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Contact-induced deformation and damage of rocks used in pavement materials

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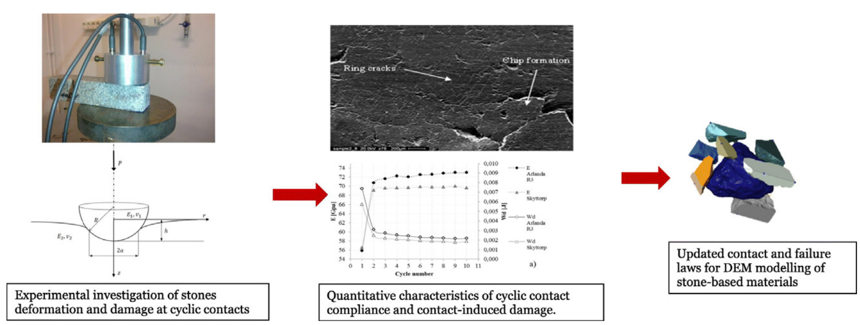
HIGHLIGHTS

- Experimental contact mechanics basis for DEM modelling of stone-based construction materials is presented.
- Dependency of stones contact law parameters on stress level, load history and surface roughness is demonstrated.
- Contact damage mechanisms controlling stones local wear and fragmentation are identified, demonstrated and quantified.
- Workflow to incorporate the reported experimental findings into DEM through particle contact and failure laws is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Performance of stone-based construction materials, such as asphalt and unbound aggregate mixtures is defined to a great extent by the mechanics of the stone-to-stone interactions. Accordingly, the Discrete Element Method (DEM) is gaining popularity as a modelling tool to investigate the mechanical behavior of these materials. Contact and failure laws defining particles force-displacement relationships and the propensity of particles to break are crucial inputs for the DEM simulations. The present study aims at providing an experimental contact mechanics basis for the development of physically based stone-to-stone interaction laws. The attention is focused on investigating stone's force-displacement relationship and damage characteristics at pure normal loading for two stone materials used by the road industry. Experiments are performed at spherical contact profiles for cyclic and monotonically increasing loads. The emphasis lies on the evolution of contact compliance and accumulation of contact induced damage. The effect of surface roughness on the materials response is examined through comparative experiments performed on the specimens with different roughness values. Optical and environmental scanning electron microscopy (ESEM) observations of the contact induced damage at the material surface are presented and discussed in the context of contact mechanics. The implications of the reported experimental findings on the development of mechanics based contact and failure laws for the DEM modelling of stone-based construction materials are discussed.

1. Introduction

Stone-based construction materials, such as concrete, asphalt and unbound aggregate mixtures are extensively used in road construction.

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The total deliveries of construction aggregates in Sweden alone were 75 Mtons in 2014, with >50% of those aggregates used in road construction [1]. Understanding factors controlling performance of road materials is crucial for road engineering, as material associated failures in roads result in high costs for both the construction industry and the society.

In stone-based construction materials, stones occupy most of the volume and stone-to-stone contacts provide the main load transfer mechanism in compression and shear. Thus, the mechanics of the grain scale interactions affects profoundly the macro-mechanical performance of the materials, cf. e.g. [2–3]. In particular, as shown in [3], the local 2D geometry and orientation of the stone contact regions significantly affect permanent deformation performance of asphalt mixtures. Furthermore, contact-induced damage in the stones may be of significant importance, in particular in case of unbound granular materials, cf. e.g. [4–5], affecting the material performance through formation of fines as a result of both stone fragmentation and localized damage in the vicinity of the contact points.

In this context, Discrete Element Method (DEM) provides a promising analysis tool for linking the particular features of the stone contact conditions to materials performance on the macro level. DEM has been increasingly applied to model macro-mechanical behavior of road materials, e.g. [6–7] and railway ballast, e.g. [8–9] and the reported models provide a significant new insight to various aspects of stone-based materials behavior. Crucial input for DEM models are particle contact laws describing normal and tangential force-displacement relationships, as well as eventual particle failure laws that define the propensity of individual particles to break based on the contact force history, cf. e.g. [10]. The majority of DEM studies on asphalt and unbound granular infrastructure materials rely on empirical contact and particle failure laws with their parameters determined as best fit of experimental observations on a macro-level. At the same time, quantitative estimation of the grain scale mechanics influence on the materials performance may be improved through incorporating the particle interaction laws based the experimentally observed particle contact behavior, as shown in e.g. [10], though for the case of DEM modelling of metal powder compaction. The present study aims to contribute to addressing this issue for the stone-based construction materials, through providing an experimental contact mechanics basis for the stone-to-stone interaction laws. Presently the attention is focused on investigating stone's force-displacement relationship and damage characteristics for pure normal loading.

The empirical nature of the particle interaction laws precludes quantitative estimation of the grain scale mechanics influence on the materials performance.

Aiming at providing a physical basis for the stone interaction laws in DEM models, Cole and Peters [11–12] performed an experimental investigation of normal and sliding contacts with naturally occurring grains of several stone types. For normal contact, in particular, they reported cyclic contact compliance of gneiss, weathered gravel, Ottawa sand as well as lunar simulants. In general, it has been observed in [11–12] that, above certain threshold loads, the force-displacement measurements followed reasonably well the 3/2 power law of the elastic Hertz contact theory. The authors attributed linear force-displacement behavior for lower contact forces to localized plasticity at surface asperities. A similar observation has been reported by [13] in their experimental study on glass ballotini subjected to different surface treatments.

Cole and Peters [11–12] also observed hysteresis in load-displacement curves for all the investigated materials; attributing the resulting energy dissipation to contact-induced damage. As the experiments in their study have been performed on natural grains, i.e. at varying and not well-defined contact geometries, the reported results may not be interpreted in terms of stress fields. Furthermore, the inherent material variability may not be separated from the effect of variable contact geometry. However, it has been reported in [12] that, in general, the dissipated energy increased with the magnitude of force and weathered stones appeared to have more dissipation as compared to the virgin ones.

Uthus et al. [2] developed a DEM model for triaxial testing of idealized unbound granular material composed of spherical gneiss particles. They used Hertzian contact law with the experimentally measured parameters reported by [14]. Based on the comparison with triaxial test data they showed that, as long as uncertainty associated with the local contact geometries is not an issue, the measured contact law parameters provide reasonable agreement between the DEM model and experiments.

While the results by Cole et al. [11–12,14] provide important insights on general characteristics of stone-to-stone cycles, the effect of several important contact cycle parameters have not been examined in detail in their studies. Since Cole et al. focused primarily on characterization of contact compliance they presented only limited qualitative observations on contact induced crack initiation. In particular, no quantitative results concerning fracture loads were reported in their studies. Furthermore, no results are available in the literature concerning the effect of stress levels on the amount of damage in the material. The effect of surface roughness on the contact compliance of stones and the resistance against contact induced damage has not been investigated systematically either. The present study aims to address these gaps by investigating experimentally the normal contact behavior for two stone materials used by the road industry.

Experiments are performed at spherical contact profiles for cyclic and monotonically increasing loads. The emphasis lies on the evolution of contact compliance and accumulation of contact induced damage. This damage is also examined with optical and environmental scanning electron microscopy (ESEM). Microscopy observations are interpreted in the context of contact mechanics. Moreover, governing parameters for accumulation of localized contact damage as well as for contact-induced stone fragmentation are discussed. In order to investigate the effect of surface roughness on the materials response, comparative experiments are performed on the specimens subjected to three different surface treatments resulting in different surface roughness values. The experimental findings are evaluated in the context of observations from standard performance tests used in road industry.

2. Theoretical background

Stone skeleton in road materials is composed of crushed stones, with a size distribution according to design specifications. The contact interactions between individual stones are not only affected by the structural loading but also by the local contact profile geometries, the mechanical properties of the stones as well as the number and position of the contact points. In a real pavement material all parameters mentioned above may vary considerably. In Fig. 1(a) a typical contact configuration for a single stone in an unbound granular material is illustrated with an X-Ray computed tomography data set. As may be seen, contact geometries can be very different with several contact points that may interact with each other. However, the spherical contact profile represents the most common idealized contact configuration since sharp contacts will flatten due to damage and localized plasticity and flat-to-flat contacts are relatively rare in the material. Accordingly, in the present study, the attention is focused on the evaluation of stone contact compliance and contact-induced damage accumulation for spherical profiles. The investigated geometry is depicted in Fig. 1b) along with the coordinate system and problem notation.

For spherical contact profiles, the boundary conditions in the contact region are expressed in cylindrical coordinates shown in Fig. 1 (b) as follows, provided that the assumption of small deformations is valid:

$$u_z(r,a) = h(a) - f(r), r \le a, z = 0 \quad (1)$$

where h and a are the indentation depth and contact area radius correspondingly; $f(r)$ is a profile geometry function defined for the spherical