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3-D cohesive finite element model for application in structural analysis of heavy duty composite pavements

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HIGHLIGHTS

- Cohesive models adequately describe the fracture behaviour of cement bound granular mixtures.
- Structural- and local crack response of slabs are highly influenced by the subgrade soil.
- The post-peak response is mainly controlled by slab dimensions and subgrade soil.
- The fracture process is more affected by the fracture energy than the tensile strength.
- Aggregate interlock behaviour has significant influence on the structural response.

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ABSTRACT

The problem of stiffness degradation in composite pavement systems from localised fracture damage in the quasibrittle cement bound granular mixture are today taken into account only by empirical formulas. These formulas deals with a limited number of materials in a restricted range of design options and would yield unrealistic results in ultimate loading conditions. Cohesive modelling is one of the primary methods to handle localised damage in quasi-brittle materials, e.g., concrete, describing the potential crack in a discrete manner. To increase the versatility of existing methods this paper presents a numerical analysis of the fracture behaviour of cement bound granular mixtures in composite concrete block pavement systems applying a cohesive model. The functionality of the proposed model is compared to experimental investigations of beam bending tests. The pavement is modelled as a slab on grade and parameters influencing the response such as geometry, material parameters and loading position are studied and compared to experimental results. It is found that a cohesive model is suitable for the description of the fracture behaviour of cement bound granular mixtures. Moreover, it can be shown that adequately good prediction of the structural response of composite pavements is obtained for monotonic loading without significant computational cost, making the model applicable for engineering design purpose. It is envisaged that the methodology implemented in this study can be extended and thereby contribute to the ongoing development of rational failure criteria that can replace the empirical formulas currently used in pavement engineering.

1. Introduction

Ports- and industries require special types of pavements to resist the heavy static loads from containers. To reduce the risk of rutting and settlements over time, concrete block pavement systems are typically applied over a stiff cemented base layer, i.e., cement bound granular mixture (CBGM). The structural design of such composite pavements are based on empirical formulas which converts the response analysis into a measure of performance, commonly referred to as the Mechanistic–Empirical (M–E) method, first introduced in pavement engineering by Kerkhoven and Dormon [1].

Degradation of the cemented base in composite pavements is mainly controlled by initiation and propagation of longitudinal cracks in wheel paths. Moreover, traffic induces further degradation of aggregate interlock joints through shear movement of the cracked edges [2]. Closely spaced transverse cracks in the cemented base have also been reported in post-processing of damaged composite pavements [3,4]. Despite the fact that cement bound

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granular mixtures are quasi-brittle materials, which degradation is controlled by tensile damage of slabs and shear damage of aggregate interlock joints, both highly nonlinear phenomena, elastic calculations are most commonly applied to determine the response [5–11]. The M–E method does not distinguish between crack initiation and crack propagation or elastic and inelastic work, model parameters are simply regression constants without direct physical meaning. This type of model deals with a limited number of materials in a restricted range of design options; each transfer function being restricted by its own design method, typically calibrated for highway traffic and specific local materials- and climatic conditions. Moreover, experimental studies [12] show that such empirically based model yields unrealistic results considering loading regime- or configuration different from typical truck wheel loads, e.g., ultimate loading condition.

In the present study a simple framework for engineering application is sought; creating a rational link between laboratory, design and field applications. For the monotonic load case, considered here, the mechanism of cracks is imagined to occur in a similar fashion to yield line mechanisms considering *Mode I* (opening mode) fracture in the form of a straight separation band where the location is known in advance. In this aspect, the concept of the fictitious crack model [13] stand out as particular attractive; as the model is straightforward in implementation and requires only few model parameters, which can be defined from standardised laboratory tests.

Production of cement bound mixtures from high quality crushed aggregates results in high stiffness and strength properties, i.e., 1/3 of those for normal plain concrete. Not only will such materials exhibit softening behaviour in tension, after the onset of cracking, but also on structural level the composite pavements will often exhibit softening, or so-called snap-back type of load–displacement response, due to the relatively low stiffness of supporting layers. This type of localised fracture behaviour can be described numerically with different classes of constitutive models, e.g., those proposed by Jirasek [14] as; (i) strong discontinuity models, (ii) weak discontinuity models, and (iii) continuum models. The first model a crack as a geometrical discontinuity, whereas the latter two approaches imagine a cracked solid to be a continuum.

The discontinuity models, e.g., the fictitious crack model, embedded elements with strong discontinuities [15] and the extended finite elements [16], incorporates jumps in displacements across a discontinuity surface corresponding to the crack. Models with localisation bands bounded by weak discontinuities can be considered as simple regularizations of models with strong discontinuities, e.g. the smeared crack model [17]. Instead of splitting the constitutive law into elastic and inelastic parts, one could use a law that directly links the stress to the total strain, as is the case for continuum models. Subsequently several models have been developed to describe the complicated fracture process in quasi-brittle materials, e.g., by coupling damage and plasticity [18–20].

Application of modern fracture mechanics to the field of pavement engineering began in the late 1960s and early 1970s, studying mainly asphalt concrete mixtures, adopting the principles of linear elastic fracture mechanics [21–25]. Subsequently, efforts to obtain a better understanding of fracture in asphalt concrete materials primarily followed an experimental approach [26–29]. Jenq and Perng [30] developed a cohesive zone model based on the principles of the fictitious crack model for asphalt mixtures and used this model to simulate low-temperature fracture of asphalt overlay on old concrete pavement structures [31] followed by extensive application- and development of cohesive zone models for simulating fracture in asphalt concrete mixtures [32–39].

Cohesive zone models and the principles of the fictitious crack model has also been extended to more practical problems for concrete pavement structures, following an extensive review of fracture mechanics applications in pavement engineering [40]. At first, a standalone computer program was coded and applied to simply supported beams [41]. Subsequently, nonlinear spring elements were adopted in commercial software for concrete beams and slabs on grade subjected to mechanical loads [42]. Roesler et al. [43] created user elements based on the fictitious crack model, and implemented them locally in commercial software to simulate crack propagation in concrete beam specimens and in fibre reinforced concrete materials [44,45]. Although these elements were two-dimensional, responses obtained were compared with experimental measurements and adequately good agreement was reported. Subsequently several independent investigations of crack propagation in beams and slabs on grade subjected to mechanical loads was carried out, with some very encouraging results [46–49]. Gaedicke and Roesler [46] found that the linear softening model applied to slabs was able to reasonably predict the flexural load capacity of the experimental slabs while significantly reducing the computation time. Aure and Ioannides [48] found, that for slabs on grade structures, the type of softening curve, cohesive zone width and mesh does not influence the response significantly.

This paper presents a numerical study of a three-layered composite pavement applying a simplified cohesive model in ABAQUS [50], including also the effects from aggregate interlock behaviour. Idealisation is applied, modelling the pavement as a slab on grade structure, neglecting the effect from the concrete block surface, resulting in computationally fast finite element (FE) models suitable for engineering applications. Numerical analysis of experimental results are presented, giving new valuable information on the behaviour of composite pavements which cannot be captured by the M–E method. Parameters influencing the response such as geometry, material parameters and loading position is then studied creating a solid basis for further application of cohesive models in analysis composite pavement systems.

2. Methodology

2.1. Model idealisations

Analysis of a three-layered composite pavement structure is considered; concrete block pavers (CBP), cement bound granular mixture (CBGM) and subgrade soil. For the fracture process, built-in traction separation based cohesive contact surfaces are inserted along the anticipated fracture plane in the cemented base layer (slab) in the orthogonal directions as per Meda et al. [51]. This is deemed a reasonable model at the edge- and interior of the cemented base layer, since the fracture plane is anticipated in the direction of the maximum stress.

The response of the composite concrete block pavement structure is mainly controlled by the cemented base layer and the subgrade soil. The properties and thickness of the concrete block pavers does hardly influence the overall response and bearing capacity of the pavement structure [52], since the loading from container castings produce a close to rigid body movement of the stiff concrete block pavers over the soft layer of bedding sand, which is unable to absorb any significant bending moments [53].

Thus, for the present study the response from concrete block pavers is simulated using a simplified approach, placing unit displacements over an approximated area, i.e., the area of blocks in contact with the container casting. Four single slabs on grade models is developed for evaluation of interior (full- and simplified model, applying symmetry conditions), edge and corner loading, assuming that the slabs are intact before monotonically loaded. Square slabs of 2.5×2.5 m^2 to 4.5×4.5 m^2, dimensions commonly applied in ports- and industrial pavements, is considered.