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Numerical visco-elastoplastic constitutive modelization of creep recovery tests on hot mix asphalt

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ABSTRACT

This paper discusses a visco-elastoplastic constitutive model to analyze the creep deformability of asphalt concretes at high service temperatures, finalized to improve the interpretation of permanent deformation phenomenon and performance design of road pavements. A three dimensional constitutive visco-elastoplastic model is introduced, in tensor as well as in numerical form. The associated uniaxial model is used to arrange a plastic element in series with the viscoelastic component. The latter is defined by an elastic spring placed in parallel with three Maxwell elements. Three different hardening laws, namely isotropic, kinematic and mixed hardening, are included in the constitutive model to compare the creep deformability. The proposed constitutive model has been calibrated and validated on the basis of uniaxial creep-recovery test results at 40 °C. This is performed with a high performance hot mix asphalt concrete (HP-HMA) at different stresses and loading times. Depending on the hardening law considered, permanent deformation data predicted by the proposed model results are reasonably consistent with the experimental creep-recovery data. A rational constitutive model that is physically congruent with the creep phenomenon of asphalt concretes was developed and calibrated to achieve a deeper understanding of the stress-strain response of such materials. The fundamental relevance of an appropriate plastic response modeling, in the study of the creep behavior of asphalt concretes for highway and road pavements.

1. Introduction

The accumulation of permanent deformations at high service temperatures, which can be observed in the form of longitudinal hollows with raised edges (conventionally called ruts), is a severe and relevant failure mode of the road flexible pavements. Rational study of such degradation requires the use of an adequate constitutive model to properly analyze the complex stress-strain response under the traffic

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loading of asphalt concretes used in road pavement surfacing.

The creep response of asphalt concretes under a constant or cyclic compressive load is categorized as the visco-elasto-plastic type and experimentally verified in several studies (Collop et al., 2003; Costanzi and Cebon, 2014; Erkens et al., 2002; Giunta and Pisano, 2006; Olard and Di Benedetto, 2003). It can be studied using rheological models (defined by elastic, viscous and plastic elements) arranged in more or less complex configurations according to the required accuracy for analysis and the possibility to solve the analytical complexity related to the number of basic elements considered (Collop et al., 2003; Costanzi and Cebon, 2014; Giunta and Pisano, 2006; Olard and Di Benedetto, 2003). Concepts typical of continuum thermomechanics, such as the Helmholtz free energy and the dissipative inequality of Clausius–Duhem, represent a significant evolution in the modeling of the mechanical behavior of bituminous materials (Drescher et al., 2010; Erkens et al., 2002; Krishnan and Rajagopal, 2005; Krishnan et al., 2006; Pasetto and Baldo, 2007, 2015a, 2015b). Other theories have been also investigated over the years, including continuum damage mechanics (Lee and Kim, 1998; Masad et al., 2005), fractional models (Celauro et al., 2012; Oeser et al., 2007, 2008; Pellinen et al., 2007), and the distinct element method (Abbas et al., 2007; Collop et al., 2004; Dai and You, 2007; Dondi et al., 2012).

To complete the mathematical formulation of an overall constitutive model in this study, a plastic flow law based on inviscid plasticity and characterized by three different hardening laws is presented after a brief summary of a viscoelastic model that represents the fundamental framework of considered constitutive equations. The main goal is to provide significant improvements to the mathematical formulations proposed in previous studies (Pasetto and Baldo, 2007, 2015b), to obtain reliable numerical predictions of the creep response of asphalt concretes. This is a fundamental requirement in the rational design of road pavements.

The constitutive modeling framework is integrated using an original numerical procedure for the calibration and validation of the proposed model. Creep recovery tests are performed on a high performance hot mix asphalt concrete (HP-HMA) for road flexible pavements to collect the necessary experimental data for the calibration and validation of the proposed visco-elastoplastic model.

2. Materials and methods

2.1. *Aggregates and bitumen*

The high performance hot mix asphalt concrete considered in this investigation is produced using both conventional aggregates, namely crushed limestone and filler, and Electric Arc Furnace steel slags provided from different steel plants located in Northeastern Italy. The limestone, as well as the artificial aggregates (EAF slags), were supplied in three grading fractions: 0/5, 5/10 and 10/15 mm. A bituminous binder modified with Styrene-Butadiene-Styrene (SBS) polymer is used in the laboratory investigation. A penetration of 44 mm/10 (EN 1426), softening point of 77 °C (EN 1427) and Fraass breaking point of −12 °C (EN 12593), were recorded in the laboratory characterization of the SBS modified bitumen. Its manufacturer has certified an elastic recovery value at 25 °C (EN 13398) higher than 50%.

2.2. *Asphalt concrete*

The design of the HP-HMA grading curve was developed according to Specifications of the Italian Association of Pavements Technologists (SITEB) (2000), with a total amount of steel slag fixed at 25% and nominal maximum aggregate size of 12 mm. Fig. 1 shows the design grading curve of the asphalt concrete. Table 1 reports the optimum bitumen content and the most relevant engineering characteristics of the mix, as well as its indirect tensile strength value (EN 12697-23).

A complete discussion of the chemical and physical-geotechnical characteristics of the aggregates, as well as the mix design procedure and performances of the mix, can be found in two previous papers by Pasetto and Baldo (2006, 2008).

2.3. *Methods*

To investigate the creep response of HP-HMA mix, tests of creep recovery (i.e., constant load uniaxial tests) were performed on Marshall cylindrical samples according to the British Standard 598, Part 111. However, different values were selected for the loading period, stress and testing temperature to properly support the constitutive model's calibration and validation.

Loading and unloading times were chosen, with the total testing time equal to 120 s. The shorter loading time was fixed at 10 s, the second one at 20 s, and the longest one at 30 s. Therefore, the corresponding unloading times were set at 110, 100 and 90 s, respectively.

For each testing time, in addition to the standard stress level of 100 kPa, two other stress values (i.e. 300 and 500 kPa) were used to cover wider and more severe creep conditions. All creep tests were conducted at 40 °C.

The creep recovery test was chosen for its calibration and validation of the constitutive model, as it is relatively easier for mathematical modelization. It was also chosen due to its wide use in the road labs.

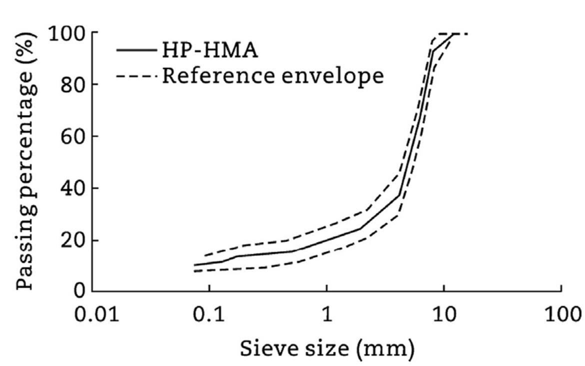

Fig. 1 – HP-HMA grading curve and SITEB reference envelope.