

Mix Design Method and Void Performance of Concrete for Pervious Concrete Pavement

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Abstract

Pervious concrete pavement is drawing increasing attention for its high content of interconnected voids which is expected to reduce the environmental impact as concrete is often counted as a causal factor of the urban heat island phenomenon. Performance of pervious concrete can be measured by water permeability, water retentivity and noise reduction effect. Although active research is being made, no established standards or indicators for pervious concrete are available in Japan. Terms are not defined yet, and no method has been established for mix design. The purpose of this study is to present a mix design method that provides pervious concrete with a design void content and required performance level. The authors developed a theoretical model of pervious concrete under different void conditions, derived theoretical equations of void content from the model, and proposed a mix design method using the theoretical equations for pervious concrete for pavement. The proposed method takes into account the physical properties of the aggregate including solid volume percentage in addition to the densities of the materials. The close relationship between the strength and water permeability of pervious concrete and the physical properties and void structures of the materials was confirmed both experimentally and analytically.

Introduction

Application of pervious concrete to motorways in Japan was first made in 1998 (Kajio et al. 1998; Nakahara et al. 2004). Until that time, it was difficult to produce pervious concrete which would fulfill the requirements of a water permeability coefficient of over 0.01 cm/s and a 28-day design flexural strength of over 4.5 MPa. With recent improvements in concrete strength, pervious concrete with adequate performance was developed, and its practical application to pavement started. Although many previous studies looked at the relationship between the total void content of pervious concrete and the properties of materials or mix proportions, their conclusions were drawn primarily from experimental results. Since little is known theoretically about the void content of pervious concrete, it takes considerable efforts to find proper mix proportions which achieve required performance (Matsumoto et al. 2005).

The purpose of this study is to present a practical design method for pervious concrete mix to achieve target performance. A theoretical model of pervious concrete was created to identify the relationship between the total void content and mix

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proportions. Using this model, equations were developed to describe the relationship between the total void content and flexural strength and also the relationship between the total void content and water permeability coefficient. The proposed method uses these calculation results to determine mix proportions that achieve the target performance.

Development of Mix Design Method for Pervious Concrete

A theoretical equation of total void content derived from a model. Figure 1 shows a simplified pervious concrete model (hereinafter referred to as “PeC-Model”) consisting of coarse aggregate, mortar and voids (Kajio et al. 2008). In the PeC-Model mortar is divided into two parts: the mortar uniformly coating the coarse aggregate particles; and the mortar partly filling the voids between the particles. The volumetric ratio of the mortar coating the coarse aggregate particles to the total mortar is expressed as β , and the volumetric ratio of the mortar filling the voids is expressed as $1-\beta$. Figure 2 shows the maximum and minimum void content states of the PeC-Model. The maximum void content state is the state where mortar is coating the coarse aggregate particles but not filling the voids between the particles. The minimum void content state is the state where mortar is coating the coarse aggregate particles and also filling the voids between the particles to the maximum possible level (but not fully).

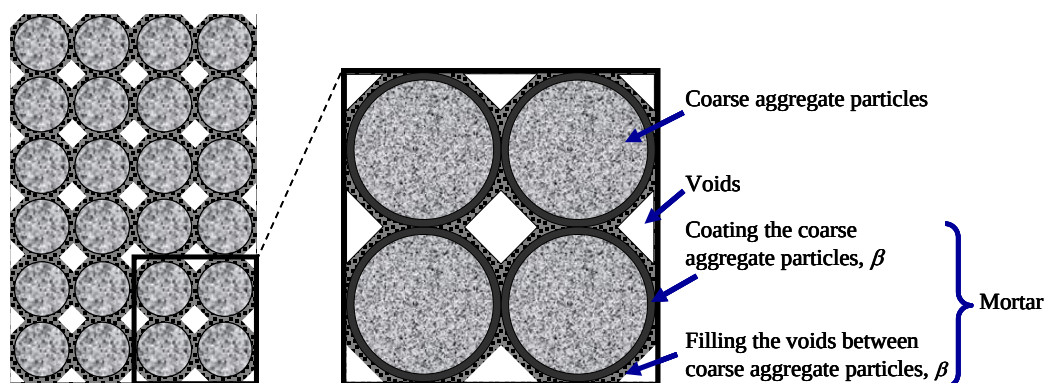


Figure 1. Pervious concrete model (PeC-Model)

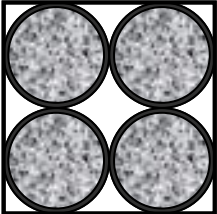
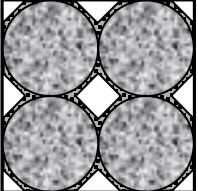
	
Maximum void content state, Vv_u (with the coarse aggregate particles coated)	Minimum void content state, Vv_l (with the voids filled to the maximum possible level)

Figure 2. Limit states of PeC-Model

The total void content in the maximum void content state is given by Equation (1), while that in the minimum void content state is given by Equation (3).

$$Vv_u = 1 - Gg \quad (1)$$

where, Vv_u is the maximum total void content of pervious concrete, m^3/m^3 ; and Gg is the solid content of the coarse aggregate.

$$Km = \frac{Vm}{Vv_g} = \frac{Vm}{Vg} \times \frac{Gg}{1 - Gg} \quad (2)$$

where, Km is the volumetric ratio of the total mortar to the voids in the coarse aggregate; Vm is the mortar content of pervious concrete, m^3/m^3 ; Vv_g is the void content of the coarse aggregate, m^3/m^3 ; and Vg is the coarse aggregate content of pervious concrete, m^3/m^3 .

$$Vv_l = (1 - Km)(1 - Gg) \quad (3)$$

where, Vv_l is the minimum total void content of pervious concrete, m^3/m^3 .

The total void content of pervious concrete is given by Equation (4) which is a fractional function of Km .

$$Vv_c = \frac{(1 - Gg)((\beta - Gg)Km + Gg)}{\beta(1 - Gg)Km + Gg} \quad (4)$$

where, Vv_c is the total void content of pervious concrete, m^3/m^3 ; and β is the volumetric ratio of the mortar coating the coarse aggregate particles to the total mortar.

Figure 3 shows the relationship between Km and the total void content in the PeC-Model, with the maximum and minimum limit states shown together. The relationship between Km and the total void content in the PeC-Model is expressed by a fractional function which has its range within the region bordered by the curves for the minimum and maximum void content states. This equation passing through $(0, 1 - Gg)$ and $[Gg/(Gg - \beta), 0]$ provides a basic formula of void content equation for pervious concrete.

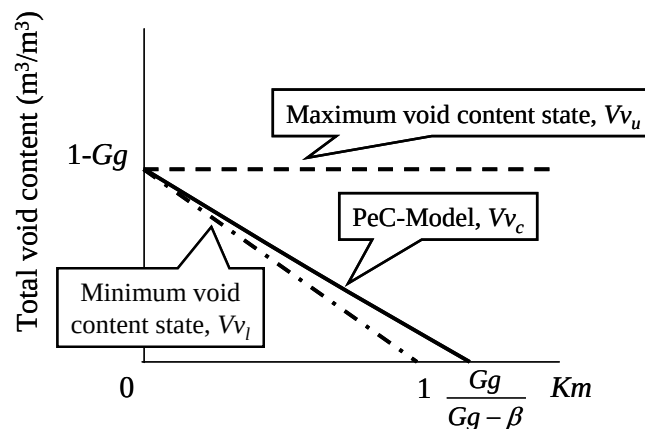


Figure 3. Relationship between Km and the total void content

An exponential equation of flexural strength in terms of total void content. The relationship between the total void content and flexural strength of pervious concrete is often obtained by approximation using linear functions derived from experimental results as described in a previous report (Center for Transportation Research and Education, Iowa State University 2006). However, homogeneous solid has strength inversely proportional to its void content. The relationship between the relative strength and total void content is similar in most materials. Equation (5) expresses the relationship between the strength and total void content (Mehta and Monteiro 2005). This equation was used in some previous studies in a regression approach (Asano et al. 2006; Maegawa et al. 2006). However, there is an inherent theoretical contradiction in Equation (5) in which strength is not 0 MPa when void content is over $1 \text{ m}^3/\text{m}^3$.

$$f = f_0 \exp(-\gamma V_{v_c}) \quad (5)$$

where, f is the strength, MPa; f_0 is the strength in the absence of voids, MPa; V_{v_c} is the total void content, m^3/m^3 ; and γ is a constant.

In the PeC-Model, strength at the maximum total void content $1-Gg$ (m^3/m^3) is assumed to be 0 MPa. Therefore, an equation was developed to have f_0 (MPa) at total void content of $0 \text{ m}^3/\text{m}^3$ and 0 MPa at $1-Gg$ (m^3/m^3). Equation (6) is the void content function where strength is 1 at total void content of $0 \text{ m}^3/\text{m}^3$ and 0 at $1-Gg$ (m^3/m^3).

$$V_f = \frac{\exp\left(1 - \frac{V_{v_c}}{1-Gg}\right) - 1}{e - 1} \quad (6)$$

where, V_f is the void content function.

Consequently, the relationship between the flexural strength and total void content can be expressed by Equation (7).

$$fb = fb_0 V_f^{\gamma_b} = \frac{fb_0}{(e-1)^{\gamma_b}} \left\{ \exp\left(1 - \frac{V_{v_c}}{1-Gg}\right) - 1 \right\}^{\gamma_b} \quad (7)$$

where, fb_0 is the flexural strength in the absence of voids, MPa; and γ_b is a constant.

A quadratic equation of water permeability coefficient using minimum continuous void content. The relationship between the total void content and water permeability coefficient of pervious concrete is often obtained by approximation using exponential functions derived from experimental results as described in the previous report (Center for Transportation Research and Education, Iowa State University 2006). However, there is inherently a theoretical contradiction in such exponential functions in which water permeability coefficient is not 0 cm/s when the void content is at a level where there should be no permeation. Therefore, the authors developed a theoretically consistent equation for the relationship between the total void content and water permeability coefficient.

Continuous voids in pervious concrete can be assumed to be a group of round tubes with different bore sizes in each cross-sectional layer (see Figure 4). The diameter of the i -th continuous void in a particular layer is expressed as Dv_i . According to the Hagen-Poiseuille's law, permeate flow rate ΣQ_{hp} for cross-sectional

area A_{tp} is given by Equation (8). This gives Equation (9) for average flow velocity v_{tp} in that layer. With the void diameters in a particular layer represented by average void diameter Dv_{ave} , and with the ratio of the diameter of the i -th continuous void to that average expressed as ε_i , the void diameter of the i -th continuous void, Dv_i , is expressed by Equation (10). Substituting Equation (10) into Equation (9) gives Equation (11).

$$\Sigma Q_{hp} = \frac{\pi g I}{128 v_w} \sum Dv_i^4 \quad (8)$$

$$v_{tp} = \frac{\Sigma Q_{hp}}{\frac{\pi}{4} \Sigma Dv_i^2} = \frac{g I}{32 v_w} \frac{\sum Dv_i^4}{\sum Dv_i^2} \quad (9)$$

$$Dv_i = \varepsilon_i Dv_{ave} \quad (10)$$

$$v_{tp} = \frac{g I Dv_{ave}^2}{32 v_w} \frac{\sum \varepsilon_i^4}{\sum \varepsilon_i^2} \quad (11)$$

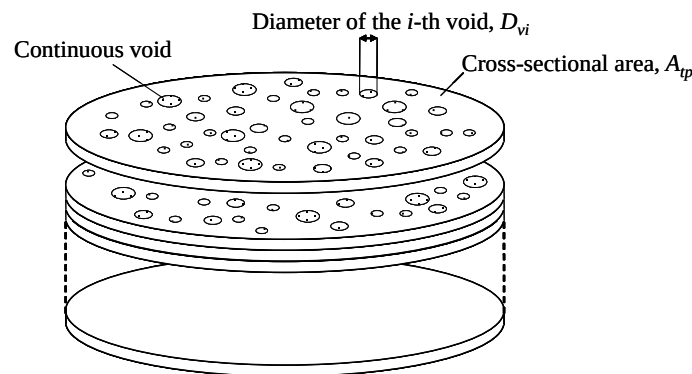


Figure 4. Continuous void structure model in cross-sectional layers

With the volume of continuous voids effective in water permeation defined as effective continuous void content Vcv_{ef} , average void diameter Dv_{ave} is given by Equation (12). Substituting Equations (12) and (13) into Equation (11) gives Equation (14). The average flow velocity v_{tp} in Equation (14) is the effective flow velocity in continuous voids in pervious concrete.

$$Dv_{ave} = 2 \sqrt{\frac{A_{tp} \times Vcv_{ef}}{n \pi}} \quad (12)$$

$$\varepsilon = \frac{\sum \varepsilon_i^4}{\sum \varepsilon_i^2} \quad (13)$$

$$v_{tp} = \varepsilon \frac{g I}{8 \pi v_w} \frac{A_{tp}}{n} Vcv_{ef} \quad (14)$$

According to Darcy's law, effective water permeability coefficient in continuous voids can be obtained using Equation (15).

$$K = \frac{v_{tp} V_{cv_{ef}}}{I} \quad (15)$$

As Equation (16) shows, water permeability coefficient is expressed as a quadratic function proportional to the square of the effective continuous void content.

$$K = \varepsilon \frac{g}{8\pi v_w} \frac{A_{tp}}{n} V_{cv_{ef}}^2 \quad (16)$$

Measurement Methods

Materials. The cement used in this study was ordinary portland cement with a density of 3.16 g/cm³. The admixture was powdered inorganic admixture with a density of 2.26 g/cm³ commonly used for pervious concrete. Table 1 shows the properties of aggregates used. Table 2 shows the mix proportions of the pervious concrete. Equation (17) gives the volumetric ratio of paste to voids in the fine aggregate (K_p).

Table 1. Properties of aggregates

	Size ranges (mm)	Saturated surface-dry particle density (g/cm ³)	Absorption capacity (%)	Solid content (%)
Fine aggregate	5 to 0	2.60	1.73	66.6
Coarse aggregate	13 to 5	2.64	0.92	60.7

Table 2. Mix proportions of pervious concrete

K_p	K_m	W/B (%)	Admixture content (%)
3.0 to ∞	0.46 to 0.87	20	$B \times 6.7\%$

$$K_p = \frac{V_p}{V_{v_s}} = \frac{V_p}{V_s} \times \frac{G_s}{1 - G_s} \quad (17)$$

where, K_p is the volumetric ratio of paste to voids in the fine aggregate; V_p is the paste content, m³/m³; V_{v_s} is the void content of the fine aggregate, m³/m³; V_s is the fine aggregate content, m³/m³; and G_s is the solid content of the fine aggregate.

Testing for void content. Figure 5 shows the set-up used for measuring the total void content in pervious concrete. Each specimen was prepared by pouring 2600 g of pervious concrete in a steel mold (100 mm in diameter, 200 mm high), placing a 4-kg weight on top of it, and applying vibration for two minutes. Height and diameter of the specimens were measured to obtain the bulk volume. Using the theoretical mass per unit volume determined from the mix proportions, the total void content was calculated in accordance with ASTM C1688M-08 “Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete”. The vibration conditions were carefully selected to give almost full compaction so that the volume of permanent voids after constant vibration was obtained.

Figure 6 shows the set-up used for measuring the continuous void content distribution (De Winne and De Somer 1998). Specimens after the total void content test were used. The specimen was suspended externally in the water tank. Measurement was taken continually without interruption while water was poured into the tank slowly. The volume of continuous voids in any desired cross-sectional layer at any depth can be calculated from the mass change, the tank and specimen dimensions, and quantity of water added.

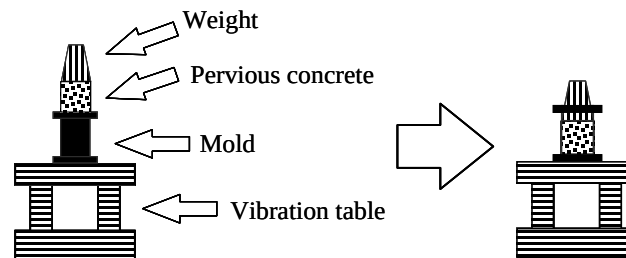


Figure 5. Total void content test set-up

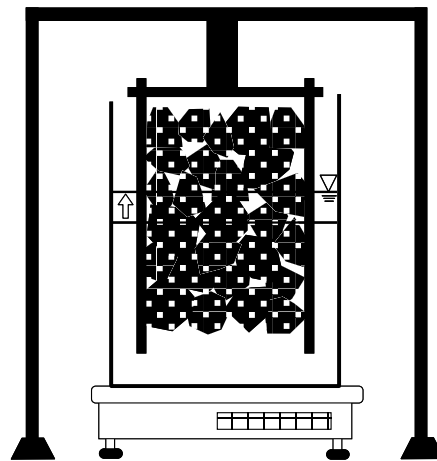


Figure 6. Continuous void content distribution test set-up

Testing for flexural strength. Flexural strength test specimens had dimensions of $100 \times 100 \times 400$ mm. The specimens were compacted by vibration, removed from the mold the following day and cured in water at 20°C . Flexural strength test was carried out at 28 days in compliance with JIS A 1106.

Testing for water permeability coefficient. Figure 7 shows the water permeability test set-up (Chen et al. 2008). Equation (18) gives the water permeability coefficient.

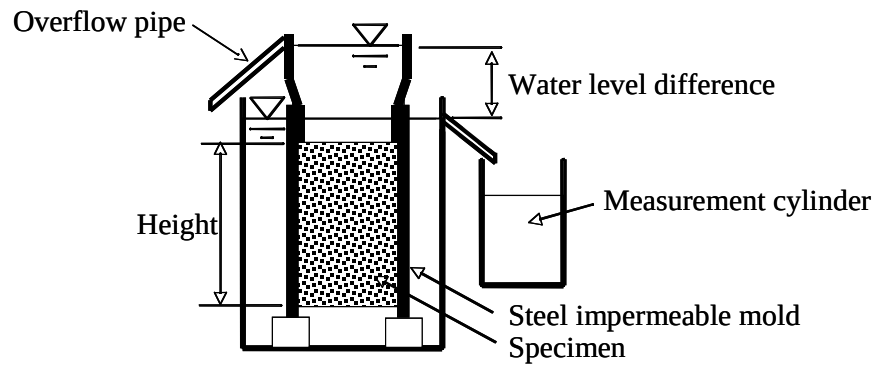


Figure 7. Water permeability test set-up

$$K = \frac{H_{tp}}{h} \frac{V_{w_q}}{A_{tp} \times t} \quad (18)$$

where, K is the water permeability coefficient, cm/s; H_{tp} is the height of the specimen, cm; V_{w_q} is the amount of water penetrating through the pervious concrete during the test time, cm^3 ; h is the measured height of water level, cm; A_{tp} is the surface area of the specimen, cm^2 ; and t is the test time, s.

Measurement Results

Void content. Figure 8 shows the plots of the total void content test results and the regression curves obtained by the least square method using Equation (4). Table 3 shows the linear regression analysis results for β . Coefficient of determination R^2 was 0.89 or above, indicating a highly accurate regression fit. This suggests that the total void content can be controlled by adjusting K_m and K_p .

Table 3 Regression analysis results for β

K_p	3.0	5.0	7.0	∞
β	0.2651	0.2442	0.2537	0.1148
R^2	1.000	0.949	0.999	0.889

Figure 9 shows an example of continuous void content distribution measurement results. It was found that continuous void content distribution was not even within a single specimen.

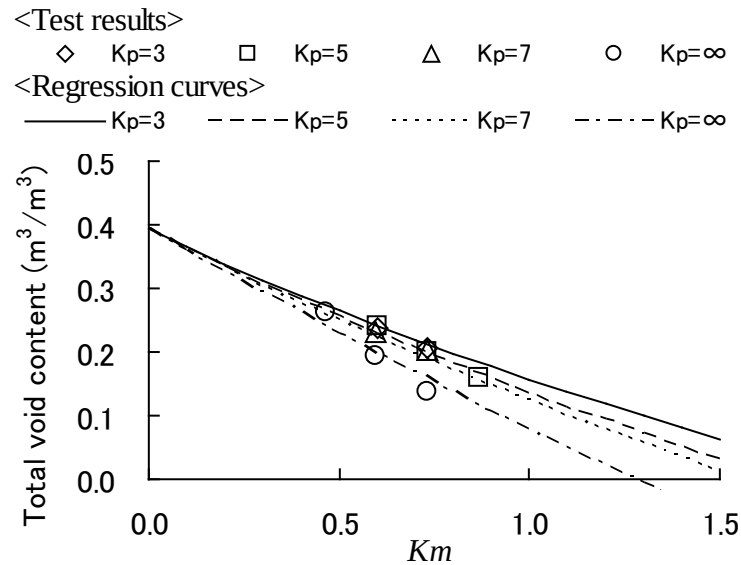


Figure 8. Total void content test results

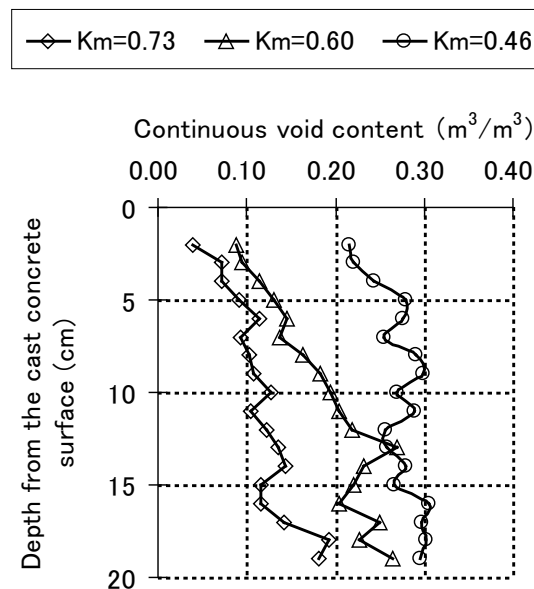


Figure 9. An example of continuous void content distribution test results

Flexural strength. Figure 10 shows the plots of the flexural strength test results and the regression curve obtained from the test results and Equation (7) by the least square method. Equation (19) is the linear regression equation. It was verified that the exponential equation for the total void content has a good regression fit to the flexural strength.

$$fb = \frac{10.424}{(e-1)^{0.6641}} \left\{ \exp \left(1 - \frac{Vv_c}{1-Gg} \right) - 1 \right\}^{0.6641}, R^2=0.7767 \quad (19)$$

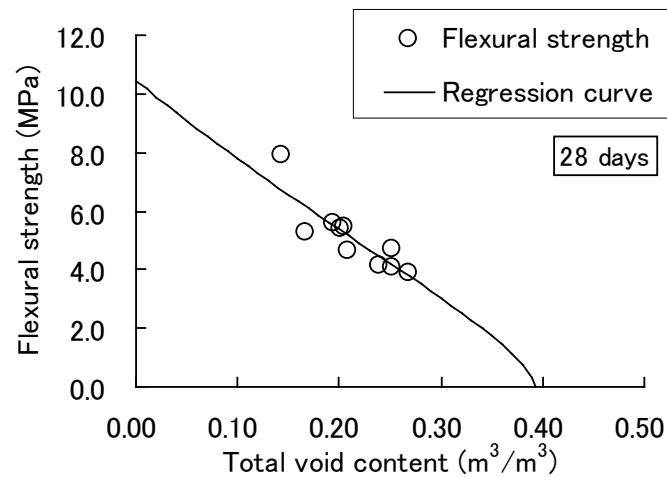


Figure 10. Flexural strength test results

Water permeability coefficient. The effective continuous void content given by Equation (16) represents the continuous void content in the bottleneck layer where the water permeability is the lowest in a specimen. Therefore, the effective continuous void content was used as the minimum value in the continuous void content distribution. Figure 11 shows the relationship between the effective continuous void and total void contents. A linear equation passing through $(1-Gg, 1-Gg)$ was used to describe the relationship, since the PeC-Model had a maximum void content of $1-Gg$ when $Km = 0$ as shown in Figure 3.

Figure 12 shows the plots of the water permeability test results and the regression curve obtained by using Equation (16) which is a quadratic equation of the effective continuous void content. It was revealed that a very good regression fit was achieved by using the effective continuous void content in describing the water permeability.

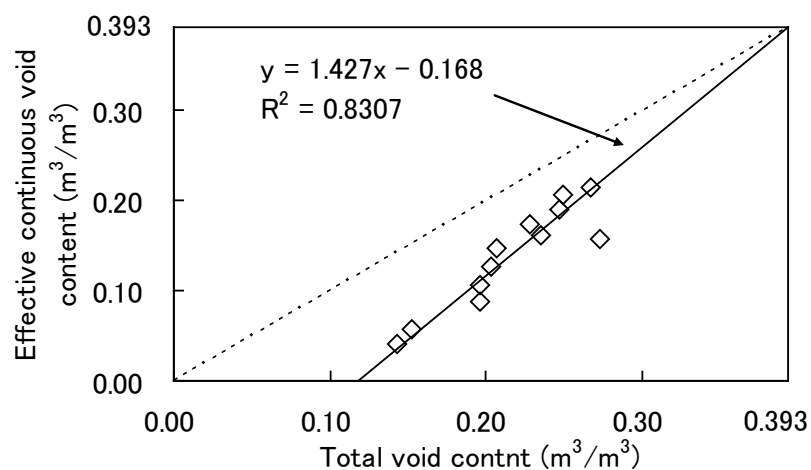


Figure 11. Effective continuous void content vs. total void content

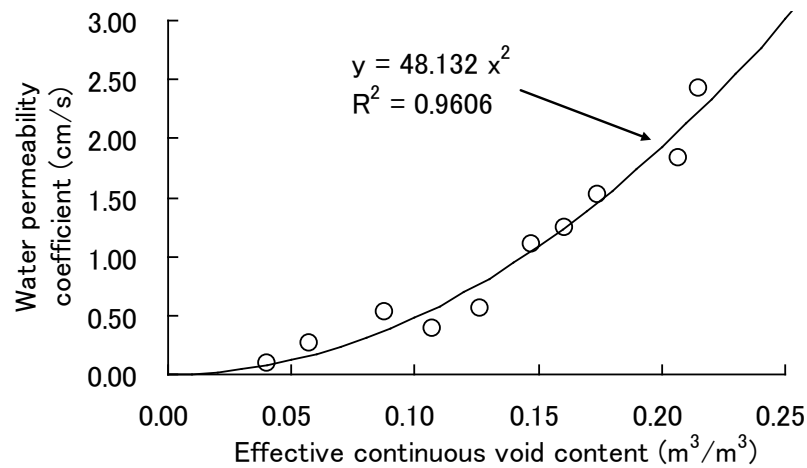


Figure 12. Water permeability coefficient vs. effective continuous void content

Mix design method. An example of mix design of pervious concrete with a target flexural strength of 4.5 MPa and a target water permeability coefficient of 0.01 cm/s is shown. Figure 13 shows the comprehensive relationship between the strength, water permeability and total void content by combining Figures 10, 11 and 12. As seen from Figure 13, total void content should be in a range between 0.128 and 0.238 m³/m³ to satisfy the strength and water permeability requirements. For example, Equation (20) derived from Equation (4) gives a Km range from 0.58 to 1.06 for $Kp = 7.0$. Within the range tested in this study, the required strength and water permeability coefficient will be obtained when Km is in the range from 0.58 to 0.87. Mix proportions can be determined as desired within this range, with quality variation and various economic factors taken into account.

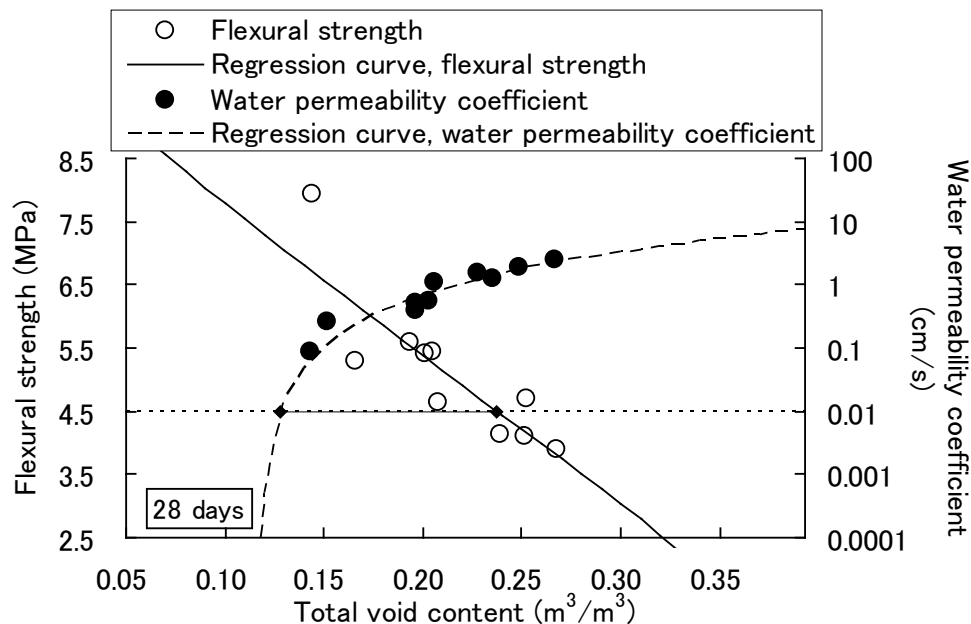


Figure 13. Relationship between the pervious concrete performance and total void content

$$Km = \frac{Gg(1 - Gg - V_{v_c})}{(1 - Gg)\{Gg - (1 - V_{v_c})\beta\}} \quad (20)$$

Conclusions

Using a theoretical pervious concrete model, equations were derived to describe the relationship between the total void content and K_m , the relationship between the total void content and flexural strength, and the relationship between the total void content and water permeability coefficient. These equations were verified experimentally using specimens under indoor conditions. The major findings of this study are summarized as follows.

1. A theoretical model of pervious concrete was developed, and an original equation of total void content in pervious concrete was derived using the model. A good regression fit was obtained in the experiment.
2. An exponential equation of flexural strength was developed, with the range of total void content taken into account. A good regression fit was obtained in the experiment.
3. A quadratic function of water permeability coefficient and effective continuous void content was derived using a void structure model of a cylinder, and a good regression fit was obtained in the experiment.
4. The relationship equations of mix proportions, strength properties, water permeation performance and total void content were demonstrated to be capable of providing a pervious concrete mix design which would achieve desired flexural strength and water permeability.

It has been recently known that the strength and water permeation performance of pervious concrete are also influenced by the maximum particle size of coarse aggregate and the strength development behavior of cement paste. The future goal is to establish a more convenient and highly practical mix design method for pervious concrete. It is also necessary to confirm the performance of actual pavement constructed outdoors using paving machines.

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