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Linking pore system characteristics to the compressive behavior of pervious concrete

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ABSTRACT

Research has been carried out linking matrix strength, total porosity, aggregate size and mean pore size of pervious concrete to its compressive strength. While matrix strength, total porosity and aggregate size are easy accessible parameters, mean pore size is derived from the pore size distribution determined using linear path function. The linear path function is tailored for pervious concrete and validated by an image analysis method. Additionally, based on the statistically extracted pore size distribution the pore size distribution density is calculated and incorporated in a semi-empirical model to predict the compressive stress versus strain behavior of pervious concrete.

In this research 27 different pervious concrete series are investigated, varying in their matrix strength (from 29 MPa to 174 MPa), their aggregate to binder ratio (from 2.5 to 3.5) and their aggregate size (from 1.19 mm to 4.75 mm). Based on the coefficient of determination a good correlation between experimental and predicted compressive behavior of the pervious concrete series is achieved.

1. Introduction

Pervious concrete is a class of concrete characterized by high volume of connected pores, typically in the range from 15% to 30%, resulting in environmental beneficial hydraulic conductivity, but also relatively low compressive strength, typically lower than 20 MPa [1]. In comparison to conventional impervious concrete, the mechanical and durability performance of pervious concrete is significantly reduced leading to low raveling resistance. Therefore, main applications of this type of material are currently limited to parking lots and pathways. To facilitate broader application, high performance pervious concrete with compressive strength exceeding 40 MPa without sacrificing its hydraulic conductivity was designed by using ultra-high strength matrix in prior experimental investigations [2,3]. Extensive efforts have been made studying the influence of pore system characteristics (PSC), such as total porosity and pore size distribution (PSD) on the hydraulic conductivity of pervious concrete [4–7]. However, limited research is available on the effect of pore system characteristics on the material's compressive behavior [1,8–10]. In those studies emphasis was laid on pervious concrete with compressive strength below 20 MPa. Little is known for pervious concrete with compressive strength exceeding 40 MPa. Furthermore, most of previous research focused only on volume of porosity without considering the PSD. In analogy to other porous materials [11] PSD is an important parameter to understand and predict the compressive behavior of pervious concrete. Deo and Neithalath [1] have used image analysis (IA) to extract PSC. Based on these parameters they proposed models to predict the compressive strength and stress versus strain curve of pervious concrete. IA is time consuming and challenging to be used in practical application. Correspondingly the input parameters to predict compressive strength and stress versus strain behavior are not readily available or measurable.

Motivated by the aforementioned limitations, the objective of this research is to characterize the pore system of pervious concrete with easily accessible parameters and incorporate these characteristics in a semi-empirical model to predict the compressive behavior of pervious concrete, including compressive strength in excess of 40 MPa. In pursuit of this objective the research is divided into three steps as follows:

1. A linear path function (LPF) proposed for two phase random material is tailored to extract the pore size distribution (PSD) of pervious concrete. Other pore system characteristics such as

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mean pore size and pore size distribution density are derived [12,13]. The LPF based PSD is validated using IA method and compared to the PSD derived from Weibull distribution (WBD).
2. The extracted PSD based on LPF is used to calculate the mean pore size which is incorporated in a model to predict the compressive strength of pervious concrete. Comparisons are made with other models.
3. The models of Carreira and Chu [14] and Popovics [15] are employed to predict the ascending and descending part of the stress versus strain relationship. The correction parameters are correlated to the pore system characteristics. The improved model is validated by the good agreement between the experimentally obtained and the predicted stress versus strain curves.

2. Experimental program

Single size quartz aggregates and type I white Portland cement conforming to ASTM C150 are used for all mixtures designed in this research. The mixture proportions, their average total porosity and compressive strength values are summarized in Table 1. The interested reader is referred to prior research [2] for further information on obtaining total porosity and compressive strengths, as well as the mixture proportions of the different matrices, such as normal strength matrix (NSM), high strength matrix (HSM) and ultra-high strength matrix (UHSM).

3. Characterization of pore system

Mercury intrusion porosimetry (MIP) is generally used to determine pore sizes and their distribution for conventional impervious concrete. However, this method is not applicable to pervious concrete due to its large pore volume and connected pore system. In this research a linear path function (LPF) proposed for two phase random material with impenetrable equal size particles is tailored for pervious concrete to extract the pore system characteristics. Fig. 1 illustrates an overview of the procedure to characterize the compressive behavior of pervious concrete. Detailed discussion is presented in the following sections.

Table 1
Mixture proportions and test results of pervious concretes.

Serial no.	Mixture No.[a]	A/B[b]	d_a (mm)[c]	f'_{c0} (MPa)[d]	ϕ_t (%)[e]	f'_c (MPa)[f]
P-UHSM	UHSM-2.5-1.19	2.5	1.19	174	19.84	65.8
	UHSM-3.0-1.19	3.0	1.19	174	24.65	52.9
	UHSM-3.5-1.19	3.5	1.19	174	29.18	42.3
	UHSM-2.5-2.38	2.5	2.38	174	20.93	47.5
	UHSM-3.0-2.38	3.0	2.38	174	27.08	31.7
	UHSM-3.5-2.38	3.5	2.38	174	31.04	21.5
	UHSM-2.5-4.75	2.5	4.75	174	22.46	34.9
	UHSM-3.0-4.75	3.0	4.75	174	26.97	23.4
	UHSM-3.5-4.75	3.5	4.75	174	30.22	14.6
P-HSM	HSM-2.5-1.19	2.5	1.19	61	23.81	23.4
	HSM-3.0-1.19	3.0	1.19	61	29.62	14.4
	HSM-3.5-1.19	3.5	1.19	61	32.03	10.6
	HSM-2.5-2.38	2.5	2.38	61	23.46	22.9
	HSM-3.0-2.38	3.0	2.38	61	29.74	12.9
	HSM-3.5-2.38	3.5	2.38	61	32.75	8.6
	HSM-2.5-4.75	2.5	4.75	61	25.88	18.1
	HSM-3.0-4.75	3.0	4.75	61	30.25	11.3
	HSM-3.5-4.75	3.5	4.75	61	31.63	9.1
P-NSM	NSM-2.5-1.19	2.5	1.19	29	17.02	23.2
	NSM-3.0-1.19	3.0	1.19	29	27.06	12.4
	NSM-3.5-1.19	3.5	1.19	29	30.94	8.4
	NSM-2.5-2.38	2.5	2.38	29	22.10	17.6
	NSM-3.0-2.38	3.0	2.38	29	27.85	11.5
	NSM-3.5-2.38	3.5	2.38	29	31.59	7.5
	NSM-2.5-4.75	2.5	4.75	29	23.35	16.0
	NSM-3.0-4.75	3.0	4.75	29	28.59	10.5
	NSM-3.5-4.75	3.5	4.75	29	30.18	8.8

[a] Mixture identifications start with the type of matrix, followed by the aggregate to binder ratio (A/B) and the aggregate size in millimeter.
[b] Aggregate to binder ratio by weight.
[c] Aggregate size = sieve size that retained the aggregate.
[d] Matrix strength.
[e] Total porosity.
[f] Compressive strength of pervious concrete.

3.1. Pore size distribution extracted from the linear-path function

The linear-path function (LPF) is the cumulative distribution function (CDF) of the probability of finding a line segment of length z entirely in one phase of a two phase material when randomly placed into the sample. One phase is designated as particles and the other one usually designated as matrix. Analytic expressions of the LPF for two and three dimensional two phase random material with impenetrable and penetrable equal size particles (Fig. 2) have been derived by B. Lu and S. Torquato [12,13].

The LPF for impenetrable equal size particle two-phase random system (Fig. 2a) is selected and tailored for pervious concrete to extract the pore system characteristics. Aggregates covered with cementitious matrix are defined as phase 1, whereas the pore system is defined as phase 2. The following two assumptions are made: 1) aggregates used to produce pervious concrete are single sized or gap graded; 2) the matrix covering the aggregates is relatively thin compared to the aggregate size. Therefore in each cross-section, pervious concrete can be treated as impenetrable equal particle system based on the aforementioned assumptions. The following LPF equations as shown in Eq. (1) have been derived from those provided by Lu and Torquato [12,13]:

$$\begin{cases} L(z) = \phi_t \exp\left(-\dfrac{3(1-\phi_t)z}{2\phi_t d_a}\right) & \textit{for three dimensions } (D=3) \\ L(z) = \phi_t \exp\left(-\dfrac{4(1-\phi_t)z}{\pi\phi_t d_a}\right) & \textit{for two dimensions } (D=2) \\ L(z) = \phi_t \exp\left(-\dfrac{(1-\phi_t)z}{\phi_t d_a}\right) & \textit{for one dimensions } (D=1) \end{cases} \tag{1}$$

where ϕ_t is total porosity, d_a is the diameter of aggregate, z is the length of the line segment. To facilitate the derivation, the following designations are defined:

$P(A)$ – Probability that the phase of interest is the pore phase.
$P(B)$ – Probability of the line segment entirely placed in the phase of interest.
$P(A \cap B)$ – Probability that the line segment of length z is entirely in the pore phase.
$P(B|A)$ – Probability that the line segment is entirely in the phase of interest given the condition that the pore phase is the phase of interest.

According to the definition of LPF, we obtain

$$L(d_p \geq z) = P(A \cap B)(d_p \geq z) \tag{2}$$

Calculation of $P(B|A)$ is given by Eq. (3) according to the probability theory:

$$P(B|A) = \frac{P(A \cap B)}{P(A)} \tag{3}$$

The physical meaning of the cumulative distribution function (CDF) of the conditional probability $P(B|A)$ is the cumulative pore