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Mechanical performance of pavement structures with paving slabs – Part II: Numerical simulation tool validated by means of full-scale accelerated tests

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ABSTRACT

In recent years, pavement structures with paving slabs have gained importance, especially in urban trafficked areas, because they provide more design options and have great potential with regard to durability and low maintenance compared to flexible pavements. In order to exploit this potential, an accurate and reliable performance prediction by means of appropriate design concepts is necessary. Contributing to this topic, a numerical simulation tool was developed and its performance evaluated by means of full-scale accelerated pavement tests (APT).

Within this paper (Part II of this work), a numerical simulation tool is proposed which is able to take into account the non-linear and plastic behavior between paving slabs (vertical joints) and between slabs and sandbed. The material parameters required for the paving concrete slabs, the vertical joints and the base courses are obtained by identification experiments. Finally, the main results from the APT could be reproduced very well with the numerical simulation tool without using phenomenological parameters.

1. Introduction and motivation

Pavement constructions with paving slabs are composed of concrete or stone slabs of different dimensions lying on a sandbed and with sandfilled vertical joints in-between. Whereas flexible pavement structures are used in all areas, from footways to highly trafficked roads (e.g. motorways), pavement structures with paving slabs are only provided for areas with light or low traffic loads, according to the Austrian regulation RVS 03.08.63 [1]. Due to the high lifespan of the slabs and not least because of the variety in design options (shape, color, texture), an extension of the application in urban areas is desirable. The main reason why this has not happened until now is a lack of suitable design concepts, often leading to damage in areas with high vertical and horizontal loads (due to braking and acceleration forces).

One of the main tasks within a pavement design process is the determination of the relevant strain and stress states within the structure. For flexible pavements this is often done on the basis of closed-form solutions for elastic half-space systems with infinite lateral dimension. The basic solution therefore was delivered by Boussinesq [4,5], which was extended by Burmister to multi-layered elastic systems [6,7]. The solutions of Burmister can be found in a large number of software programs, e.g. in [14,12,13]. For rigid slab superstructures, a limited number of analytical solutions are available. Selected stress states in concrete slabs can be estimated using the solution in [15], where the subgrade reaction cannot be considered, or the well-known solutions of Westergaard [16,18], which are discussed in [17]. Design charts for concrete slabs can be found in [19,20], and a method based on limit state considerations is proposed in [21]. Analytical solutions for different slab shapes resting on a Pasternak foundation and different boundary conditions are derived and presented in [11].

Numerical simulation tools based on the finite element method were the first to be developed for block pavement structures. One of the first publications was [33], in which rigid elastically bedded blocks are connected with springs, and in a subsequent calculation the loaded concrete block is considered. Later, some similar models were developed, [34–37], which all had in common a linear elastic interaction behavior between blocks and a rather simple material behavior of the underlying base courses. An interesting model was developed by Ascher in [38], where the non-linear elastic Dresdner model [23] was assigned to the base course, and the performance of the model was evaluated by experiments in [39]. For concrete paving slabs, the commercial software ISLAB2000 [41] is often used in engineering design, but this program is also based

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on linear elastic relationships between modeled parts. With respect to temperature and moisture loading, the numerical model presented in [40], based on the software tool DIANA, is quite sophisticated. A good overview of design methods for slab paving structures can be found in [8–13,22].

Despite the good quality of the existing methods, there is still need for improvements. Many design concepts fail to capture the structural system realistically, leading to the following discrepancies of state-of-the-art engineering design approaches:

- Since some engineering design concepts for paving slab structures have evolved from, and hence are heavily based on, concepts for flexible pavement structures, for the determination of relevant stress states in the base courses, blocks/slabs are often modeled as a continuous layer with an effective stiffness obtained from empirically derived relationships. With this approach, stress states due to edge loading, especially in the upper base courses, cannot be captured realistically.
- Even if concrete blocks/paving slabs are modeled appropriately by using, e.g., solutions according to Westergaard [16,18] or Cauwelaert [11], respectively, the plastic material behavior of the base courses is usually not taken into account.
- The vertical joints between blocks/paving slabs are either not considered (effective stiffness) or their mechanical behavior is highly simplified. Plastic material behavior or the degree of joint filling, both effects which highly influence the performance, are usually not taken into account.
- The required thicknesses of the base courses are only dependent on the occurring vertical loads, horizontal loads, e.g. braking and acceleration forces, are not considered. For flexible pavement structures this is an acceptable approach, but due to the vertical joints of paving slab structures, the horizontal load capacity is very likely an important factor influencing the overall performance.

These issues motivated the following work, which focuses on the investigation of paving slab structures experimentally and numerically.

Within Part I of this work, presented in [2], accelerated pavement tests (APT) with the New Mobile Load Simulator (MLS10) were carried out. In these tests four different slab pavement structures were considered and two of them were equipped with strain gauges and soil pressure cells. Within Part II of this work, which is proposed in this paper, a numerical simulation tool which is able to address all aforementioned issues of current engineering design concepts was developed. This simulation tool is validated by means of the data obtained from the APT. The knowledge gained from the APT together with the validated numerical simulation tool should contribute to the improvement of existing design schemes and/or development of new design methods/rules. Moreover, a better utilization of slab paving products and the evaluation of new large-format slabs may be achieved.

In the following section, identification experiments for the mechanical behavior of the vertical joints, the unbound base courses and the concrete slabs are described. The identified material properties serve as input to a numerical simulation tool which is presented in Section 3. In Section 4, the simulation results are compared to measured values from the APT. Finally, a summary of the results is given and conclusions are drawn in Section 5.

2. Identification experiments

Responsible for the overall performance of a pavement structure with concrete paving slabs are: (i) the joint behavior between slabs, (ii) the mechanical properties of the slabs themselves, and (iii) the behavior of the bedding and base courses including the subgrade. For a reliable simulation tool the mechanical behavior of all these parts needs to be characterized. For this reason, different identification experiments have been carried out which will be presented in the following.

2.1. Joint behavior

For the determination of the joint behavior three different new experimental setups were developed, which are illustrated schematically in Fig. 1. From the first and second test setup (Fig. 1(a) and (b)) the frictional behavior in vertical and horizontal direction, respectively, was obtained. By varying the confinement force in the normal direction to the joint and by assuming a frictional behavior according to Mohr–Coulomb, a vertical and horizontal friction angle describing the tangential joint behavior can be determined from these experiments. Moreover, the amount of tangential deformation γ_e before plastic effects occur as well as a maximum shear stress τ_{max}, which is independent of the confinement stress, were identified. With all this information the tangential joint behavior can be described by an anisotropic friction criterion, illustrated in Fig. 2 and reading

$$\frac{|\tau_h|^2}{\tau_h^{crit\,2}} + \frac{|\tau_v|^2}{\tau_v^{crit\,2}} = 1, \tag{1}$$

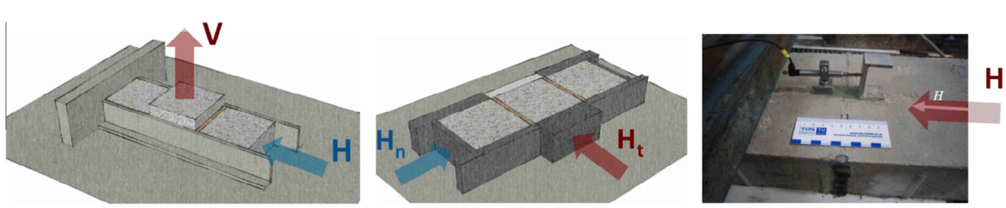
with $\tau_v^{crit} = \varphi_v \sigma_n \leqslant \tau_{max}$ and $\tau_h^{crit} = \varphi_h \sigma_n \leqslant \tau_{max}$, where φ_v and φ_h denote the vertical and horizontal friction angle, respectively, obtained from experiments.

From the third experiment (see Fig. 1(c)) a relationship between the joint normal stress σ_n and the joint deformation in the thickness direction δu_n is obtained, reading

$$\sigma_n = E_0 \delta u_n^n, \tag{2}$$

where E_0 denotes a secant-bedding modulus and n is a dimensionless parameter.

A detailed description of the test-setup, the test program and the evaluation of all three experiments can be found in [3]. The parameters identified as input for the numerical simulation tool are finally: $\varphi_h = 1.21, \varphi_v = 0.58, \tau_{max} = 2.41$ MPa for the tangential joint behavior, and E_0 = 11.482 N/mm^3 and $n = 1.795$ for the normal joint behavior.



(a) (b) (c)

Fig. 1. Schematic illustration of identification experiments of mechanical joint behavior in (a) vertical, (b) horizontal, and (c) normal direction.