Multi-Phase Material Model for Freezing Damage in Open Graded Asphaltic Mixes

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Summary

The high permeability of open graded asphaltic mixes keeps the wearing surfaces of roads under fairly dry conditions, leaving the asphalt itself at most times partially or fully saturated. During wintertime this water can cause damage due to freezing. A computational model is developed that enables the simulation of the damage that is caused by this freezing action. By varying the material characteristics of the asphalt mix, a sensitivity study is performed. The study shows that damage due to freezing is mainly pronounced in the interface region between the aggregates and the surrounding mastic. The model uses a multiphase material formulation. A Hoffman type fracture criterion is utilized for the simulation of the freezing damage.

Introduction

Open graded asphalt mixes are used for wearing surfaces of roads in countries that have to deal with a lot of rainfall through out the year. The high permeability of this type of asphalt mix ensures a fast drainage of the rain from the wearing surface, and thus increases the road safety. The downside of this high permeability is that the asphalt itself remains partially or fully saturated at most times This paper focuses on the simulation of the damage that is caused when the temperature at the top of the asphalt pavement drops below 0 degrees Celsius, causing the water inside the asphalt to freeze.

Figure 1(a) gives an indication of the composition of a fully saturated open asphaltic mix. The dark blue colour shows the mastic and the red shows the interface areas between the aggregates and the mastic. The density of water above the freezing point is approximately 1.0 g/cm^3. At freezing point the liquid water undergoes a phase change and solidifies. The density of ice is approximately 0.917 g/cm^3. This indicates that when liquid water turns into ice, the volume expands 9 % (1/0.917 =1.09). Consequently, an extra strain of about 3% is imposed on the mix due to the formation of ice, Figure 1(b).

A computational model is developed that enables both the qualification and the quantification of damage caused by this freezing action. Insight into the damage modes is valuable for road design and prevention of damage in asphaltic wearing surfaces due to freezing.

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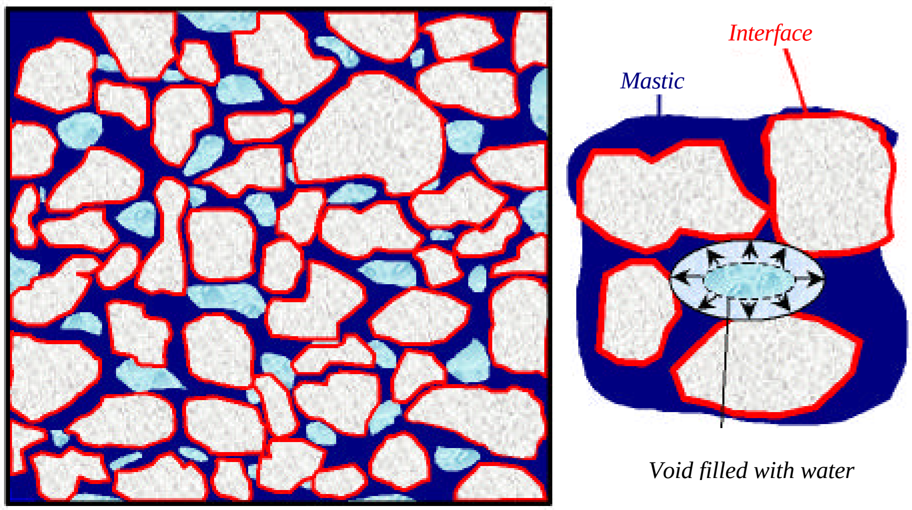

Figure 1: (a) an impression of the composition of a fully saturated open graded asphaltic mix. (b) Volume expansion of the water in the void when turning into ice

Elastic Multi-Phase Material Formulation

Consider a multi-phase material formulation, [1], where one phase represents the asphalt mix and the other phase represents ice. Furthermore, the phase of the asphalt mix consists of an aggregate, a mastic and an interface phase. The stresses in this multi-phase material are

$$\begin{aligned}\sigma_{ij} &= \frac{\partial \Psi}{\partial \varepsilon_{ij}} = \frac{\partial \Psi^{a}}{\partial \varepsilon_{ij}} \cdot \frac{V^{a}}{V} + \frac{\partial \Psi^{ice}}{\partial \varepsilon_{ij}} \cdot \frac{V^{ice}}{V} \\ &= \frac{\partial \Psi^{ag}}{\partial \varepsilon_{ij}} \cdot \frac{V^{ag}}{V} + \frac{\partial \Psi^{m}}{\partial \varepsilon_{ij}} \cdot \frac{V^{m}}{V} + \frac{\partial \Psi^{if}}{\partial \varepsilon_{ij}} \cdot \frac{V^{if}}{V} + \frac{\partial \Psi^{ice}}{\partial \varepsilon_{ij}} \cdot \frac{V^{ice}}{V} \qquad (1) \\ &= \sigma^{ag} n^{ag} + \sigma^{m} n^{m} + \sigma^{if} n^{if} + \sigma^{ice} n^{ice}\end{aligned}$$

where Ψ is the strain energy function of the material and n^{ag}, n^{m}, n^{if} and n^{ice} are the volume fractions of the aggregates, the mastic, the interface and the ice phase, respectively.

In terms of the respective material constants, assuming a negligible shear modulus for ice, the three dimensional stress components can be expressed as

$$\sigma_{ij} = \left[\left(K^{a} - \tfrac{2}{3}G^{a}\right)\varepsilon_{kk}\,\delta_{ij} + 2G^{a}\varepsilon_{ij}\right]n^{a} \;+\; K^{ice}\left(\varepsilon_{kk} - \kappa\left|\Delta T\right| - \varepsilon_{\phi}\right)n^{ice}\,\delta_{ij} =$$
$$= \left[\left(K^{ag} - \tfrac{2}{3}G^{ag}\right)\varepsilon_{kk}\,\delta_{ij} + 2G^{ag}\varepsilon_{ij}\right]n^{ag} + \left[\left(K^{m} - \tfrac{2}{3}G^{m}\right)\varepsilon_{kk}\,\delta_{ij} + 2G^{m}\varepsilon_{ij}\right]n^{m}$$
$$+ \left[\left(K^{if} - \tfrac{2}{3}G^{if}\right)\varepsilon_{kk}\,\delta_{ij} + 2G^{if}\varepsilon_{ij}\right]n^{if} \;+ K^{ice}\left(\varepsilon_{kk} - \kappa\left|\Delta T\right| - \varepsilon_{\phi}\right)n^{ice}\,\delta_{ij} \tag{2}$$

Note that in Eq.(2) the strain caused by the formation of ice consists of two parts: the strain caused by the linear temperature expansion, $\kappa\Delta T$, and the strain that is caused due to the phase change, ε_{ϕ}. Since the phase change imposes a strain of 3% and the temperature expansion coefficient of ice, κ, is 50e-6 K^{-1}, the volume expansion of ice due to a further drop of the temperature can be neglected for the case under consideration.

In the model, the aggregates are assumed linear elastic. For the simulation of damage in the mastic and the interface regions however, a Hoffman type fracture criterion is utilized.

Cracking Simulation

The theory of plasticity is used as a platform for the development of a three dimensional fracture criterion for the mastic and the interface phases. Along the lines of the classical notion of fixed cracking, for states of stress exceeding the magnitude of the Hoffman surface, shown in Figure 2(b), a plane of cracking is introduced perpendicular to the principal tensile stress direction, for the mastic and interface regions. On the crack plane, the criterion specified to control the subsequent softening response [2],[3] is:

$$\sigma^{2} + q\left(\tau_{s}^{2} + \tau_{t}^{2}\right) = f_{t}^{2}\left(\dot{\delta}, T, \alpha\right) \tag{3}$$

in which σ is the normal stress on a given crack plane of any given phase, Figure 2(a), τ_{s} and τ_{t} are the shear stress components, f_{t} the uniaxial tensile stress after crack initiation and α some measure of softening.

Up to three orthogonal cracking planes can be introduced at a material point, Figure 3(a). Compatibility of shear stresses along orthogonal crack planes is ensured, Figure 3(b).

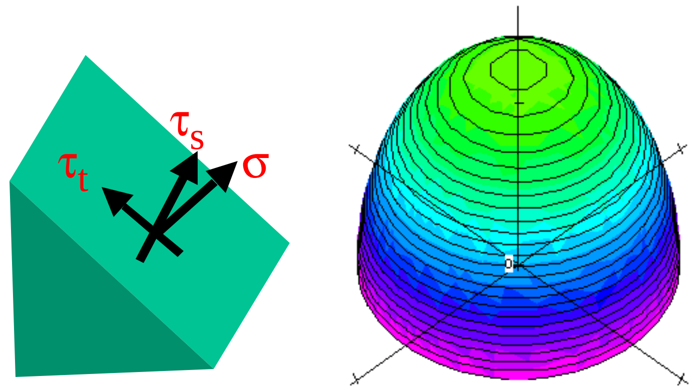

Figure 2: (a) Stresses on crack plane, (b) Schematic of Hoffman surface on crack plane

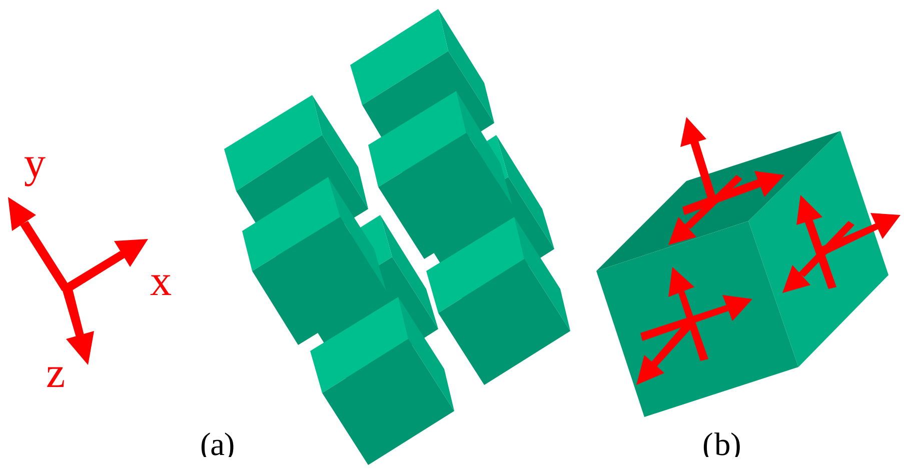

Figure 3: (a) Orthogonal cracking planes,(b) Shear stresses compatibility on cracking planes

Numerical Simulation

For the simulation of damage due to freezing, an open graded asphaltic mix of the following volume percentages is considered: 20% voids, 60.7% aggregates, 12.3% mastic and 7% interface regions. The Finite Element mesh represents a cube of asphalt of 20 cm by 20 cm, which is restrained in three orthogonal planes. At $t=t_0$ the mix is fully saturated and has a temperature throughout the specimen of +1 °C. At $t=t_1$ the top half of the specimen reaches the temperature of -5°C, Figure 4. The analyses are made with CAPA-3D [4].

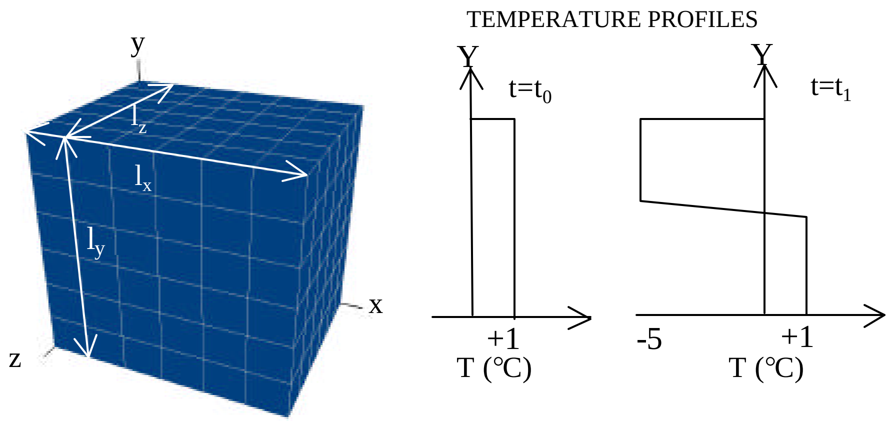

Figure 4:Applied temperature profiles

The stiffness of the mastic, E^m, at these temperatures is estimated at 3000 MPa and the tensile strength of the mastic f_t^m is taken at 2.0 MPa. The stiffness of the aggregate phase, E^{ag}, is 4000 MPa. The poison ratio, ν, of each phase is kept at 0.2.

A sensitivity study has been performed in which the material parameters were varied. It has been concluded that damage due to freezing is mainly pronounced in the interface regions around the aggregates. As expected, this adhesive debonding increases with lower tensile strengths and higher stiffness of the interface phase.

Figure 5 shows the distribution of cracking damage in the interface phase of the material for a range of interface tensile strengths. Cracking damage is defined as

$$\text{Cracking} = \sqrt{\varepsilon^2_{\text{cr,plane1}} + \varepsilon^2_{\text{cr,plane2}} + \varepsilon^2_{\text{cr,plane3}}} \qquad (4)$$

in which $\varepsilon_{\text{cr,plane}\,i}$ is the cracking strain on the i^{th} crack plane.

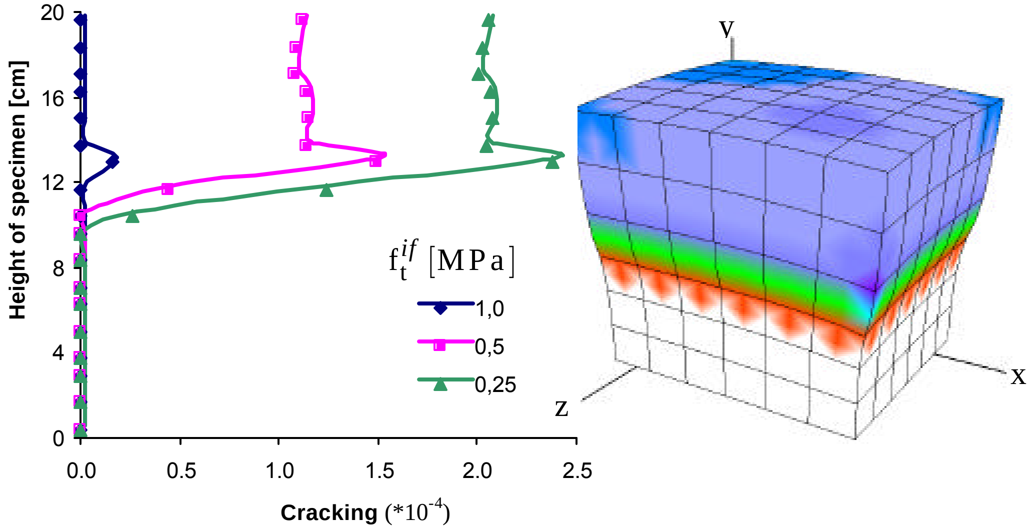

Figure 5: Cracking in the interface region for different tensile strengths of the interface. The stiffness of the interface region is 5000 MPa.

Similar analyses were performed for densely graded mixes with an effective void ratio of 4-10%. It was found that in this type of mixes damage due to freezing is not a main concern. Of course this observation is not valid for cracked pavements where water can infiltrate and collect in the cracked faces resulting thus to freezing damage.

References

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