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MODELLING DAMAGE TO ASPHALT CONCRETE SURFACE: THEORY AND NUMERICAL APPLICATIONS

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ABSTRACT

This paper presents a micro-scale model to investigate the damage to a surface in asphalt concrete under an impulsive load. Our aim is to reproduce the micro-damage due to detachment among the elementary components of the asphalt concrete in airports pavements. The general framework for models to describe adhesive contact between rigid bodies is developed supposing the intensity of adhesion decreasing under tangential and normal displacement fields. Finally, a numerical implementation has been performed by FEM approach and the results are illustrated in the paper.

Keywords: micromechanics, asphalt mixture, damage, FEM, RVE.

1. INTRODUCTION

The behavior of a heterogeneous solid, as asphalt concrete, appears very complex, as the interaction between rigid bodies (inert) and the bitumen matrix recall models of difficult solution.

In previous papers, the authors investigated the response in terms of stress field of complex granular solids subject to different superficial actions. In Buonsanti, et al. [1]by formulating an appropriate representative volume element (RVE) the micro-damageability has been investigated assuming the adhesion descendant under the action of displacement fields. In [2] a finite elements analysis was performed to compare the simulations results with experimental data and theoretical solutions. In [3, 4] the problems of flexible pavement response under the action of dynamic loads was investigated. Further developments of these basic papers concerned the response modelling of airport flexible pavement subject to actions of touchdown and braking [5, 6].

In this paper, we want to investigate the integrity of the asphalt concrete from the point of view of the adhesion between aggregates and asphalt matrix. To this aim, several numerical models have been developed in order to simulate besides the normal touchdown also the effect of temperature. The temperature influences the bitumen viscosity coefficient and the adhesion resistances.

2. MATERIALS AND METHODS

The heterogeneous consistency of many materials, including the granular kind, led the interest of researchers to study new behavioral patterns based on the hypothesis of the microstructure as element that influences the macroscopic response of the material [7-10].

An important method for numerical modeling of multiphase granular materials can be found in Cundall and Strack [11], which allows finite displacements and rotations of discrete bodies (grains), gaps and new contacts. It is the starting point used in the proposed model in which a cluster of grains is assembled within a bituminous mixture, under the assumption of grains almost rigid (high rigidity) and viscoelastic response of the mixture.

Finally yet importantly, the "doublet mechanics" of Ferrari [12] represents the response of heterogeneous solid bodies in discrete form as ordered set of interacting particles through given reports of micromechanics.

When the granular medium has no voids or water but viscous fluids (as in the case study) then we have to approach the case with greater rigor. In the case of the asphalt mixture, the asphalt fills the voids between the grains, in these conditions the solid becomes a material poly-phase, and its behavior depends on the asphalt–aggregate interface (Hicher, 1998).

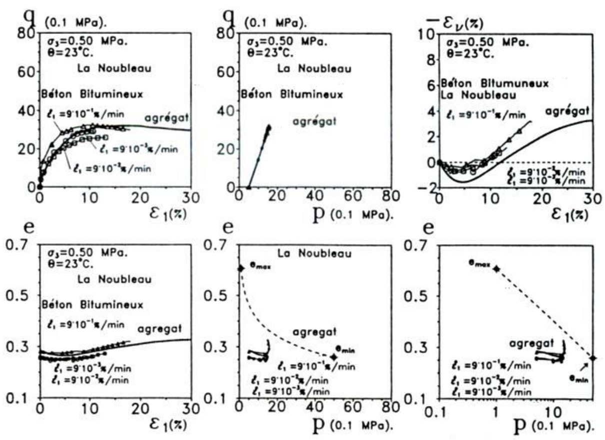

Figure-1. Influence of strain rate on unsaturated bitumen mixture at 23°C (Bard, 1993).

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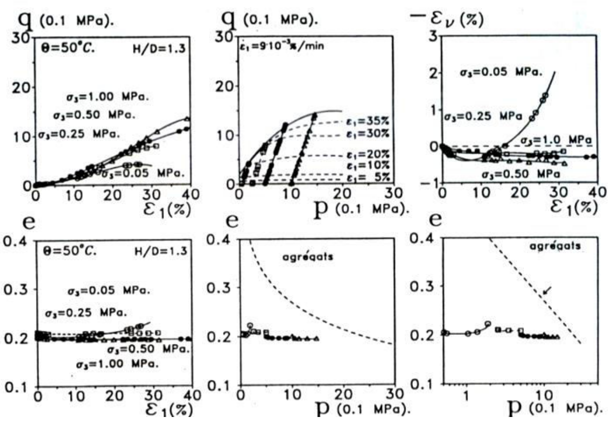

Figure-2. Influence of strain rate on unsaturated bitumen mixture at 23°C (Bard, 1993).

In the study of the mechanical behavior of granular materials, it is appropriate to consider the micro - scale level of the individual grain and assume the continuous medium as a set of beads, with suitable boundary conditions.

The physics of the proposed modeling includes grains of irregular shape immersed in the asphalt without any presence of vacuum and/or water.

The contact between the elements is unilateral under traction, therefore not compelling interpenetration between bodies but a separation between the elements.

When a material is characterized by its microstructure, the problem of homogenization remains, which must be performed in order to sort a set that is substantially "constituted randomly". To this aim, on the basis of the "ergodic principle", it is possible to define the concept of RVE, "representative volume element" [13]. The RVE is usually regarded as a volume of heterogeneous material large enough to be statistically representative of the material, also containing all the heterogeneous microstructures that are present in the solid. For example, the stress field in a medium RVE can be placed in the form:

$$< T > x = 1/V \int_v T\left(x, X\right) dV_x \tag{1}$$

where F (x, X) is a tensor field defined in each RVE, x is the position vector for a point within a material RVE, while X denotes the position of an RVE within the macro-scale.

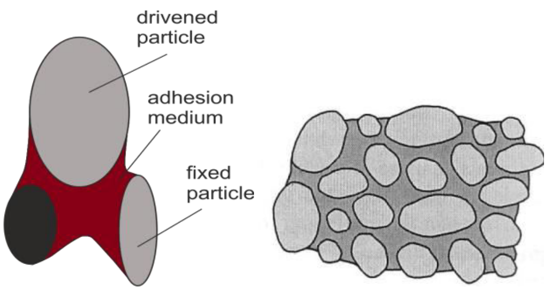

Figure-3. A plane RVE representation.

If the material is homogeneous to the macro-scale, we have:

$$< T > = \frac{1}{V} \int_v T(x) dV_x \tag{2}$$

If $T = \sigma(x)$ is a field of micro-stress, the macro-stress of a set of material points is denoted by $<\sigma>$, as emphasis to the average size of the domain. We want to investigate the theoretical aspect concerning the response on a RVE where some quasi-rigid elements are distributed randomly in the elastic asphalt matrix. The implemented numerical model has a spatial character but the elementary basic considerations can also be developed according to a plane RVE as shown in the previous Figure-3.

On this model, the doublet mechanics approach is implemented which, in the case of a similar Flamant problem (Figure-4), leads to the following solutions in terms of micro-stress:

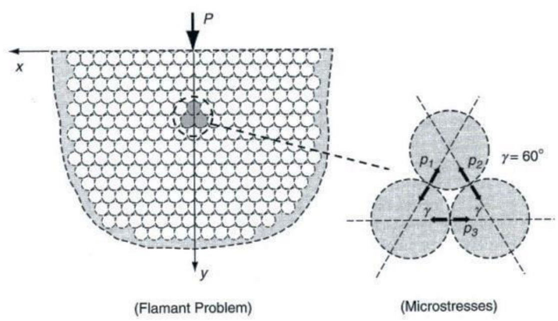

Figure-4. Flamant problem for the Doublet Mechanics model [13].

$$t_1 = -\frac{4Py^2\left(\sqrt{3}x + y\right)}{3\pi\left(x^2 + y^2\right)^2} \tag{3}$$

$$t_2 = \frac{4Py^2\left(\sqrt{3}x + y\right)}{3\pi\left(x^2 + y^2\right)^2} \tag{4}$$

$$t_3 = \frac{2Py^2\left(3x^2 - y^2\right)}{3\pi\left(x^2 + y^2\right)^2} \tag{5}$$

Here we want to consider two or more granular particles glued together with asphalt mastic and we consider the granular particles embedded at the bottom of the RVE. The upper particles can easier detach in the direction of the external force. Physically speaking, the phenomenon of damage fracture starts through a first peeling followed by a superficial separation and after by the break of the adhesive bond between the aggregate surface and the asphalt cement. Therefore, we have a problem of dynamic contact with adhesion [14]. Following Figure-4, assumed constant the tension in the strip of adhesion, in accordance with Frémond [15]the following equation of motion is found:

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$$\rho u_{tt} - \sigma u_{xx} = 2F\delta(x) \tag{5}$$

where ρ is the density of the medium, $\delta(x)$ denotes the delta function, F denotes the external force, $u = u(x, t)$ denotes the linearized displacement field.

In the case of a thin membrane Eq. 5, defined over the whole domain of detachment with the boundary condition $u = 0$, takes the form:

$$\rho u_{tt} - \sigma \nabla^2 u = F \tag{6}$$

It is therefore possible to write the deformation energy as:

$$W = \frac{1}{2} C\left[I^2 - (2+c)J\right] \tag{7}$$

where C and c are constitutive constants, I and J are, respectively, the first and third invariant of the deformation gradient. Wanting to perform an analysis at the microscale we restrict our investigation to a micro model (RVE) at the contact point between rigid elements glued by asphalt mastic film which is highly elastic. In this way, it is possible to recall the basic theory of Hertz in the case of adhesive contact under strain loads. In the case of negligible friction, the stress distribution between two bodies in elastic contact is:

$$\sigma_{zz}(r) = \frac{P' - P}{2\pi a^2}\left[1 - \left(\frac{r}{a}\right)^2\right]^{-1/2} \tag{8}$$

where, *P'* and *P* respectively represent the possible tensile stress with adhesion and the stress without adhesion; with *P'* generally very small compared to *P;*
a is the radius of the contact area and *r* is the radial distance from the axis of symmetry.

The JKR stress distribution is obtained as (Shull, 2002):

$$\sigma_{zz}^{JKR}(r) = -\frac{3P'}{2\pi a^2}\left[1 - \left(\frac{r}{a}\right)^2\right]^{-\frac{1}{2}} + \frac{P' - P}{2\pi a^2}\left[1 - \left(\frac{r}{a}\right)^2\right]^{-\frac{1}{2}} \tag{9}$$

Additional information about the distribution of stress, in areas close to the adhesive bond break between the aggregate surface and the asphalt cement, may be found through the role played by the factor of intensity of stress:

$$\sigma_{zz}(r) = \frac{K_I}{\left[2\pi(a-r)\right]^{1/2}}; \qquad \sigma_{rz}(r) = \frac{K_{II}}{\left[2\pi(a-r)\right]^{1/2}} \tag{10}$$

where K_I and K_{II} are the first and second mode of the stress intensity factors.

In the case of non-confined systems $a/h = 0$, (with h the thickness of asphalt film), in the case of tensile loads, the stress distribution is dominated by the singularity of the contact sides. The magnitude of this singularity of the stress field decreases with the ratio a/h. When this ratio tends to infinity, the magnitude of the stress singularity continues to decrease and the field is dominated by the hydrostatic contribution that has his peak at the center of the contact, decaying to zero on the frontier:

$$\sigma_{zz}^{adh}(r) = \frac{2(P - P')}{\pi a^2}\left[1 - \left(\frac{r}{a}\right)^2\right] \tag{11}$$

3. RESULTS AND DISCUSSION

A model of RVE was developed to investigate the response under dynamic actions (by impact and sliding) with addition of thermal actions. The computer code used is COMSOL and FEM implementation involved the use of brick elements with 8 nodes. The geometry shows schematically that the aggregates (quasi-rigid part) is represented by spheres and ellipsoids, the adhesive matrix, highly elastic material (soft), represents the asphalt cement. We analyzed the state of stress and strain filed at the contact between aggregates comparing the three load conditions (normal loads, thermal surface and normal loads, thermal and normal surface loads after 6 hours).

The time interval chosen is of 6 hours (from 01:00 pm to 07:00 pm) because the temperature measurements carried out on the pavement identified this as the range where the thermal action is most active. This condition appeared to be the worst with a strong reduction of the viscosity coefficient and a loss of adhesion between the grains. The expected loads are represented by the equivalent actions at impact of a typical main landing gear of Airbus A321 aircraft [4]. The simulated pavement structure is typical of flexible pavements for airport runways as given by the International Civil Aviation Organization (ICAO) standard [4]. The results of the simulation demonstrate sufficient reliability with the theoretical illustrated models.

It is useful to observe how the stress and strain fields are depend by volumetric heat distribution inside the RVE in particular when the initial surface heat proceeds inside the RVE. The heat proceeds bringing, in medium time, high temperatures in the bottom layers of the pavement package.

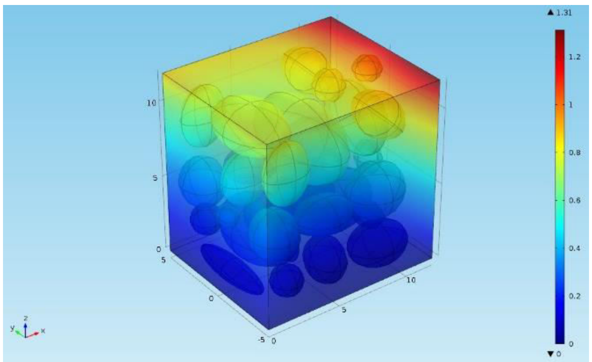

Figure-5. RVE global displacement field (cm).

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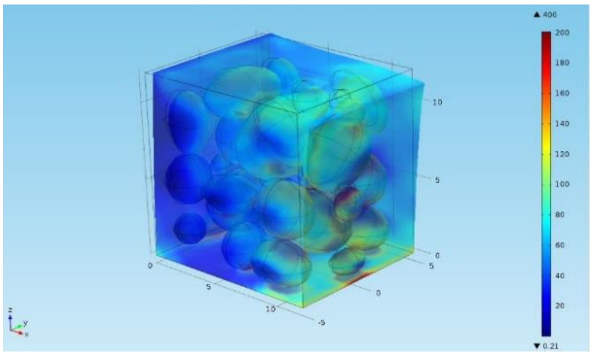

Figure-6. RVE Von Mises stress field (MPa).

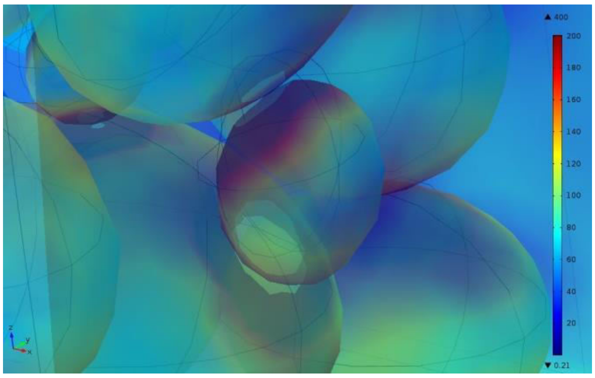

Figure-7. RVE- Detailed Von Mises stress field (MPa).

Figure-8. RVE- Detailed global displacement field.

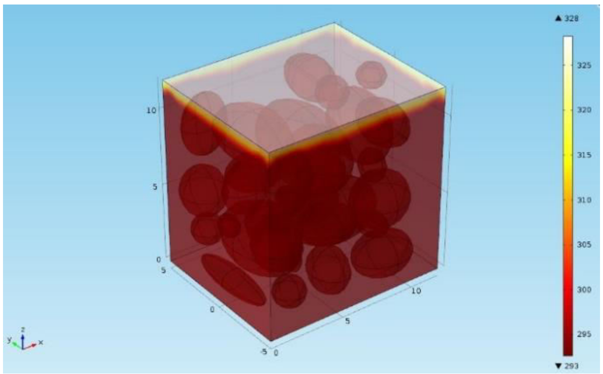

Figure-9. RVE Temperature (°C) distribution (t = 0 h).

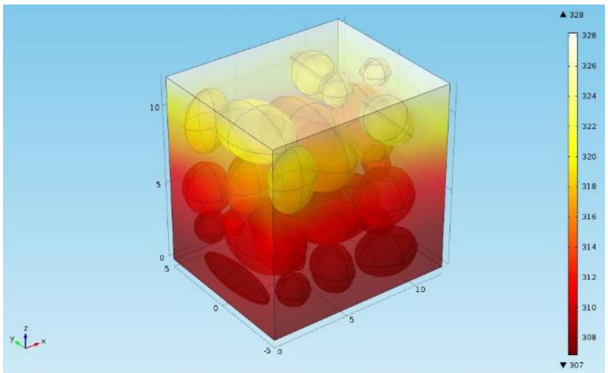

Figure-10. RVE Temperature (°C) distribution (t = 6 h).

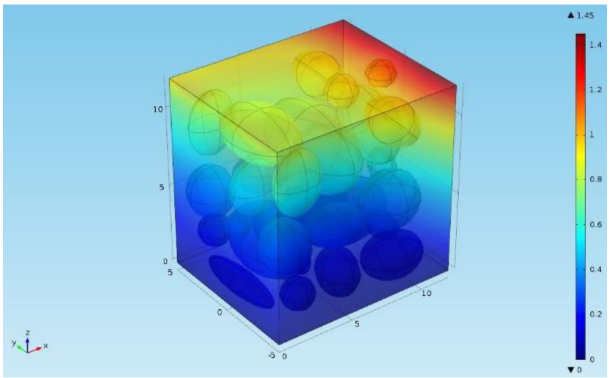

Figure-11. RVE global displacement field after 6 h (cm).

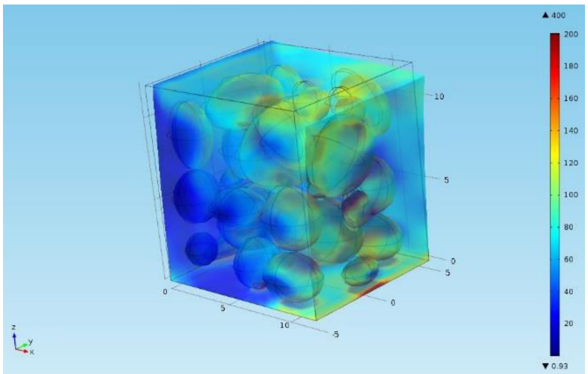

Figure-12. RVE Von Mises stress field after 6 h (MPa).

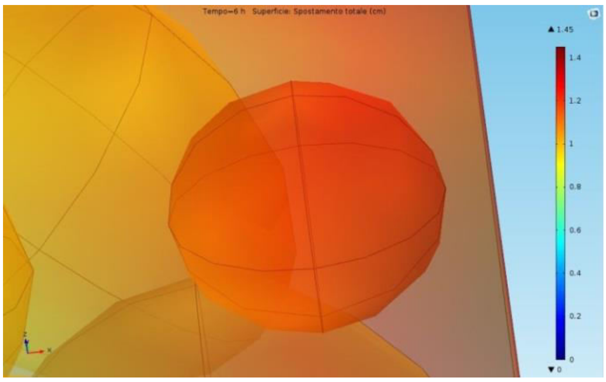

Figure-13. RVE Detailed global displacement field after 6 h (cm).

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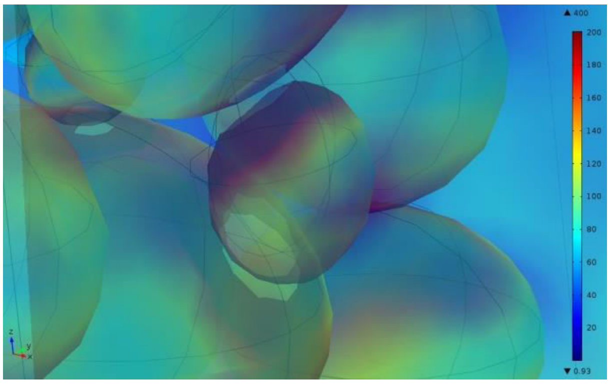

Figure-14. RVE Detailed Von Mises stress field after 6 h (MPa).

The results of numerical simulations show a suitable response with the illustrated theoretical models. The numerical results can be useful to predict the temporal pavement deterioration.

4. CONCLUSIONS

The illustrated figures report the stress (MPa) filed and the global displacement (cm) filed of the considered RVE in function of the pavement surface temperature.

In the numerical simulation, initially the temperature influence is only on the superficial layer, then the heat proceeds inside the pavement and the temperature increases in the deep layers of asphalt conglomerate.

It is possible to observe the response of the RVE in the initial condition, when it is subject only to the wheel loads and with no temperature gradient (Figures 3-9). In this condition, we can observe a quasi-isotropic behavior of the RVE with displacements only in the surface of the RVE.

When the temperature gradient (+ 55°C) has been applied, after 6 hours (t = 6 h), it is possible to observe a distribution of heat in the entire model with a difference of temperature of 20°C between the superior and the deepest surface of the RVE (Figures 10-14).

We can observe that the Von Mises stresses distribution present an inversion in a limited area near the base (Figure-14).

All these elements can be used in an appropriate analysis of aging and structural durability, considering cyclic loads (thermal and mechanical).

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