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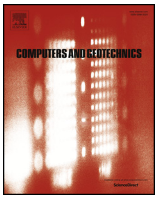

Research Paper

An experimental and numerical study on the compressive behavior of sand-rubber particle mixtures

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ABSTRACT

This paper discusses the behavior of sand-rubber particle mixtures under one-dimensional compression tests. First, experimental results on ideally prepared sand-rubber particle mixtures with different rubber contents are discussed. Then, novel simulations using the Discrete Element Method are presented. The grain-scale deformability of the rubber particles is considered using a bonded particle model. The model is calibrated based on the experimental results of pure sand and pure rubber and it is further validated for all intermediate rubber contents. The numerical model is able to accurately predict the compressive behavior of the mixtures as well as the residual strain.

1. Introduction

Huge number of scrap tires in recent decades and the environmental problems evoked due to their dumping, have led to the investigation of various options for their recycle and reuse. Nowadays, dumping is an unacceptable choice from economic and environmental perspective and hence, recycling of scrap tires for civil work purposes is an interesting option. They could be used as whole tires or pieces of cut tires called tire derived aggregate (TDA). Whole tires are generally used to construct retaining walls, drainage culvert and erosion protection [1], whereas TDAs have a large variety of applications, from being used on playgrounds and playing fields to being used as a filling material in geotechnical projects.

Depending on the size, a terminology is presented for different types of TDA [2]: tire shreds for aggregates larger than 50 mm, tire chips for aggregate in the range of 12–50 mm and tire crumb for TDAs smaller than 12 mm. TDAs with suitable engineering properties have become an option in small scale and large scale construction projects. Low specific weight, high damping, high permeability, and proper shear strength are features that make TDA suitable for engineering applications. They can be used as filtration material in landfills or filling materials in embankments. However, high compressibility is the main concern about TDA whenever settlement is important. To mitigate this, soil is added to TDA to increase its stiffness. This addition also decreases the risk of fire in the TDA mass.

Sand-rubber mixtures (SRM) might have preferred engineering properties over pure TDA while avoiding high compressibility. SRM was widely studied after 1990 and various experimental investigations were performed to understand the importance of each parameter on its shearing and compressibility behavior. TDA size, TDA shape, TDA content in mixture, and compaction energy are some of the investigated parameters. Based on these investigations, nowadays, SRM is suggested as filtration material in landfills or small-scale urban projects, backfill of retaining walls and highway embankments.

Compressibility (or settlement) of a sample made by TDA due to loading became a concern after 1993 and some early investigations included compressing TDAs in a large cylinder [3,4]. Humphrey et al. [3] investigated TDA by conducting direct shear, compression and permeability tests. A large diameter cylinder was equipped with vertical and horizontal strain gauges to obtain vertical stress, horizontal stress, and sidewall friction. They also suggested values of lateral pressure, Poisson's ratio, Young's modulus and constrained modulus. They concluded that TDA size practically has no effect on the compressibility behavior. However, with larger particles, a small increase in compressibility was observed.

A comprehensive experimental study on TDA was conducted by Ahmed et al. [4]. Samples were different in size. The test plan included triaxial test, direct shear test, compression test, physical properties test and compaction test. Based on their compression tests, they observed that TDA size and compaction energy had little effect on compression response. Similar to Humphrey et al. [3], they found three characteristics contributing to the compressive behavior of TDA. The first one is

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irreversible compression due to rearrangement and sliding of TDA in the initiation of loading which has a small effect. The second characteristic is the reversible compression due to bending and flattening of the tire chips. This was assumed to be responsible for the major portion of the total compression. The third one is the compression due to elastic behavior of the tire chips which is a small portion of the total compression. It is important to note that rubber is generally considered as incompressible. Hence, in theory, the last characteristics does not contribute in sample compression.

During the last two decades, SRM has been investigated more precisely as an option for geotechnical works. Important aspects including shear strength [5–9], initial stiffness [9–11], compaction procedure [4], gradation [12,13], and tire grain shapes [6,4,14–16] were investigated in great detail. An important concern was environmental issues such as the pollution of underground water and the increase in the internal temperature. Based on recent research [17,18], it can be concluded that the SRM or even embankments made by pure TDA have no negative effect on the environment. ASTM D6270 [1] states that TDA has no inferior effect on water quality, however, the standard warns about the risk of heating reaction in TDA fill with a thickness in excess of 7 meters.

Among many investigations conducted on pure tire and sand-tire mixtures only a few are related to numerical simulations. Lee et al. [2] modeled pure tire as a backfill of a retaining wall using the Finite Element Method (FEM) and compared the results with field data. A hyperbolic model was adopted to simulate rubbery backfill with the FEM. Simulation results overestimated the horizontal pressure behind the retaining wall, especially at the bottom where computed horizontal pressures were twice the measured field data. The authors believed that grain interlocking and large deformations are the main reasons for the incompatibility of field and simulation results.

To the best of the authors' knowledge, Valdes et al. [19] were the first who employed the Discrete Element Method (DEM) to model pure tire and sand-tire mixture. The commercial package PFC2D was used to perform the simulations. They modeled each rubber particle as a circular disc with varying shear modulus and friction coefficient depending on contact overlap. The model was able to represent the loading-unloading hysteresis but missed the residual strain. The authors attributed this to sidewall friction which could not be captured properly in a two-dimensional (2D) model.

Another DEM investigation on SRM has been recently reported by Lopera Perez et al. [20] where samples with different tire contents were confined isotopically and sheared. The three-dimensional (3D) simulations were performed using spherical particles and the Hertzian contact model. In the case of contact between two different materials, the average stiffness was used to compute the contact forces. The pure tire and pure sand samples were calibrated using data found in the literature. The same authors also studied the liquefaction potential and critical state of SRM at large strains [21,22]. Their results qualitatively agreed with previous experimental results found in the literature but a rigorous quantitative comparison for different mixtures is missing.

Lee et al. [23] conducted a 2D study on one-dimensional (1D) compression of SRM. Disks were used to represent the sand and rubber particles. Although they reported an experimental 1D compression tests on SRM, there is no comparison of model predictions with experiments. However, the general trend of the numerical predictions agreed with the experiments. Their model could not capture the residual strain. A discussion on the lateral pressure coefficient was presented.

It seems that the modeling of SRM requires some special considerations since the literature review of experiments shows a unique behavior. The pure tire crumb sample exhibits an almost linear stress-strain behavior with no peak or asymptote and decreasing volume-strain behavior in a monotonic triaxial test. Generally, addition of rubber to sand changes the dilative behavior to compressive behavior. In the field, when pure rubber mixtures would be used as a backfill of a retaining wall, the backfill would easily stand up vertical after removal of the wall. In numerical studies, it is important to realistically model the key feature of rubber particles to obtain reasonable results.

Although the shape of rubber grains is undetermined, it seems that the deformability plays a vital role. Rubber grains deform under compressive force. This leads to larger contact surfaces between grains and hence a larger frictional strength against sliding. On the other hand, the unknown shape of a rubber grain causes the formation of more contacts between rubber grain and the adjacent grains. Hence, deformability and shape can result into significant interlocking.

This paper presents an experimental and numerical study conducted on ideal sand-rubber particle mixtures. The DEM is used to consider grain-scale features of the mixture and to observe its micromechanical behavior. The deformability of the rubber particles is considered directly in the model. Given that the DEM needs micro parameters of grains, such as grain size, grain shape, inter-particle contact parameters etc., for the first time, a systematic experimental test procedure is proposed. Section 2 presents the experimental setup and the results of the 1D compression tests using well-defined sand and rubber grains. Section 3 describes the details of the numerical simulations including the representation of the grains, the contact laws used and the procedure to generate the samples. For the first time, a deformable approach is used to model rubber particles in a 1D compression test. Each rubber grain includes several bonded spheres that can move relatively to each other. Hence, shape effect and deformability are considered. The section also includes subsections on calibration and validation where the numerical predictions are compared to the experimental results. A discussion on lateral pressure coefficient, sidewall friction and coordination number is presented in Section 4 and conclusions are summarized in Section 5.

2. Experimental tests

The experimental behavior of SRM under 1D compression has been investigated widely. However, numerical simulations by the DEM require details of grain shapes and morphology. Therefore, a systematic experimental program was included in this study as a reference to calibrate and validate the simulations.

2.1. Materials

Since compatibility between experiments and simulations is a major objective of this study, it was decided to use ideal grains with similar shape and size. In fact, the average diameter of the sand and rubber grains is the same. The rubber grains were prepared manually in order to limit the variability in shape and size. Cubic rubber particles were obtained by cutting rubber sheets of 4 mm thickness. This is a simplification as TDA is generally quite irregular. However, in this form, the random shape effect is reduced. The sand grains were selected from Firoozkooh sand. Sharp-edged grains and non-silicate grains were removed to obtain a well-defined round-edged sand material. The average diameter of the sand grains was 4 mm with a very low dispersity since only grains between sieve number 4 (4.75 mm) and 6 (3.35 mm) were used. Fig. 1 shows the materials used in this study.

2.2. Setup and procedure

The compression cell was a 100 mm diameter steel cylinder with a height of 100 mm, which is a bit larger than a standard oedometric cell. For a constant loading rate, a triaxial setup was used where the triaxial cell was replaced by a compression cylinder. During loading, the underlying jack rises up the pedestal and the cylinder whereas the top cap is fixed with a rod connected to the load cell to measure the applied load on the sample. The vertical displacement of the cap is recorded by a 50 mm range LVDT. A data acquisition system saves the vertical displacement and force every 0.4 s. The setup is shown in Fig. 2.

Sample preparation follows a simple procedure including mixing the