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Combining performance based lab tests and finite element modeling to predict life-time of bituminous bound pavements

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HIGHLIGHTS

- Combining data from stress in motion and 4-PBB tests with finite element simulation.
- Using data of dynamic measurements from actual tires instead of static data.
- Comparing impact of super-single and twin tires on fatigue of European pavements.
- Super-single tires mean higher stresses for pavements and thus shorter life-times.
- The influence of the tire pressure is stronger for super-single tires.

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ABSTRACT

As roads are subjected to high traffic loads due to the strong growth in heavy vehicle traffic and new trends in the automotive and tire industries, the traditional asphalt mix tests are often inadequate for a reliable prediction of the in-service performance of flexible road pavements. With performance-based test methods (PBT) at hand, the thermo-rheological properties of hot mix asphalt can be obtained. This paper presents results of a research project where 4-point bending beam (4-PBB)-tests are carried out on different AC mixes for base layers at various temperatures and frequencies to obtain stiffness and fatigue behavior. At the same time, linear elastic finite element simulations are performed with input data for the materials different from the 4-PBB. These simulations are carried out on two different pavement structures, different tire types (twin-tires and wide base super-single tires) and wheel configurations (tire load and pressure). Loading data for the tires are obtained from stress-in-motion measurements using the Vehicle–Road Surface Pressure Transducer Array (VRSPTA). The strain at the bottom of the bituminous bound layers are taken from the simulations and used in combination with the fatigue functions to evaluate the life-time in permissible load cycles for different tire configurations. The main findings are that super-single tires lead to significantly lower pavement life-times than the standard twin-tire configuration and that the relative difference increases with decreasing thickness of the pavement structure. Also, the tire pressure has a strong impact on the pavement life-time; an increase in tire pressure by 60% decreases the life-time by 25–52% (super-single) and 15–38% (twin-tire) respectively.

1. Introduction

For decades the characterization of bituminous bound materials was carried out by a simple and easy method, the so called Marshall Mix Design [15,23,8]. The method seeks to select the asphalt binder content at a desired density that satisfies minimum stability and range of flow values. Implemented during World War II by the U.S. Army the Marshall method, despite its shortcomings, was up to the recent past the most widely used mix design method in the world [25].

As roads are more and more subjected to high traffic loads due to the strong growth in heavy vehicle traffic, new trends in the automobile and tire industries, and higher maximum axle loads limits today, the traditional Marshall method developed in the 1930s does not take into account the mentioned developments and is thus often inadequate for a reliable prediction of the engineering properties and in-service performance of bituminous bound pavements. The problem facing designers of flexible road pavements is the need to fully characterize the complex thermo-rheological properties of asphalt mixes on the one hand while on the other hand also providing a realistic simulation of the traffic- and climate-induced stresses to which pavement structures are

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exposed over their design lives. Since the mid 1990s efforts in pavement research have been focused on the setup and implementation of performance based tests (PBT) for bituminous materials on the basis of mechanical characteristics [13,9,16,26,20,3]. These methods are now implemented in European Standards and used for specifying the mix properties within an advanced type testing procedure required to meet customized quality standards for materials defined in tender documents as well as for mix design. As the new generation of pavement tests lead to mechanical parameters, like stiffness modulus, tensile strength etc., the results can be used for further analysis. One example for this is presented in this paper. In combination with data obtained from measurements with the stress-in-motion (SIM) system Vehicle–Road Surface Pressure Transducer Array (VRSPTA) [4], results from stiffness and fatigue tests are used for a simulation to predict and compare the life-time of different pavement structures with various tire types and wheel configurations [18].

2. Performance-based lab tests

To describe the structural performance of HMAs, three main indicators have to be taken into account: (1) the low-temperature cracking, (2) the pavement stiffness and fatigue at intermediate temperatures and (3) the permanent deformation at high temperatures (rutting). The 4 point bending beam test (4-PBB) used for stiffness and fatigue testing is the test method employed for the research presented in this paper and will be illustrated in the following section.

2.1. Pavement stiffness and fatigue at intermediate temperatures

Fatigue testing of asphalt mixes has been a major topic in pavement engineering in the last three decades [14,21,7,19,12,24]. Presently, a European Standard specifies the methods for characterizing the fatigue behavior of asphalt mixes by alternative tests, including bending tests and direct and indirect tensile tests, but without imposing a particular type of testing device. Stiffness and fatigue testing is used to derive basically two material characteristics: the material's stiffness, expressed by the dynamic modulus $|E^*|$ as function of temperature and frequency, and the long-term fatigue behavior, expressed by the number of permissible load repetitions N_{perm}. The initial dynamic modulus $|E^*|_{init}$ of the undamaged material can be determined on the basis of specimen geometry, load impulse and simultaneous measurement of the resulting strains by displacement sensors. The modulus is calculated from the quotient of the applied stress and the resulting strain, which is time-shifted by the corresponding phase angle (φ) as a result of the viscoelastic material behavior of asphalt [5].

The traditional fatigue criterion of asphalt mixes is linked to the number of load-cycles resulting in reduction of modulus to half its initial value. Usually, a series of fatigue tests for one material is carried out at different levels of the horizontal strain levels ε on the bottom of the specimen. The number of permissible load-cycles $N_{perm}(\varepsilon)$ is determined for each of the fatigue tests. When the horizontal strains ε are plotted against N_{perm}, the so called Woehler-curve can be determined. An example is illustrated in Fig. 3. The Woehler-curve gives information for the derivation of fundamental relationships between mix composition and stiffness properties and serves as input for material and structure optimization.

For the 4-PBB a prismatic shaped specimen is used, which is symmetrically clamped on the load frame by two inner and two outer clamps, representing the four points. The specimen is subjected to four-point sinusoidal bending, which is realized by loading the two inner load points (inner clamps), in the vertical direction, perpendicular with regard to the longitudinal axis of the beam. The vertical position of the end-bearings (outer clamps) is fixed, thus resulting in a constant moment, and hence, a constant strain between the two inner clamps. The strain applied to the specimen is small and thus keeping the test in the linear domain (Fig. 1).

The dynamic modulus can be calculated from the stress–strain-relationship. As a result, the change of the modulus over the number of load cycles is determined at different temperatures, frequencies and strain levels.

3. Life-time prediction of pavement structures – case study

One way to benefit from PBT is to use the results together with load data to simulate a pavement structure, compute the representative stresses and strains and determine the life-time of the respective pavement loaded by a certain tire type with a given axle load and tire pressure. Following this principle, the fatigue performance of different pavement structures, as well as the effect of

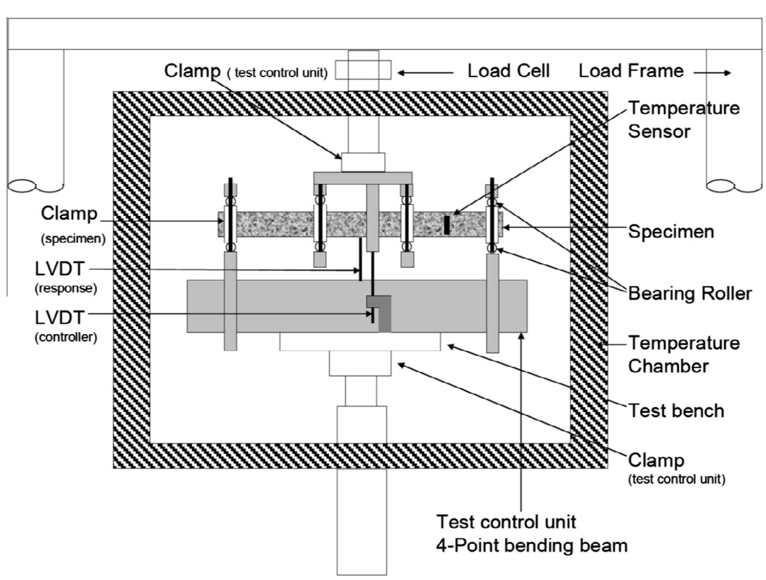

Fig. 1. Layout of the 4-PBB equipment.