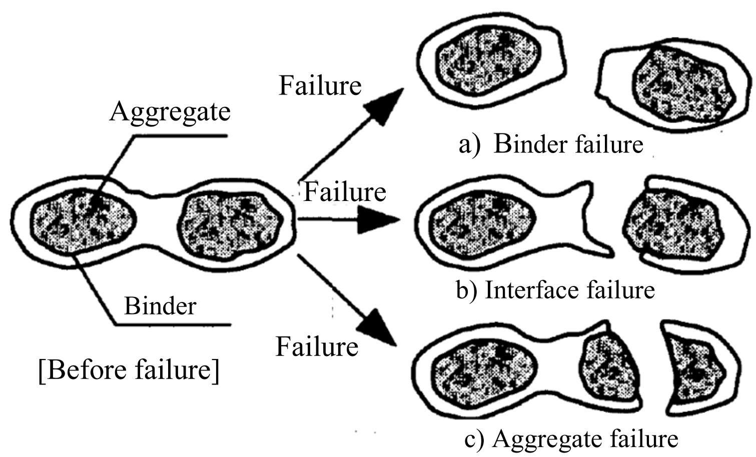


Fig.1 Failure pattern of POC [6]

2. Outline of Experiment

2.1. Experimental Factors and Testing Level

The experimental factors and levels are presented in Table 1, and Table 2 lists the materials used in the experiment, including OPC, SFPC, and GP as binding materials. The W/C ratio for OPC was set at 0.25, and designed porosities of 0%, 15%, 20%, 25%, and 30% were utilized. For SFPC, two different W/C ratios of 0.25 and 0.15 were employed, with designed porosities of 0%, 15%, 20%, 25%, and 30%. For GP, the W/P ratio was set at 0.5, and designed porosities of 15%, 25%, and 30% were used. The solution-powder ratio for GP was determined based on the study by Maekawa et al. [7], and water glass and ground granulated blast-furnace slag of 4000 mesh size were used as the solution and powder, respectively. Various binding materials were used to produce paste for testing purpose.

Table 1 T Experimental factors and testing levels

Factor	Level
Binding materials	Ordinary portland cement(OPC) Silica fume premixed cement (SFPC) Geopolymer (GP)
Porosity(%)	0, 15, 20, 25, 30 (OPC and SFPC with W/C=0.25) 0, 15, 25 (GP and SFPC with W/C=15%)

Table 2 Materials used for PC

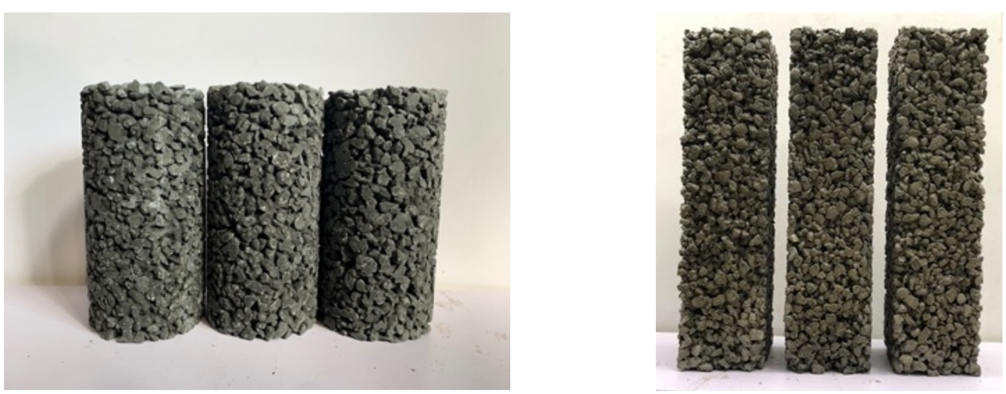
Cement	Ordinary portland cement (OPC), density: 3.16g/cm^3, baline value: 3350 cm2/g Silica fume premixed cement (SFPC), density: 3.04 g/cm^3, baline value: 6690 cm^2/g
Water	Ordinary tap water
Powder	Ground granulated blast-furnace slag 4000 (BS), density: 2.91g/cm^3
Solution	Water glass (WG), JIS 1408 No.2, density: 1.45g/cm^3
Aggregate	Crushed stone No.6 aggregate particle size 5-13 mm, density: 2.73 g/cm3, water absorbption:0.93%, solid content: 58.1%
Admixture	High-performance AE water-reducing agent (HAE, polycarboxylic acid)

2.2. Creating Test Specimens and Curing Method

The example views of POC specimens are shown in Figure 2. Cylindrical and prismatic specimens were produced with the same mixing ratio and used for compression strength and flexural strength tests, respectively. Cylindrical POC specimens were made using a cylindrical mold with a diameter of 100 mm and a height of 200 mm, while prismatic POC specimens were made using a prismatic mold with dimensions of 100 x 100 x 400 mm^3. The paste specimens were made using a cylindrical mold with a diameter of 50 mm and a height of 100 mm, and a prismatic mold with dimensions of 40 x 40 x 160 mm^3. Each type of POC and paste was replicated three times.

The POC mixing was performed using a 30 L oscillating mixer. The method included pre-mixing of the cement paste, in which cement, water, and admixtures were added to the mixer and mixed at low speed for 60 seconds. Subsequently, the mixture was scraped off the mixer wall, and the mixing process was repeated at high speed for 120 seconds. The resulting cement paste was tested for flow value and subsequently returned to the mixer, where it was mixed with the aggregate at high speed for 120 seconds. Fresh POC was compacted into the mold using a vibrating rod. The OPC and SFPC specimens were demolded a day after compaction and cured in standard water (20°C) until 26 days of age. The GP specimens were cured by sealing the molds until 27 days of age.

Moreover, the POC specimens were capped at 27 days of age. The cylindrical specimens were capped with sulfur, while the prismatic specimens were capped with water-stop cement.



a) Cylindrical specimen(Φ100mm × 200mm) b) Prismatic specimen (100 × 100 × 400 mm^3)

Fig.2 Example views of POC specimens (V_P=25%)

2.3. Testing Method

2.3.1. Porosity test

The porosity test for POC specimens was conducted using the mass method , in accordance with the test method for POC porosity proposed by the Japan Concrete Institute [8]. In this study, the term “total porosity” in this study refers to the porosity directly measured through experimental testing, while “designed porosity” refers to the porosity calculated from the mix proportions provided in Table 1.

2.3.2. Compressive strength test

The compressive test for POC cylindrical specimens was performed following the Japanese Industrial Standards (JIS A 1108) and the indoor test method for POC prescribed by the Japan Concrete Institute. A universal testing machine was used as the testing equipment, and a compress meter (as shown in Figure 3) was utilized to measure the POC’s strain displacement simultaneously during the test. Figure 4 illustrates the view of the compressive strength test of the POC cylinder specimen.

Fig.3 View of Compress meter

Fig.4 View of compressive strength test

2.3.3. Flexural strength test

The flexural strength test for POC rectangular specimens was undertake in accordance with the Japanese Industrial Standards (JIS A 1106) and the indoor test method for POC by the Japan Concrete Institute. The strength of the rectangular specimen ($100 \times 100 \times 400$ mm^3) was measured using the three-point loading method, while the strength of the paste prismatic specimen ($40 \times 40 \times 100$ mm^3) was measured using the center-point loading method. Figure 5 illustrates the flexural strength test of the POC prismatic specimen.

Fig.5 View of the flexural strength test

3. Experimental Results and Discussion

3.1. Porosity

Figure 6 illustrates a comparison between the total porosity and the designed porosity of the POC specimens. The red red dashed line in the figure represents a line where the difference between the total porosity and the design porosity is within ±5%. As depicted in the figure, the total porosity of all POC specimens fell within ±5% of the designed porosity, indicating that nearly all specimens were produced as designed.

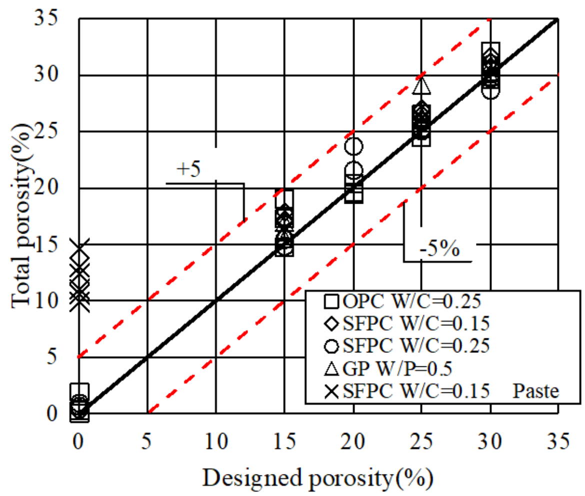


Fig.6 Comparison between the total porosity and designed porosity of POC

In addition, the paste specimens using various binding materials showed almost 0% air content. Therefore, their results were excluded in the same figure. However, the paste specimen with SFPC(W/C = 0.15) showed air content of 9–14%, which was confirmed and plotted at the position of 0% designed porosity in the figure. The high viscosity of the paste is considered to be the reason for exceeding the design amount of air content in the paste. This prevented bubbles from escaping completely during compaction. Moreover, a large amount of high-performance AE water-reducing agent was mixed into the extremely low water–cement ratio range during paste and POC production to easily reach the mixing range. As the amount of high-performance AE water-reducing agent increases, the air content increases linearly. Therefore, in this experiment, using a large amount of high-performance AE water–reducing agent for paste is believed to have caused an increase in air content. However, unlike the paste, POC has coarse internal pores. Since the paste is filled and has high viscosity, the bubbles remained inside. However, in the case of POC, it is believed that the bubbles in the paste disappeared because the bubbles in the cement paste were released into the coarse internal pores.

3.2. Compressive strength

Figure 7 depicts the relationship between the compressive strength and total porosity. The compressive strength results of POC were plotted in the figure. Furthermore, the results of the paste were extrapolated to the point where porosity equals zero. For SFPC (W/C = 0.15), as shown in Figure 6, the paste contained a significant amount of air, resulting in a very small paste strength. Therefore, only the data for POC were used for the approximation. In addition, the approximation formula for compressive strength and porosity is provided for each type of binder, indicating that they can be well approximated by exponential functions with high correlation coefficients.

When a compressive strength of 22.5 N/mm² is used as a reference, POC with each binder reveals that OPC and SFPC (W/C = 0.25) have a porosity of approximately 20%, while SFPC (W/C = 0.15) and GP have a void ratio of approximately

25%. These results suggest the possibility of ensuring strength comparable to OPC and SFPC with W/C = 0.25 even with a high-porosity (20–25%).

Moreover, according to a previous study [8], the compressive strength of POC using GP paste (W/P = 0.6) with blast furnace slag powder was approximately the same as that of POC using OPC with W/C = 0.25 in this experiment.

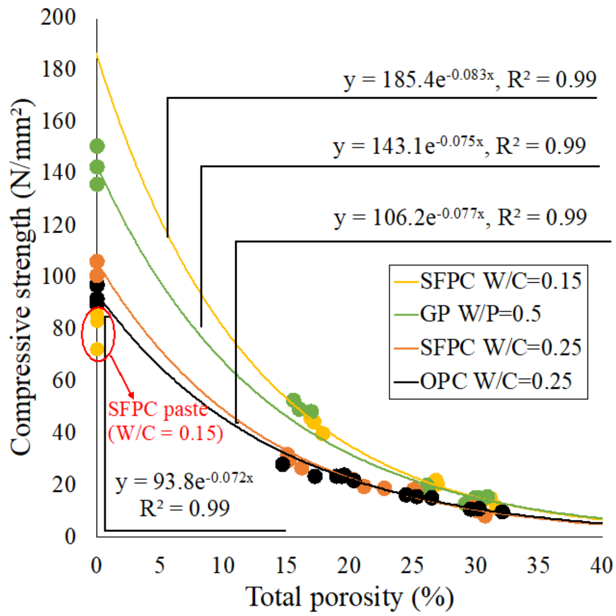


Fig.7 Relationship between compressive strength and total porosity

Figure 8 highlights an example of a compressive stress-strain curve of the specimen with a designed porosity of 15%. As shown in the figure, POC using SFPC (W/C = 0.15) and GP can bear higher stress compared to OPC and SFPC (W/C = 0.25). However, regarding GP, the slope of the curve was approximately the same as that of OPC and SFPC (W/C = 0.25).

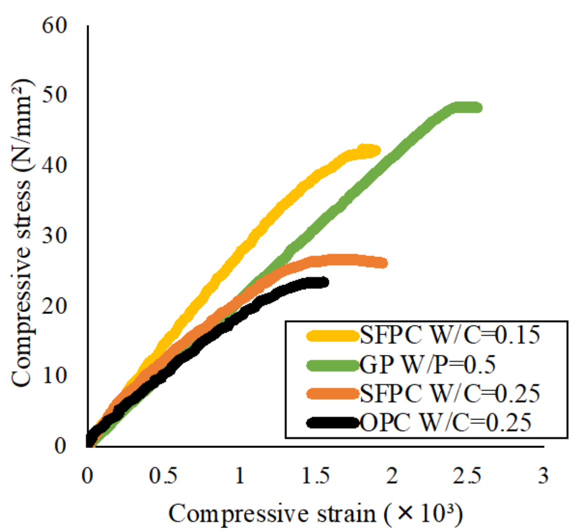


Fig.8 Example of compressive stress-strain curve (V_P＝15%)

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3.3. Flexural Strength

Figure 9 shows the relationship between the flexural strength and total porosity. The flexural strength results of POC POC were plotted in the figure. Furthermore, the results of the paste were extrapolated to the point where porosity equals zero. In the case of SFPC (W/C = 0.15) and GP, only data from POC were used to approximate. The approximate equations equations for flexural strength and porosity are also shown for each type of binder material. Similar to the results for compressive strength, they can be approximated by an exponential function with a high correlation coefficient.

The relationship between compressive strength and flexural strength is generally reported to be approximately 1/5–1/7. In this experiment, by calculating the ratio of the approximate curve equations for flexural and compressive strength in the region (V_P = 15–25%) where permeability was emphasized, the ratio was approximately 1/6. This indicates that the relationship between compressive strength and flexural strength is generally good. In the case of SFPC (W/C = 0.15), according to the approximate curve equation, the range of application is up to a total porosity of 20% (with a flexural strength of 4.5 N/mm² or higher). This indicates that it is sufficiently applicable to road paving with a porosity of 15–20%. For GP, the approximate curve equation indicates that it is partially applicable with a porosity of approximately 16%.

Furthermore, considering the flexural strength of POC using OPC as a reference, POC using SFPC with W/C = 0.25 was almost 1 times, the flexural strength, while POC using SFPC with W/C = 0.15 was 1.5 and POC using GP was 1.3.

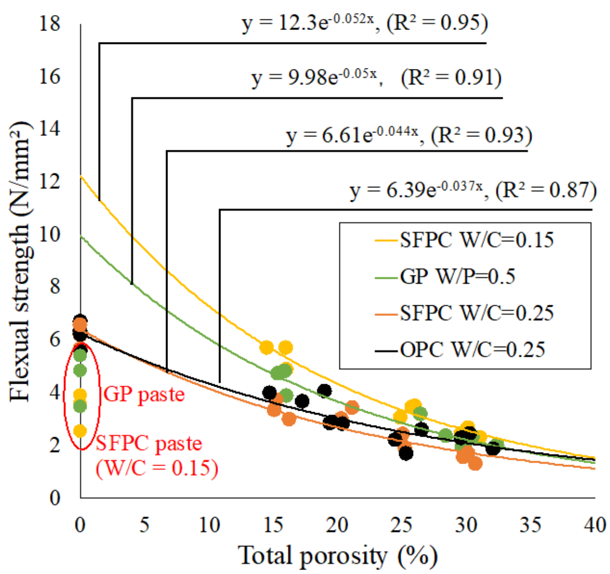

Fig.9 Relationship between flexural strength and total porosity

4. Conclusion

This study investigated the porosity and strength properties of high-strength POC using various binding materials: OPC, SFPC, and GP. The focus of the study was to evaluate the potential of POC for application in high-speed highways with higher porosity (20–25%). The following findings were obtained from the experiments:

1) The relationship between compressive strength and flexural strength of POC using high-strength binding materials (with compressive strength of 150N/mm or higher) such as SFPC (W/C = 0.15) and GP (W/P = 0.5) and their porosity can be approximated by an exponential function, similar to that of POC using conventional OPC.

2) POC using SFPC (W/C = 0.15) could achieve a compressive strength of 22.5N/mm^2 and a flexural strength of 4.5N/ mm^2 up to 20% porosity, with a focus on water permeability.

3) POC using GP could achieve a compressive strength of 22.5 N/mm^2 in the high-porosity range (20–25%) and partially meet the flexural strength of 4.5 N/ mm^2, also in the region emphasizing water permeability.

Future tasks

This study only evaluated the mechanical properties of high-strength POC and examined its applicability to highways. However, when considering paving a roadway, an evaluation of its workability, abrasion resistance, and wear resistance is required. Therefore, future experiments must be conducted to evaluate these properties.

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