Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Advanced numerical assessment of the permeability of pervious concrete

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ARTICLE INFO

Keywords:
Pervious concrete
Permeability
Compaction process
Composition
DEM
CFD

ABSTRACT

The most singular characteristic of pervious concrete is its interconnected porosity that allows water to flow through at high rates. The objective of this paper is to develop and validate an advanced DEM-CFD model to assess the permeability of pervious concrete numerically, taking into account the influence of the composition and of the compaction process. An extensive experimental program with 1 aggregate grading size, 4 paste contents and 3 degrees of compaction was conducted to validate the numerical approach. Results show that the DEM-CFD model is capable of predicting the permeability depending on the variables considered here. Moreover, flow parameters derived from the numerical simulations help understand the experimental results. The study confirms that, instead of relying on trial and error experiments, it is possible to use advanced numerical models to accelerate the definition of mixes and the production process, reducing the time, efforts and costs required.

1. Introduction

Pervious concrete (PC) is material that has been used to insulate elements, to favor the permeability of surfaces [1–6] or to dissipate dynamic loadings [7–10]. Probably one of the most important applications is found in urban pavements as a sustainable alternative to reduce rain runoff, mitigate floods and recharge aquifers [1–6]. The most singular characteristic that favors the selection of this special type of concrete is its interconnected porosity - usually ranging from 15% to 30% [11] - that allows water to flow through at high rates [12,13].

The porosity is achieved by reducing the amount of fines provided by the sand, as well as by the precise control of the level of compaction applied during execution. The compaction process governs the spatial distribution and sizes of the pores [14,15], having a crucial influence in the final permeability [11,16]. Slight variations in the compaction applied may render a highly permeable PC into an almost watertight material.

In practice, the selection of the mix composition and of the compaction that guarantee the target permeability relies in costly and time-consuming experimental studies based on trial and error. Instead, the assessment of the porosity and permeability coefficient depending on the composition and compaction process by means of numerical simulations is still a relatively unexplored field.

Several authors have simulated the water flow through PC in order to predict the permeability. Sumanasooriya et al. [17] proposed a method to reconstruct 3D models from planar images taken from hardened PC specimens. A 3D Stokes permeability solver for porous media was used to predict the permeability of the models once the meso-structure had been reconstructed. The permeability predicted numerically agreed with the obtained experimentally.

In line with that, Chung et al. [18] used computer tomography images to generate 3D models of PC samples. From this models, they proposed a method using low-order probability functions to generate reconstructed 3D model from the hardened specimens. The comparison between the permeability results obtained from Computational Fluid Dynamics (CFD) simulations of the original and reconstructed models showed similar values. Akand et al. [19] applied Fast Fourier Transformation to generate reconstructed 2D models of pervious concrete. They used CFD to predict the permeability of the models. The results obtained from the numerical simulations after calibration showed errors of < 8% in comparison with experimental results.

Despite the advances and good predictions, notice that studies from the literature count on reconstructed models, most of which depend on the image analysis of existing hardened specimens. In other words, they still require the experimental production of PC prior to assessing the permeability. Therefore, since the influence of the compaction process is not assessed numerically, the practical application of existing numerical methods for the design of PC mixes and the production process is limited. In order to overcome this drawback, it is necessary to integrate the model to predict the permeability with a model to

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http://dx.doi.org/10.1016/j.cemconres.2017.09.009
Received 30 March 2017; Received in revised form 19 August 2017; Accepted 15 September 2017

numerically assess the meso-structure formed depending on the compaction applied. Hence, it will be possible to account for the important influence of the compaction in the assessment of the permeability without the need of resorting to experimental studies.

The objective of this paper is to develop and validate an advanced model to assess the permeability numerically, taking into account the influence of the mix composition and the compaction process. For that, an integrated model that combines discrete element modeling (DEM) and computational fluid dynamics (CFD) is proposed here. The DEM is used to simulate the compaction process of the PC in the fresh state and to obtain the meso-scale geometry, assuming some simplifications to account for the cement paste contact bridge and the approximation of the aggregates. The CFD estimates the flow profile and the permeability of the meso-scale geometry generated previously as an input.

In addition to the proposal of the DEM-CFD model, an extensive experimental program was conducted to estimate the permeability coefficient of PC with 1 aggregate grading size, 4 paste contents and 3 degrees of compaction. The experimental results were used to validate the DEM-CFD model. The conclusions derived from this study represent a step forward in the development of alternative approaches to design concrete mixes and define the production process for certain target properties. Instead of relying mainly on experiments, the study confirms that it is possible to use advanced numerical models to accelerate the definition of mixes and processes, increasing the likelihood of finding optimum solutions and reducing the time, efforts and costs required.

2. Experimental program

The production and characterization of the PC were performed at the Laboratory of Technology of Structures Luis Agulló (UPC). First, 4 PC compositions were defined and produced. The compositions used were selected in order to reproduce those typically found in practice. After the production, different degrees of compaction were applied by uniaxial compression. Finally, tests were conducted to evaluate the porosity, density and permeability of mixes. The materials, composition and production process applied here are based on those described by Pieralisi et al. [15].

2.1. Materials properties

The compositions used in this study are summarized in Table 1. Crushed limestone was selected as aggregate. The aggregate was sieved to ensure a particle size distribution between 5 and 12 mm. In order to maximize the porosity achieved the aggregates were washed to eliminate remaining limestone dust after the sieving process.

Fig. 1a shows the surface aspect of the crushed limestone aggregates after the sieving and washing process. Fig. 1b shows the grading curve of the aggregate used. The density and the water absorption of the crushed limestone after the washing process were 2640 kg/m^3 and 0.83%, respectively. For all mixtures compositions the content of aggregates selected was fixed at 1400 kg/m^3. CEM II/A-L 42.5 R was selected as the binder. The content of cement was another variable of the study, going from 300 to 450 kg/m^3, in intervals of 50 kg/m^3.

The water-to-cement ratio (w/c) was the same for the compositions teste here. This intended to assure a similar rheology of the cement paste surrounding the aggregates in all of them. Such consideration simplifies the numerical simulation and the validation of the models using the results from the experimental program.

The amount of water to correct the absorption of the crushed limestone was added to the mixing water. Moreover, 1% of retardant by cement weight was added in order to diminish variations in the fresh state properties of the concrete during the compaction of the several specimens that had to be produced for each composition.

One of the main variable of the study related with the composition of the pervious concrete was the ratio between paste (cement + water) and aggregate by weight (P/A ratio), which ranged from 0.27 to 0.41. This parameter affects the compaction process and may also have repercussion in the final permeability. In theory, for the same degree of compaction, a composition with bigger P/A ratio should present smaller permeability. According to the P/A ratio, the mixture compositions were divided in 4 families: namely L0.27, L0.32, L0.36 and L0.41 (see Table 1).

The mixing process was the same for all mixes. The PC was prepared in a planetary mortar mixer type 65/2 K-3, using a container with nominal capacity of 65 l. Paddle rotation and planetary rotation were 150 rpm and 40 rpm, respectively. First, cement and aggregates were mixed during 60 s. Then, 70% of the total water was added and mixed during 30 s. Finally, the rest of the water and the retardant was added and mixed during 60 s. Batches of approximately 20 l were produced for each mix from Table 1.

The fresh PC obtained was immediately placed in cylindrical molds (with height equal to 200 mm, diameter equal to 100 mm and that followed the specifications from UNE-EN 12390-1 [20]), in three layers. The excess of material surpassing the top of the mold was removed to ensure that the initial height of specimens was 200 mm. This removal was performed with care, to avoid introducing compaction forces. The weight of each specimen was measured to achieve comparable levels of initial porosity in mixtures with the same P/A ratio.

The second variable of the experimental program that holds close relation with the permeability is the degree of compaction (DoC), calculated here as the ratio between the reduction of height and the initial height of the specimen. In order to guarantee homogeny conditions in all specimens, the compaction was applied in a hydraulic press with 10 kN of nominal load capacity and with closed loop capability. Uniaxial compaction with displacement control was employed to achieve 3 values of DoC: 10, 15 and 20% (see Table 1).

In total, 12 mixes were produced considering the combination of variables described. For each of them, 10 specimens were cast. After the compaction process, the molds were wrapped in a plastic bag during the first 24 h to ensure good curing conditions. Then, specimens were demolded and submerged in water for 98 days.

Table 1
PC compositions and degrees of compaction.

Family	Aggregate (kg/m^3)	Cement (kg/m^3)	w/c	Retardant (kg/m^3)	P/A	Degree of compaction (%)
L0.27	1400	300	0.27	3.0	0.27	10
	1400	300	0.27	3.0		15
	1400	300	0.27	3.0		20
L0.32	1400	350	0.27	3.5	0.32	10
	1400	350	0.27	3.5		15
	1400	350	0.27	3.5		20
L0.36	1400	400	0.27	4.0	0.36	10
	1400	400	0.27	4.0		15
	1400	400	0.27	4.0		20
L0.41	1400	450	0.27	4.5	0.41	10
	1400	450	0.27	4.5		15
	1400	450	0.27	4.5		20

2.2. Test methods

After the curing period, specimens were tested for their porosity and density (measured according to ASTM C1754 [21]). Once this test was finished, they were characterized for the permeability. Notice that the assessment of permeability does not follow a specific standard due to the lack of widely accepted standard testing procedures available in the scientific community for that purpose. All specimens were kept under submerged curing in between tests.

2.2.1. Porosity and density

Before the determination of the porosity and density, specimens