Evolutionary lattice model for the compaction of pervious concrete in the fresh state

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HIGHLIGHTS

- Approach allows simplified representation of fresh pervious concrete under compaction.
- Evolutionary lattice model proposed to simulate the intensive particle rearrangement.
- A biphasic particle is developed to simulate rigid particles covered with flexible binder.
- The method shows reasonable results compared with numerical and experimental results.

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ABSTRACT

This paper presents a simplified model for the simulation of the compaction of deformable granular materials such as pervious concrete in the fresh state. The strategy is to use an evolutionary lattice system with local instability to simulate the intensive internal rearrangement expected during compaction. This is associated with a bar layout and material properties that vary with the time steps. Furthermore, a biphasic particle composed by a rigid inner core involved by a deformable exterior layer is considered. This versatile approach allows a simplified representation of complex granular media made of very deformable particles or of rigid particles covered by a flexible binder. Numerical and experimental comparisons were conducted to evaluate the capacity of the method to predict the behavior of different materials. The results indicate that the model may provide an estimation of the forces applied during the compaction, being suitable for a wide range of applications.

1. Introduction

Granular materials are widely employed in construction, ceramic, metallurgy, seeds and pharmaceutical industries. In some cases, they are composed by grains involved by a binder layer that will harden with time or temperature, providing cohesion to the system. An example of such materials is pervious concrete. This special type of concrete is obtained by eliminating part of the sand to create a system with enough voids to allow water flow.

In the non-hardened state, pervious concrete may be discretized as several independent aggregates particles involved by fresh cement paste [1]. During the production process, the fresh material is subjected to compaction pressure before hardening occurs in order to achieve a predefined density. The energy applied is of great relevance for engineering purposes since it determines the equipment required and the efficiency of the process. An approximated evaluation of this compaction process could contribute to the optimized definition of the equipment required, of the composition of the concrete or of the aggregates grading.

In line with that, an increasing interest on the simulation of the compaction process of granular media is observed in the literature. Generally, two types of computational methods are used to simulate this problem: the discrete-particle approach and the continuum approach. A well-known example of the former is the discrete or distinct element method (DEM) [2,3], where the interactions between particles are usually classified as rigid or soft depending on whether the particle deformation during a collision is explicitly incorporated in the model or not. Even though it has been successfully used for the simulation of granularly media [4–9], this approach usually presents a high computational cost. In addition to that, some simplifications and new implementations have to be assumed for the simulation of biphasic deformable particles in DEM.

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In the second approach, a finite element method (FEM) is used to simulate a continuous media whose behavior is described with the elastoplastic theory. This numerical solution was widely used to evaluate the compaction of powder metals and ceramics [10–13]. Although the computational cost is lower than with the DEM and deformations may be directly taken into account, the assessment of parameters such as the porosity or the particles position with the compaction pressure is not possible.

A recent alternative to simulate the compaction process more realistically is to integrate both methods [14–19]. In this case, the discrete element consideration from the DEM is combined with a continuum representation of particles and contacts, which is typical of the FEM. This combined simulation is more accurate than the previous ones and is considered promising since it accounts for aspects such as the deformation of particles and allows the estimation of the porosity. However, the high computational demand still limits its use.

A more simplified analysis may be performed with lattice models. Table 1 summarizes some of the most relevant studies conducted with this approach to simulate either the compaction process of different materials or the behavior of concrete. Notice that all studies focus on the simulation of materials in the hardened state, that is, no binder in the fresh state is considered in the analysis. Moreover, although several studies on the simulation of the compaction process of granular media or rock are available in the literature, to the authors' best knowledge no simulation of the compaction process of fresh concrete may be found.

In most of the studies regarding the compaction process, the materials simulated present an initial porosity of up to 20%, meaning that the level of rearrangement of particles is small and the same lattice layout may be maintained throughout the analysis. On the contrary, in the case of particles with a binder layer found in pervious concrete, the initial porosity may vary from 20% to 50% when it is poured in the molds. Consequently, the level of initial disorder and of rearrangement experienced during the compaction process is much higher than in the case of rock masses. This means that a lattice model with fixed distribution of bars might not be representative of the material in intermediate compaction stages due to the high level of internal reorganization, which is characterized by a significant increase in the number of contacts.

The *objective* of this study is to propose a simplified approach for the simulation of the compaction of highly deformable granular media such as pervious concrete in the fresh state. The strategy is to use an evolutionary lattice system with local instability to allow the intensive rearrangement expected during compaction, associated with a bar layout and material properties that vary with the load steps. Furthermore, a biphasic particle composed by a rigid inner core involved by a deformable exterior layer is considered. It allows a simplified representation of complex granular media made of very deformable particles or of a rigid inner core covered with a viscoelastic binder layer.

Initially the model proposed is described and its application is evaluated. Then, a numerical comparison using the results by other authors with DEM/FEM simulation is presented. Finally, an experimental program is conducted to evaluate the compaction process of pervious concrete. The results from the tests are compared with those numerically estimated with the new model. The good fit obtained supports the use of the model proposed here, which is capable of providing a simplified straightforward representation of the compaction process.

2. Work philosophy

The model to simulate the compaction of granular media was divided in two complementary stages. The sole purpose of the first stage is to create a particle distribution with the desired initial porosity. The algorithm applied organizes the particles in space, creating a system similar to that obtained by pluviation with Hertzian contacts in DEM with limitations of no particle movement and with the desired initial porosity (other distribution laws could be implemented depending on the type of material simulated). The distribution generated is the input for the second stage, which is the focus and main contribution of the present study. Based in an adapted lattice method, it simulates the reorganization of the particles after an imposed compaction displacement or vibration. As mentioned before, the algorithm generated is versatile and may be simply adapted to a wide range of applications. The program MATLAB 7.10.0 was chosen for the development since it is of common usage in the scientific community and includes a large math library that is capable of solving complex matricial problems. A detailed explanation of both stages is presented in the following sections.

Although the model described here was developed for 2D simulations of circular particles, it could also be generalized to 3D. For that, it would be necessary to modify the original algorithm, including an additional degree of freedom. Furthermore, the verifications performed in the lattice model would have to be adapted for a 3D condition. This would imply additional computation time but would lead to a model more representative of the particle distribution.

2.1. Stage 1 – random fall

The numerical approach used is based on a simple algorithm designed by Vold [31] for the packing of circular random particles. This approach was modified by several authors [32–34] that implemented new types of contact between particles. Here, the algorithm was further modified to represent the packing of circular particles that might be involved by a binder with special characteristics, considering several simplifications that would allow reaching an initial porosity typical of pervious concrete. The interaction between particles is based in the Hertzian contact

Table 1
Studies with lattice model to simulate compaction of different materials or the behavior of concrete.

Study	Material	State	Phases	Type of analysis	Dimensions	Load
[20]	Granular media	Hardened	Particle/void	Compaction	1D	Tapping
[21]	Granular media	Hardened	Particle/void	Compaction	2D	Tapping
[22]	Granular media	Hardened	Particle/void	Compaction	2D	Tapping
[23]	Rock	Hardened	Continuum	Compaction	2D	Compression
[24]	Rock	Hardened	Continuum/void	Compaction	2D	Compression
[25]	Concrete	Hardened	Continuum	Fracture	2D	Tension and compression
[26]	Concrete	Hardened	Aggregate/mortar/void	Fracture	2D	Tension and compression
[27]	Concrete	Hardened	Aggregate/mortar	Fracture	2D	Tension and compression
[28]	Concrete	Hardened	Aggregate/mortar/rebar/fiber	Fracture	2D	Tension and compression
[29]	Concrete	Hardened	Aggregate/mortar/ITZ	Fracture	2D/3D	Tension
[30]	Concrete	Hardened	Aggregate/mortar	Fracture	3D	Compression