Micromechanical Modeling Of Aggregate-Aggregate Interactions With Distinct Particle Element Method For Virtual Laboratory Simulation

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ABSTRACT: Road pavement performances are still not fully understood because it has been necessary to simplify its materials behavior, modeling them as continuous. In reality, however, they exhibit discontinuous performances, which do not always fit for the advanced continuum models based on non-linear behavior very well.
To overcome this limitation, the Distinct Particle Elements Method (DEM), which schematizes a granular material by particles that displace independently from one another and interact only at contact points, becomes a good answer. In this way, in fact, is possible to analyze the discrete character of mixes through a microscopic approach.
The author in a previous study have confirmed the DEM potentialities in the investigation of the fatigue performances of asphalt mixes and have observed the great influence of particles geometry on the materials response. So, in this paper, in order to deepen the effects of aggregate shape and dimensions on the fatigue behavior of a road pavement, several triaxial laboratory compression tests on specimens of steel particles have been simulated and the numerical results have been compared with the lab ones.

KEYWORDS: Distinct Particle Element Method, road pavement, bituminous materials, triaxial test, steel balls

1 INTRODUCTION

The traditional approach to modeling asphaltic materials is to treat them at the macro-scale using continuum-based models. Numerous research works, however, show that for these types of mixtures is very important to take into consideration theirs micromechanical behavior, at the scale of an aggregate particle, because it is an essential factor in terms of overall system performance (Collop et al. 2004). In this way the Distinct Particle Element Method (DEM) represents a very useful tool (Cundall and Strack. 1979).

Although the DEM has been applied to represent the behavior of soils and granular materials, it has not been widely used to investigate the mechanical behavior of asphaltic ones. Limited studies have been undertaken, although they have been restricted to modeling two dimensional systems and small specimens (Collop et al. 2004).

To overcome these limitations, the authors have developed a simple 3D model that permitted a visualization of the load carrying behaviour of a flexible pavement at microscopic level (Dondi et al. 2005, 2007, 2008). The obtained results have permitted to evaluate that DEM approach, allowing a very reliable description of real phenomena, represents a valid evolution of the traditional methods, especially in the investigation of the fatigue performances of asphalt mixes. It permits, in fact, to identify both the number of load-cycles causing fatigue, in the same way of the traditional approaches, and especially the localization of cracks formation points. The introduction of parameters as aggregates shape and geometry, in particular, has allowed to deepen the fatigue behavior of a flexible pavement, detecting new starting points of cracks. So is very important to take into consideration the particles geometry, because it greatly influences the materials response.

In order to analyze its influence, in this paper several triaxial laboratory compression tests on specimens of steel particles have been simulated and the numerical results have been compared with the lab ones. The experimental study, in particular, has been divided in two step:

- the first one, characterized by samples of steel spheres with specified distribution of ball diameters, aimed to estimate preliminarily the system micro-scale parameters. In this way, in fact, the specimen geometry can be captured accurately in the numerical simulation, so that a one-to-one mapping can be achieved between the particles in the physical sample and the ones in numerical model;
- the second one, carachterized by samples of steel clumps, aimed to analyze the impact of grains arrangement and geometry on the fatigue behavior of a granular assembly. Clump, in particular, are modeled by groups of spheres that are physically bonded together, that behave as a single rigid body (Cho et al. 2007).

An extensive search has been undertaken to identify suitable test type and balls material. Following the findings presented in Cui et al. (2007), the most satisfactory option for the first problem is the triaxial laboratory compression test because:

- it is a very useful standard test for determining the stress-strain behavior and strength parameters of unbound materials under drained and undrained conditions;
- being one of the most commonly test used in both research and practice, is possible to appreciate fully the details of material response in this apparatus;
- since a great number of DEM simulation of this test have been performed by earlier researchers, is possible to accurately replicate the physical boundary conditions.

For the second problem, instead, following the findings presented in O'Sullivan et al. (2003, 2004), it is required that:

- the ball geometry (i.e. the diameter and the roundness) be tightly controlled;
- the particles surface be uniform and subject to a quantifiable tolerance in quality control;
- the balls be available in a range of diameters, to allow experimental investigation of the specimen response to small changes in particle size distribution.

So the most satisfactory option is to use 420C stainless steel balls, characterized by a density of 7800 kg/m^3 and a manufacturing tolerance on both diameter and roundness according to ISO 3290:2001.

In order to simulate a triaxial test using the DEM approach, it has been necessary to generate first a specimen that replicates the laboratory mixture and second a suitable test equipment.

2 TRIAXIAL TESTS SIMULATION

2.1 Introduction

In a triaxial test a cylindrical specimen is encased within a rubber sleeve inside a pressure chamber. The lower and the upper loading platens have porous disks connected to the drainage system. The confining pressure is applied by adjusting the camber pressure and the axial stress is applied by pushing the piston. During consolidated and drained (CD) test, in particular, the sample is first consolidated to an initial effective stress state and then the drainage is opened and the interstitial water filling the material voids can drain freely. The axial loading is applied very slowly so that the excess pore pressure has time to dissipate through the drainage system (Bardet. 1997).

The principal features of the test equipment are (Bardet. 1997):

- triaxial cell, composed of the base, which forms the pedestal on which the sample rests and incorporates the various pressure connections, of the removal cylinder and of a top cap, which encloses the sample and enables fluid pressure to be applied, and of the loading ram, which applies the deviator stress to the sample;
- apparatus for controlling the cell pressure and measuring the pore pressure;
- loading system.

2.2 Particles generation

The models parameters have been determined by comparing experimental triaxial results with the numerical ones.

The particles generation procedures has been defined in according with the lab one as shown in figure 1. The membrane with two O-rings has been placed on the bottom platen and the split mold has been assembled with particular attention to folding the sleeve on its top rim. The air between the membrane and its stretcher has been evacuated using a vacuum pump and a cylinder of filter paper has been introduced inside the framework. Its function is to confine the sample during its preparation avoiding the collapse, unavoidable because of its weight, without provide to it strength resistance during the test. Then the steel balls have been placed inside the cylinder and the desired density has been achieved by vibrating the specimen. After having filled the forming jacket with particles, the specimen cap has been placed on top of specimen and the membrane has been rolled over its upper cap and it has been fastened with O-rings. The connector to the vacuum line has been attached to the mold and, once the vacuum has been applied internally to the sample, the split mold has been removed and the triaxial chamber has been assembled.

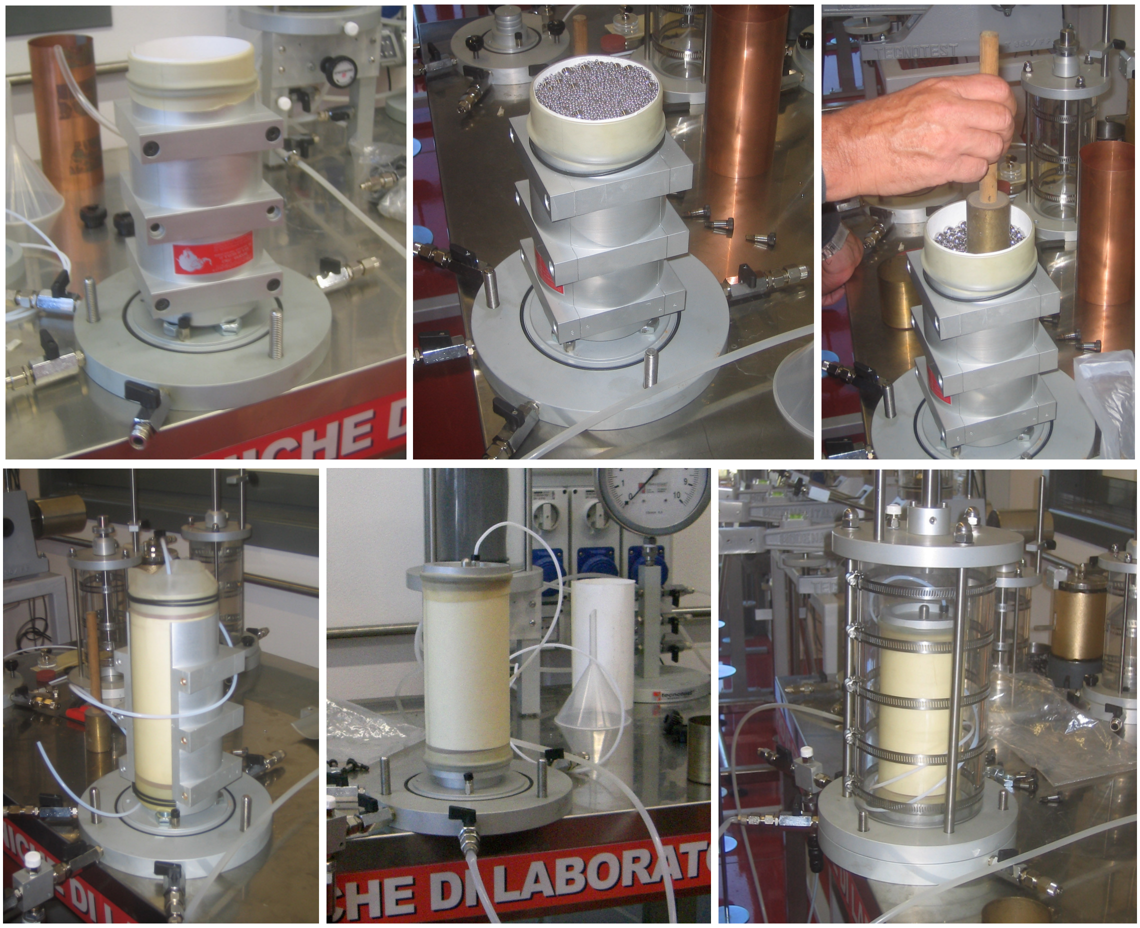

Figure 1: Laboratory samples preparation procedure

In according with the granulometric curve of the lab mixture (figure 2), following the findings presented in Cui et al. (2007) and Salot et al. (2009), the specimens, 0.1 m large and 0.2 m height, have been created using dry pluviation, consisting in positioning the elements by gravitational deposition which tends to generate anisotropic assemblies. In this way they are composed of 32886 particles as shown in table 1 (figure 3).

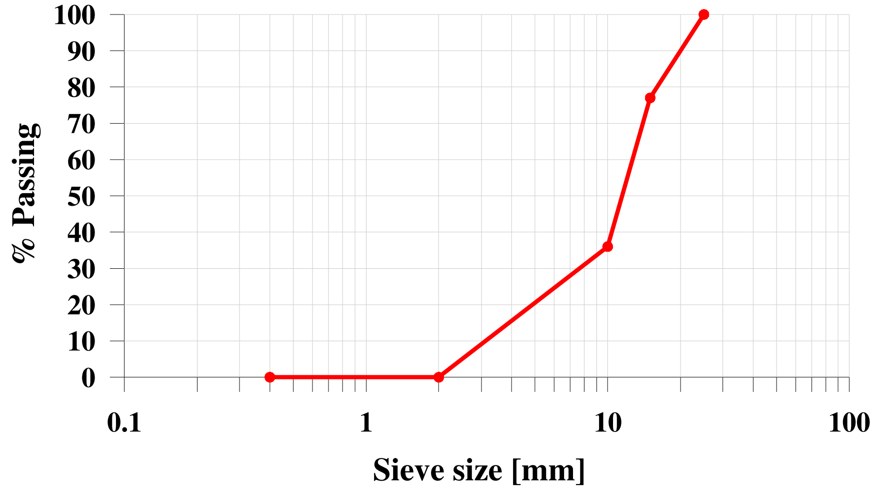

Figure 2: Granulometric curve of the lab mix

Table 1: Granulometric composition of the lab mixture

Diameter [mm]	Number of spheres
2.77	32204
11	605
18	77

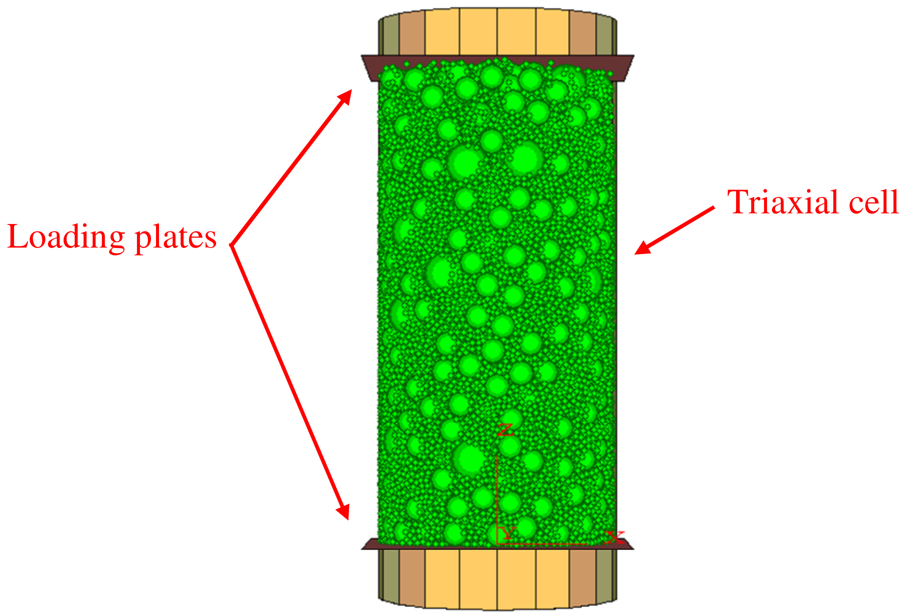

Figure 3: DEM model for triaxial test

2.3 Contact models definition

Since the steel balls are an unbound material, bond models have not been introduced. The system behavior has been defined only by:

- a contact-stiffness model, that provides a relation between the normal (F_n) and shear (F_s) components of contact forces and the relative displacements (U_n, U_s) by the contact stiffness (k_n, k_s):

$$F_n = k_n \cdot U_n, \quad F_s = -k_s \cdot U_s \qquad (1)$$

- a slip and separation model: the slip condition occurs when the shear component of force (F^i_s) reaches and exceeds the maximum allowable shear contact force (F_s^{max}). This value is taken to be the minimum friction coefficient of the two entities in contact (μ) multiplied by the magnitude of the compressive normal component of force (F^i_n):

$$F_s^i \geq F_s^{max} = \mu \cdot \left|F_n^i\right| \qquad (2)$$

In this case, in particular, the stiffness has been evaluated following the findings presented in Cui et al. (2007), the interparticle friction coefficient (μ) has been estimated from the friction angle of the aggregates of the laboratory mixture ($\phi = 23°$) and the particle-boundary friction coefficient, assumed to be zero, follows the findings presented in Cui et al. (2007) and Frost et al. (2003) (table 2).

Table 2: Contact models features of the DEM specimens

Normal stiffness (k_n) [N/m]	10^8
Shear stiffness (k_s) [N/m]	10^8
Wall stiffness (k_w) [N/m]	10^8
Interparticle friction coefficient (μ)	0.43
Particle-boundary friction coefficient	0

2.4 Laboratory equipment modelling

The triaxial cell has been modeled by a cylindrical element, closed at the top and the bottom end by walls which simulate the loading plates (figure 3). The samples are subjected to CD tests and are loaded in a strain-control method by specifying the velocities of the top and bottom walls (1 mm/min). During all stages of the test, the velocity of the cylindrical wall is controlled automatically by a function that maintains a constant confining stress within the specimen (Itasca. 2002). For each test the following variables have been monitored:

- the contact forces inside the sample, that develop at contact point when two balls or a ball and a wall overlap;
- the mean confining stress (σ_c);
- the axial stress (σ_a);
- the axial deviatoric stress ($\sigma_d = \sigma_a - \sigma_c$);
- the axial strain (ε_a);
- the volumetric strain (ε_v).

The axial and the deviatoric stresses, in particular, are computed by taking average wall forces divided by appropriate areas. The strains in the radial and axial directions, instead, are determined on the base of the initial volume and height of the specimen.

2.5 Modelling results

Several tests have been carried out under different confining stresses (σ_c) (table 3) and the numerical results have been compared with the lab ones.

Table 3: laboratory triaxial tests

Number of the test	Mean confining stress (σ_c) [kPa]
1	300
2	400
3	500

For each test have been monitored:

- the maximum contact force inside the sample;
- the variation of deviatoric stress ($\sigma_d = \sigma_a - \sigma_c$) versus axial strain ($\varepsilon_a$);
- the variation of volumetric strain (ε_v) versus axial strain (ε_a).

The contact forces, in particular, increase to growth of confining stress and the normal component is always greater than the tangential one (table 4).

Table 4: Contact force inside the specimen at the end of numerical triaxial tests

Number of the test	Normal contact force [N]	Tangential contact force [N]
1	7.400	0.860
2	8.600	1.110
3	11.600	1.400

In terms of variation of deviatoric stress versus axial strain, there is a good agreement between numerical results and experimental ones (figure 4). All tests, independently of confining stress value, show the same trend: an initial linear stress-strain relationship, which becomes nonlinear at higher strains before the peak load is achieved. It is possible, in particular, to divide it in three stages:

- one initial, during which strains are very small;
- one at and near the peak, which starts when the specimen begins to yield and which includes the peak of the curve and the gradual decrease of resistance post the peak;
- one final, the ultimate condition, during which the resistance is constant with further straining.

Both compressive strength and shear strength, moreover, increase to growth of confining stress.

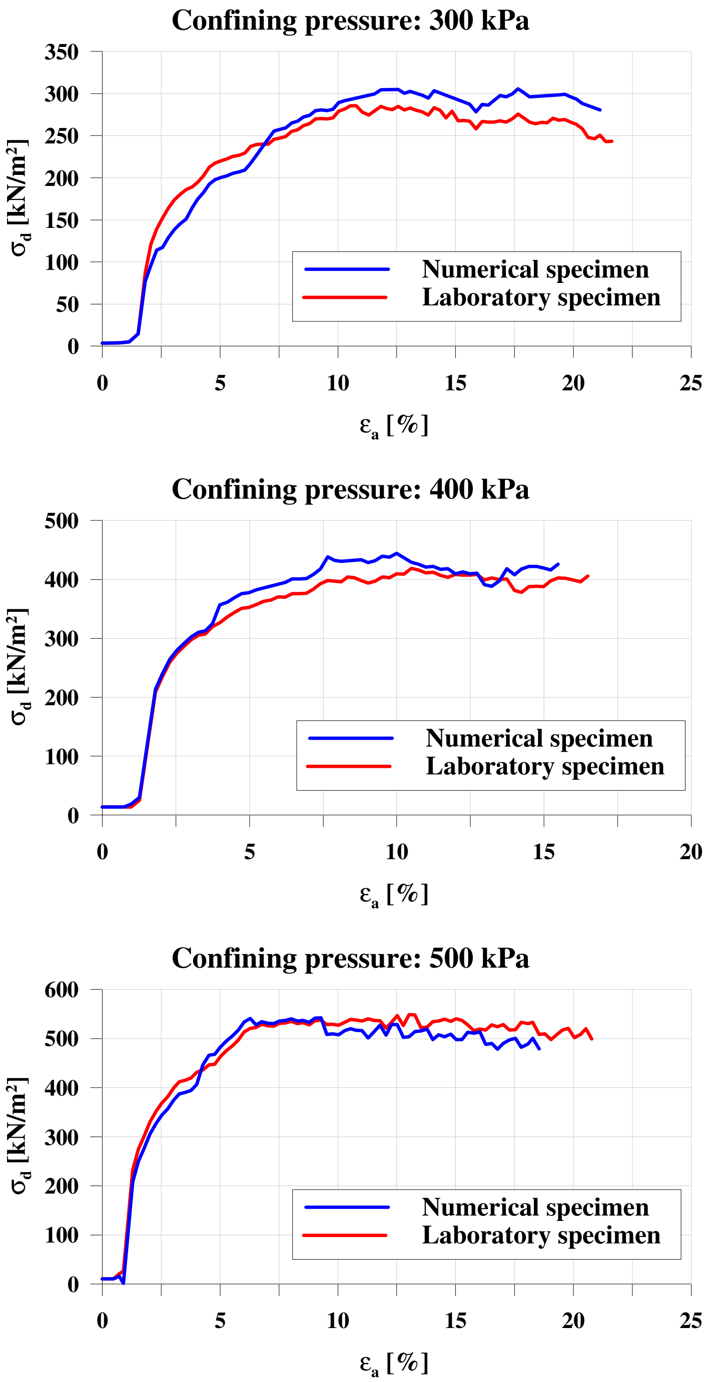

Figure 4: Variation of deviatoric stress (σ_d) versus axial strain (ε_a) under different confining stresses (σ_c)

Also in terms of variation of volumetric strain versus axial strain, there is a good agreement between numerical results and experimental ones (figure 5). All tests, independently of confining stress value, show the same trend:

- an initial range, in which the volume of specimens decrease slightly because, when the compressive stresses are increasing, the particles are being pushed into a denser arrangement;
- one at and near the peak, in which the spheres, because of vertical compression, shift laterally and this motion is accompanied by an increase in the volume of the sample;
- the ultimate condition, in which the interlocking between the particles has decreased to the point where shear deformation can continue without further volume change.

So the numerical models and the lab ones show a dilatant behavior.

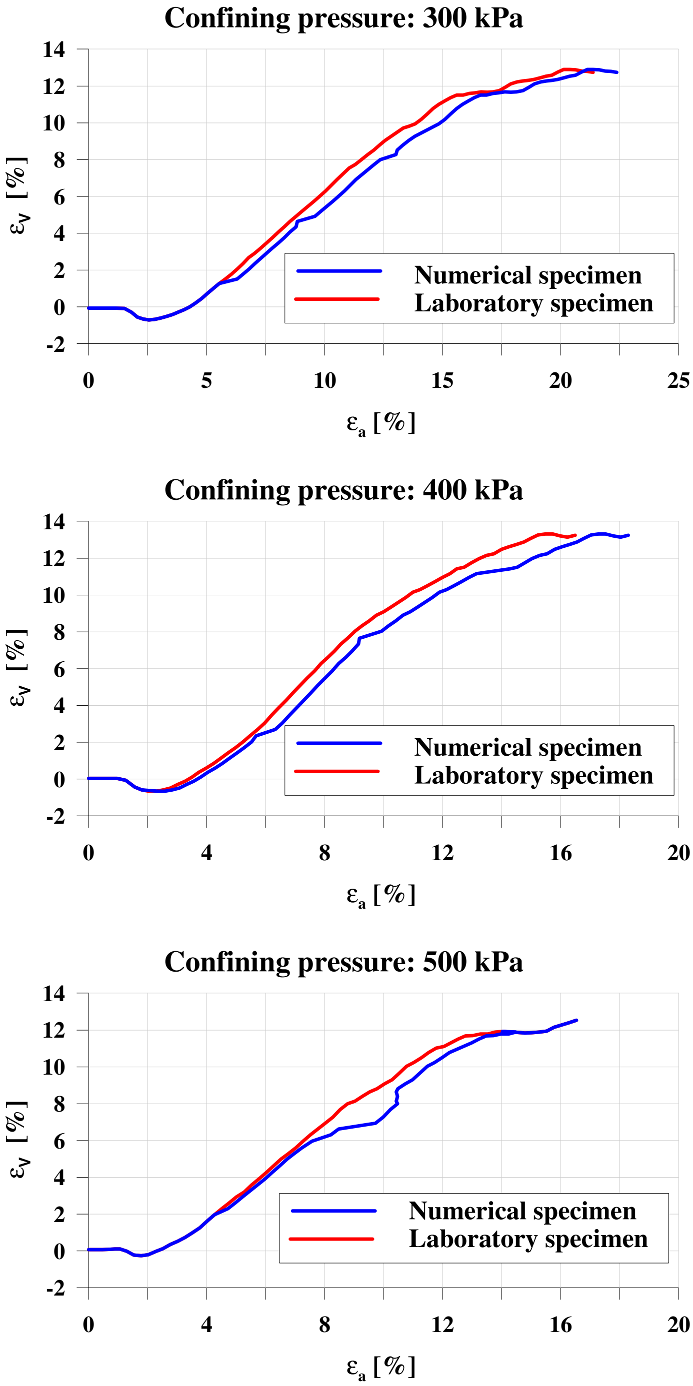

Figure 5: Variation of volumetric strain (ε_v) versus axial strain (ε_a) under different confining stresses (σ_c)

For the obtained results Mohr circles have been plotted and a linear failure enveloped constructed (figure 6, table 5). From it, the material properties of cohesion and angle of friction can be determined as the intercept and the slope of the failure envelope respectively (Tan et al. 2007).

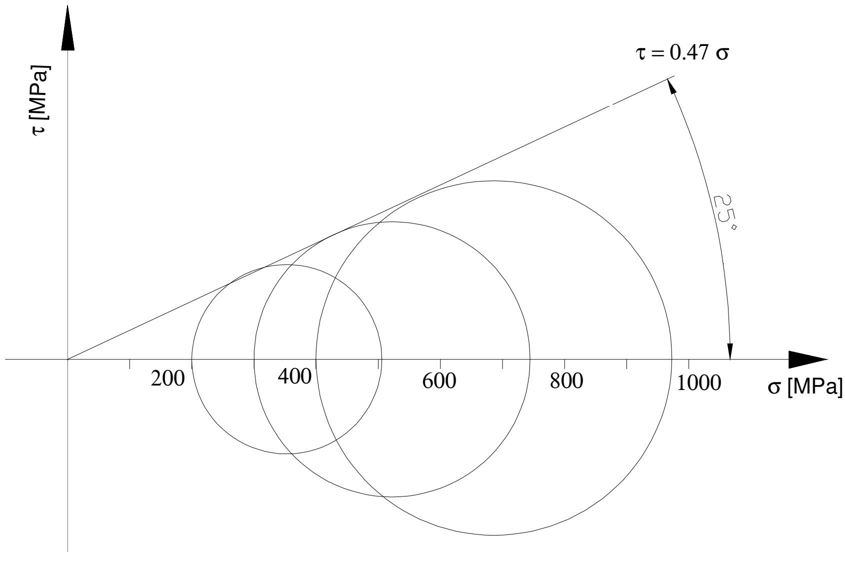

Figure 6: Mohr circles from triaxial tests of numerical specimens

Table 5: comparison between numerical tests and lab ones

	c [kPa]	ϕ [°]
Numerical specimens	0	25 ($tg\phi_1 = 0.47$)
Lab specimens	0	23 ($\mu = 0.43$)

The numerical specimens derive theirs resistance entirely from the angle of friction (equal to 25°) ($tg\phi_1 = 0.47$), which is the same as the interparticle friction coefficient ($\mu = 0.43$).

3 CONCLUSIONS

Based upon the developed research work, in which the 3D DEM approach has been used to analyze the effects of grains arrangement and geometry on the fatigue behavior of a road pavement, the following concluding remark can be stated: the DEM method, knowing the relationships between the macroscopic and the microscopic mechanical behavior, is able to reproduce the main features of a triaxial test, both in qualitative and quantitative manner. More information about the micromechanics of real road aggregates can be achieved by incorporating more realistic particles geometries in the model. The granular assembly formed of spheres used in this research step, in fact, has been selected to have a simple grain shape to describe mathematically for comparison with results from DEM simulations, in order to estimate preliminarily the system micro-scale parameters, but it differs very much from real road aggregates. So this is a first step toward more advanced simulations to model materials response using DEM approach. The second one, in fact, will be characterize by triaxial test on samples of steel clumps of spheres (figure 7), in order to introduce the great influence of particles geometry on the materials response.

Figure 8: Steel clumps of spheres used in the second research step

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