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Discrete element modelling of the fresh state behavior of pervious concrete

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ABSTRACT

The objective of this paper is to propose a novel numerical approach to evaluate the fresh state behavior of pervious concrete (PC). A new constitutive law applied to Discrete Element Method was developed for the simulation of the interaction between aggregates connected by fresh cement paste. Several innovative aspects regarding the type of contact model, the consideration of the contact bridge and the inclusion of the rheology coefficients were proposed. A calibration was performed with data from the literature. Furthermore, an extensive experimental program considering different shapes of aggregates, grading curves and aggregate-to-cement paste ratios was conducted to evaluate the fresh state behavior and validate the numerical models. The good fit obtained between numerical and experimental results confirm the model and the constitutive law reproduce the under uniaxial compaction, thus representing a step forward in the design and application of pervious concrete mixes.

1. Introduction

Pervious concrete is a material that combines adequate mechanical properties and high permeability [1–4]. These properties are governed by the mix composition and, especially, the compaction process applied to the material in the fresh state. In terms of mix composition, the traditional philosophy used to achieve a pervious concrete is to reduce the amount of fines provided by the sand and to use cement paste contents just enough to create a connection between coarse aggregates. The fresh state mixture obtained may be dissociated in several unities. Each unity is composed by an aggregate involved by a thin layer of dry cement paste obtained by using low water-to-cement ratios or special thickening admixtures. The low fluidity achieved is a key point that helps to reduce the risk of segregation of the mixture.

The bulk material obtained after mixing usually has a porosity around 50% by volume. On the other hand, values ranging from 15% to 30% [5–7] are commonly found in the final application after the compaction process. It is evident that a significant reduction on the porosity occurs in the compaction process, which plays a fundamental role on the performance of the material [8–10] since bigger porosities increase the drainage capacity but compromise the mechanical strength.

In general, the evaluation of the compaction process and of the final porosity of pervious concrete is performed experimentally through a trial and error approach according with a time-consuming process. The assessment of the fresh state behavior of the material and the compaction using numerical simulations is still a relatively unexplored field.

The discrete element method (DEM) [11–13] is a powerful tool capable of simulating the dynamic movement and the interaction of a large number of particles found in granular materials. Particles are assumed as spherical bodies that may have contact with each other. Traditionally, a linear elastic contact approximation is used to simulate interactions, considering that an overlap is possible between two particles at the points of contact. This overlap generates forces of interaction governed by a constitutive law.

Several authors have simulated the fresh state behavior of concrete using DEM. Almost all of them focus on highly flowable concrete (self-compacting). Nabeta [14] introduced the simulations of fresh concretes flow using DEM. Chu et al. [15] used DEM to simulate the filling capacity of fresh concrete. The authors considered a homogenous material approach in which all particles share the same properties. Afterwards, other studies [16–17] introduced a heterogeneous approach, using some particles to simulate the aggregates and others to simulate the cement paste or mortar. Nevertheless, with the advances in processing capabilities of modern computers, it becomes possible to use models with elevated complexity. A recent approach to simulate the flow of self-compacting concrete was proposed by Chu et al. [18]. In the latter, a bi-phasic particle with an aggregate-like kernel involved by a mortar layer was used to simplify the computation of interactions. In a similar way, Zheng et al. [19] proposed a GPU-based parallel algorithm for particle contact detection in self-compacting fresh concrete simulations.

In order to simulate the fresh state properties of self-compacting concrete, Gram [20] proposed an adaptation of the Bingham contact

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using a spring connected in parallel with a serial connection of a damper and a Saint-Venant element. Other authors [21–24] have proposed contact models based on stress-strain (σ-ε) curves obtained with laboratory tests in which two spheres surrounded by mortar or cement paste are put in contact. In another study, Remond et al. [25] proposed a bi-phasic model with the simulation of a fluid-like interaction between the external layers of the particles. Roussel et al. [26] compared several numerical techniques (DEM, Computational Fluid Dynamics and Lattice Boltzman) for the simulation of the concrete flow. In their work [26], the authors suggested that all these numerical techniques have reached a level that allows simulating practical problems.

Despite the advances observed, it is important to remark that the great majority of the studies with DEM focuses on self-compacting concrete with a high fluidity and without accounting for external compaction or vibration. On the contrary, scarce information about the evaluation of the fresh state properties of pervious concrete may be found, especially regarding the simulation of the compaction process.

The objective of this study is to propose and validate a DEM approach for the simulation of the compaction process of pervious concrete in fresh state. In this sense, it is necessary to propose a constitutive law that represents the interaction of two particles (or aggregates) surrounded by a thin layer of cement paste in fresh state. A biphasic particle and a new constitutive law for the interactions between particles more representative with pervious concretes were proposed and implemented in the open source framework YADE [27].

A calibration of the constitutive law with the experimental results from Shyshko et al. [21] was performed and an experimental program related to the compaction process of the pervious concrete in fresh state was conducted. In this experimental program, 3 different types of aggregates and 4 aggregate-to-cement paste ratio were tested. The good fit obtained between numerical and experimental results confirm the model and the constitutive law reproduce the fresh state behavior of the pervious concrete under uniaxial compaction. The results obtained represent a step forward, showing that it is possible to apply advanced numerical tools for a preliminary assessment of the performance of pervious concrete, which might have positive implications in the design and use of mixes in the future.

2. Experimental program

The experimental program was divided in two phases. Phase I focused on the effect of the cement paste-to-aggregate ratio (P/A) in mixes with regular mono-sized particles. Phase II was centered on the effect of the type and grading of the aggregates.

2.1. Materials properties

In Phase I, spherical glass aggregates (see Fig. 1a) with diameter of 18 ± 0.5 mm and density of 2570 kg/m^3 was used. In Phase II, crushed limestone with density of 2640 kg/m^3 and water absorption of 0.83% by weight was used. The crushed limestone aggregates were sieved to ensure that particle sizes were between 5 and 12 mm (see Fig. 1b) and between 9 and 20 mm (see Fig. 1c). In order to maximize the porosity achieved, after the sieving process, the aggregates were washed to eliminate remaining limestone dust. The grading curves and the properties of the aggregates are presented in Fig. 1d. The cement used all mixes was CEM II/A-L 42.5R.

2.2. Compositions

The compositions used in the experimental program were defined to simulate those found in typical applications of pervious concrete. All compositions had a fixed theoretical content of aggregates equal to 1400 kg/m^3. The water-to-cement ratio (w/c) was also the same for all mixes in order to guarantee that the cement pastes obtained had similar rheology. 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 specimens.

The content of cement was defined depending on the type of aggregate. In the case of mixes from Phase I, contents of cement equal to 215, 245, 275 and 305 kg/m^3 were used. The cement paste-to-aggregate ratio (P/A) by weight ranged from 0.15 to 0.22, approximately. Mixes from phase II had a theoretical content of cement set at 400 kg/m^3, equivalent to a P/A of 0.29.

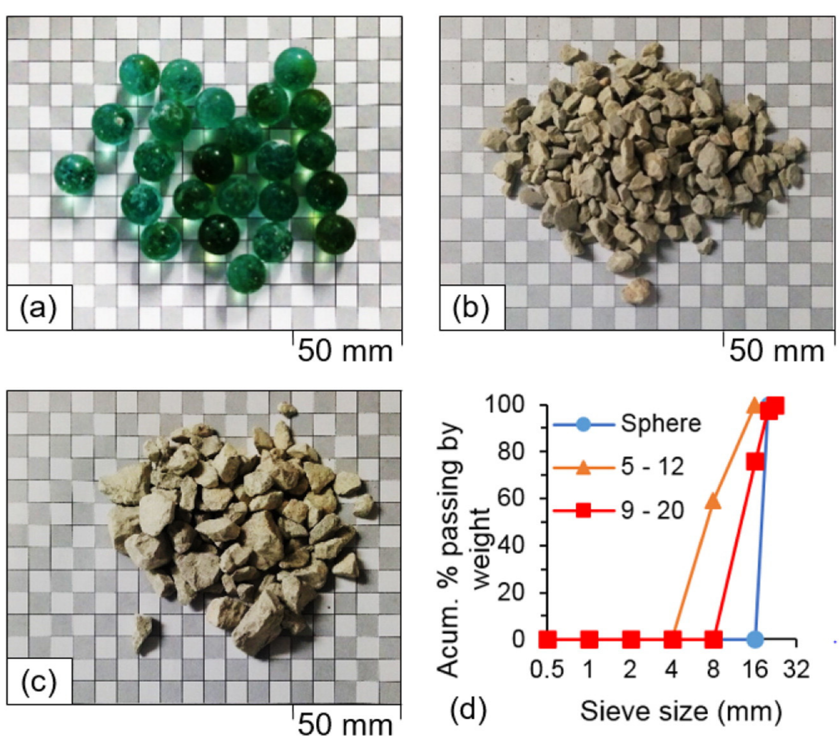

Fig. 1. Surficial aspect of spherical glasses (a), limestone from 5/12 (b), limestone 9/20 (c) and the grading curves (d).