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Experimental study and modeling of the behavior of partially saturated asphalt concrete under freezing condition

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HIGHLIGHTS

- Effect of pore water solidification on the behavior of partially saturated AC.
- Experimental investigation of the swelling strain and dual stress in AC materials.
- Development and validation of a thermo-viscoelastic constitutive law.
- Capability of the developed model to relate swelling strain - frost induced stress.

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ABSTRACT

In relation to the sudden and generalized occurrence of potholes observed on pavements subsequently to rainfalls and freezing temperatures, this paper is focused on studying the behavior of partially-water-saturated asphalt concrete (AC) under freezing conditions. Most of previous work on that topic has been devoted to the damaging effect of repeated frost/thaw cycles on wet AC, viewed through the loss of stiffness of the material. The novel aspect presented in this paper deals with the characterization and modeling of the swelling strain effect induced by solidification of pore water at negative temperatures. Transposed to the case of a pavement, we believe indeed that this effect is prone to generate tensile stress at interfaces between AC layers and to generate delamination at short term, ending up into potholes. The present research is a first step towards assessment of this assumption by means of future experimental and numerical analyses at the structural level.

Investigations reported in this paper rely on two types of experimental test carried out in the laboratory. The first is performed under free stress condition while the other is subjected to restrained strain. The experimental results from these two tests show the development of significant swelling strains and induced stresses in the partially saturated asphalt specimens, respectively. These two effects are attributed to the phase change of pore water from liquid to solid. A constitutive law taking into account viscoelasticity of AC, thermal expansion and swelling induced by frost is elaborated. This law is implemented in a numerical program and validated against the experimental results. In particular, it is shown that this law is able to make the connection between the magnitudes of the swelling strain and the frost-induced stress stemming from the two tests.

1. Introduction

This research was motivated by field feedbacks showing the apparition of series of potholes taking place in some asphalt pavements in France and other Northern Europe countries. Such degradation occurred almost simultaneously (typically in half a day) over some important part of road sections and under particular weather circumstances combining cold temperatures and rainfall events. Early investigations of these disorders [1,2] have pointed out that a specific mechanism could be at the origin of the problem and that this mechanism was likely related to the mechanical behavior of asphalt concrete (AC) partially saturated with water when subjected to freezing. Traffic and initial damage might represent propitious or aggravating factors to this deterioration mechanism.

The mechanical response of partially saturated AC specimens undergoing freezing then started to be studied in the laboratory [3,4]. Experimental tests were performed at the timescale of one (or a few) frost/thaw cycle(s) focusing on the strain evolution

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during freezing. Results from these studies show that large swelling strain develops in the AC sample during cooling starting at the time at which temperature in the sample reaches some negative value. This swelling strain is attributed to freezing of the pore water occluded in the AC specimen.

In this paper, we present additional tests performed on partially saturated AC to quantify the level of strain but also of stress that can originate from freezing of pore water. The objective is then to use these tests to elaborate a constitutive law dedicated to partially saturated AC. Two tests are considered. One is run considering traction free boundary condition that let the sample deform freely. The other test is performed under restrained strain and makes thermal stress occur in the sample. The tests performed clearly show the impact of the pore water phase change on the experimental data.

It is only recently and following feedbacks from the field that the combined effects of moisture and frost is considered as possibly leading to a frank mechanism of pavement structure deterioration, which often results from fatigue process. This mechanism is not well understood yet and for this reason is investigated in the present work.

Note that in the past, moisture susceptibility and moisture damage of AC were studied putting into evidence their long-term consequences on stripping, raveling, shelling and hydraulic scour [5–8]. On the other hand, the impact of frost on pavements was also studied in the laboratory but rather from the sight of the long-term effect of repeated cycles [9,10]. Interestingly, the results from this research shows that the internal structure of AC is modified according to the number of cycles applied, resulting in an increase of void ratio and permeability [11,12] and a decrease of the AC stiffness [13]. All these effects can contribute to weaken AC pavements but cannot explain the sudden and simultaneous onset of potholes.

This paper is divided into three main sections. First we present the experimental testing of partially saturated AC materials. Based on the test results, the development of a constitutive law as well as its implementation in a numerical program is presented in a second part. Finally, this law is validated against experimental data.

2. Experimental testing

Two tests are considered in this section to investigate the behavior of partially saturated AC under freezing. The first test performed according to traction free boundary condition is denoted CTFS which is the acronym for Cooling Test in Free Stress condition. This test is used to evaluate swelling strain that develops in partially saturated AC under freezing condition. The associated dual variable is the freezing-induced stress which is quantified by means of TSRST which stands for Thermal Stress Restrained of Specimen Test. AC samples are subject to restrained strain during this test.

In this section, the AC material used in the present study and the experimental procedures applicable to each tests is detailed prior to the experimental results are commented. Note that even though a single asphalt mixture is considered in this study, we also obtained similar results on other AC formulas composed of different aggregates and bitumen.

2.1. Material properties and preparation of the AC specimens

The asphalt mixture used in this study is designed according to the French formulation method [14] and is denoted BBSG. The aggregate is diorite with nominal size of 0/14 mm; its grading curve is shown in Fig. 1. The binder content is equal to 4.45 ppc and the bitumen grade is 35/50.

The test specimens used in CTFS and TSRST are cored in slabs of BBSG 0/14 that were compacted using the plate-compactor machine. Note that the coring process yields smooth surface of the AC samples well adapted to strain gage measurements. Two series of cylindrical specimens are designed:

- The 6 samples of the first series used only in CTFS are 80 mm in diameter (∅80) and 120 mm in height. These specimens are cored vertically from the same slab.
- The 8 samples of the second series used for both tests are 50 mm in diameter (∅50) and 160 mm in height. These are cored horizontally according to the European standard NF EN 12967-46 [15].

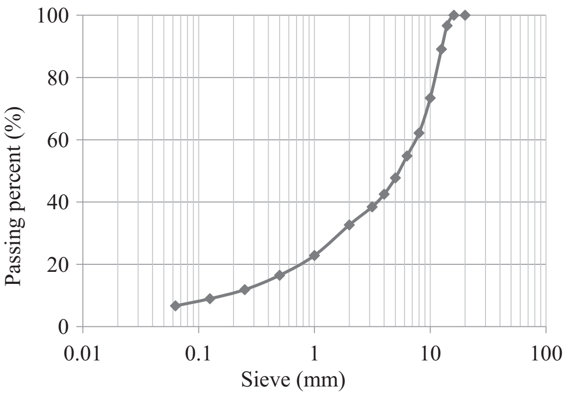

Fig. 1. Grading curve of the aggregates.

Porosity of every specimen is checked by means of the X-ray method [16], which is performed for both dry and partially saturated AC samples. Saturation of an AC specimen is obtained considering the following process: (i) a negative pressure of −86 kPa is applied during one hour to the initially dry specimen placed in a tank, (ii) water is slowly added until full immersion of the specimen then maintaining the negative pressure during three hours. For all the specimens tested, the degree of saturation determined by weight measurements after this process is found to be around 60% (Table 1). Actually, we know from another test campaign not reported in this paper that the current samples loose approximately 10% of degree of saturation by self-draining in a time lapse of 10 h subsequently to this process and prior to decreasing the temperature in the tests.

2.2. Experimental procedures

Some specific experimental devices were developed to perform strain free or stress free tests on AC materials. In particular the Asphalt Thermal Cracking Analyser (ATCA, reference) makes it possible to carry out both tests at the same time on two samples subjected to the same temperature regime. In this research, the devices already available in our laboratory were used to run these two types of test without seeking to enforce similar temperature evolutions to the samples since not required by the development of the constitutive law. Rather some samples were tested successively with CTFS and TSRST devices in order to avoid any material discrepancy in the comparison between the responses of the two tests.

The experimental procedures specific to the CTFS and TSRST tests are described in this section. In particular, instrumentation of the samples is focused on as well as the evolution of temperature imposed to the samples.

2.2.1. Cooling test in free stress conditions (CTFS)

In this test, the cylindrical AC specimens (∅80 × 120mm) are equipped with two strain gages and a temperature sensor glued on surface of the specimen at mid-height (Fig. 2a). One of the strain gages is positioned vertically and thus measures the axial strain while the other placed horizontally measures strain in the (ortho) radial direction. Both gages are protected against external temperature and moisture by a silicone coating.

The instrumented specimens are tested imposing traction-free boundary condition all over their outer surface within a climatic chamber. The controlled temperature of the climatic chamber is varied from 10 °C to −10 °C during 0.5 h (or 40 °C/h) as shown in Fig. 2b. The specimens are tested first under dry conditions and then after partial saturation performed as explained before. The axial and radial strain evolutions are recorded during cooling of the AC samples which are free to deform given the mechanical boundary conditions.

Since strain gages are sensitive to temperature, their raw measurement must be corrected to obtain the correct value of strain under variable temperature. In this study, the correction is done based on the measurement of a particular gage glued on an invar rod also placed in the climatic chamber and thus subjected to the same controlled temperature as the AC samples. Invar is an alloy having a very small coefficient of thermal expansion ($\alpha_{Invar} \approx 0.03$ μm/m/°C).

The strain recorded on the AC sample can be decomposed into the following parts:

$$\varepsilon_{AC}^{measure}(t) = \varepsilon_{AC}^{true}(t) + \varepsilon_{gage}^{err}(t) \tag{1}$$

And that recorded on the Invar rod as follows:

$$\varepsilon_{Invar}^{measure}(t) = \varepsilon_{Invar}^{true}(t) + \varepsilon_{gage}^{err} \tag{2}$$

Quantity $\varepsilon_{gage}^{err}(t)$ reflects the measurement bias brought by the gage sensitivity to temperature. However, considering that α_{Invar} is negligible then $\varepsilon_{Invar}^{true}(t) = \alpha_{Invar}\Delta\theta \approx 0$ and the actual (corrected) strain of AC samples is given by:

$$\varepsilon_{AC}^{true}(t) = \varepsilon_{AC}^{measure}(t) - \varepsilon_{Invar}^{measure}(t) \tag{3}$$