Advances in Computational & Experimental Engineering & Science

Development of a Finite Element Tool for Simulation of Ravelling of Asphaltic Mixes

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Summary

Open graded asphalt mixes are often used for wearing surfaces of roads that are exposed to large amounts of rainfall throughout the year. The high permeability of the mix guarantees a fast drainage of the water away from the surface, thus increasing the road safety. However, the large amounts of water that flow through the asphalt have a negative effect on the material characteristics of the mastic and cause debonding of the aggregates from the mastic. For this purpose an extensive, experimental and analytical, investigation is being undertaken at TU Delft. The goal of the investigations is the development of the Finite Element tool RoAM (Ravelling of Asphalt Mixes), capable of simulating the gradual development of damage throughout asphalt mixes due to water infiltration. Advection, diffusion, dispersion and desorption are included as fundamental processes. Some preliminary results of the utilization of RoAM for the simulation of the washing away of mastic from an asphalt mix are presented.

Introduction

In countries that suffer from large amounts of rainfall each year, the asphalt wearing surfaces of the roads are often constructed of open graded asphalt mixes. The high permeability of these wearing surfaces ensures a fast drainage of the water away from the surface, thus increasing the road safety. This water infiltration has, however, a negative effect on the material characteristics of the individual components of the asphalt and damages the bonds between the components, leading to premature separation of the aggregates from the wearing surfaces (ravelling). Insight into the different phenomena that cause ravelling will lead to better asphalt mix design and better road maintenance strategies.

For this reason a Finite Element tool, named RoAM (Ravelling of Asphalt Mixes), is being developed as a sub-system of INSAP [1]. RoAM enables the simulation of water flow through open graded asphalt mixes. The phenomenon of ravelling of asphalt mixes is a complicated process that involves diffusion through the interfaces of the asphalt components, desorption of the mastic from the aggregates, chemical reactions of the salt species in the water with the mastic film and constant changing material characteristics and surface energy properties. In the following, the flow and transport equations are derived for the particular case of simulation of water infiltration through asphalt mixes.

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Proceedings of the 2004 International Conference on Computational & Experimental Engineering & Science
26-29 July, 2004, Madeira, Portugal

Derivation of the Flow Equations

For a generic conserved variable ψ the conservation equation may be written as [2]:

$$\mathrm{div}(\rho\mathbf{v}) - \mathrm{div}\mathbf{F} = \frac{\partial(\rho\psi)}{\partial t} \tag{1}$$

where $\mathbf{v}$ is the local velocity value of ψ, $\mathbf{F}$ is the flux vector associated with ψ and $\frac{\partial(\rho\psi)}{\partial t}$ is the rate of change of the mass of ψ.

According to Darcy's Law

$$\mathbf{v} = \mathbf{K}\nabla\Phi \tag{2}$$

where the hydraulic conductivity tensor $\mathbf{K}$ can be related to the intrinsic permeability $\mathbf{k}$ via

$$\mathbf{K} = \frac{\mathbf{k}\rho}{\mu} \tag{3}$$

where ρ is the density of the fluid and μ is the dynamic viscosity of the fluid.

The quantity of flow per unit time through a porous medium is proportional to the hydraulic gradient. The hydraulic gradient is defined in relation to the gradient of the hydraulic potential. The hydraulic potential Φ is composed of the following [3]:

$$\Phi = \Phi_D + \Phi_P + \Phi_v \tag{4}$$

where the components are defined as the datum potential Φ_D, the pressure potential Φ_P and the velocity potential Φ_v. In most general cases $\Phi_D + \Phi_P \gg \Phi_v$, consequently, the hydraulic potential takes the reduced form:

$$\Phi = \Phi_D + \Phi_P = \rho g z + p \tag{5}$$

in which z is the hydraulic height and p is the pore pressure.

The flux $\mathbf{F}$ carried by the general flow field is defined as:

$$\mathbf{F} = \rho n S \mathbf{v}_c \tag{6}$$

where ρ is the fluid density, n is the porosity of the solid, S is the degree of saturation and $\mathbf{v}_c$ is the velocity of the deformed solid asphalt components due to consolidation of the mix.

By substituting (2), (3), (5) and(6) into (1) and defining $\psi = nS$, the conservation equation for flow can be written as:

$$\mathrm{div}\left[\frac{\rho \mathbf{k}}{\mu}\left(\rho g\,\mathrm{grad}\,z + \mathrm{grad}\,p\right)\right] - \mathrm{div}\left(\rho n S \mathbf{v}_c\right) = \frac{\partial(\rho n S)}{\partial t} \tag{7}$$

where the terms on the left hand side are the diffusion flux and the convection flux, respectively.

By expanding the right hand side of (7), postulating that $\rho = \rho(p, C)$ and $S = S(p)$, where p is the fluid pressure and C is a chemical species (for instance salt):

$$\frac{\partial(\rho n S)}{\partial t} = nS\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial t} + nS\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} + \rho S\frac{\partial n}{\partial t} + \rho n\frac{\partial S}{\partial p}\frac{\partial p}{\partial t} \tag{8}$$

where the second term on the right hand side shows the coupling between the density and the concentration.

By substituting (8) into (7), rewriting $\mathrm{div}\left(\rho n S \mathbf{v}_c\right) = \rho S\,\mathrm{div}\left(n\mathbf{v}_c\right)$ (whereby making the approximation of neglecting the second order term $n\mathbf{v}_c\,\mathrm{grad}\left(\rho S\right)$) gives:

$$\begin{gathered}\mathrm{div}\left[\frac{\rho \mathbf{k}}{\mu}(\mathrm{grad}\,\Phi)\right] = \\ nS\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial t} + nS\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} + \rho S\frac{\partial n}{\partial t} + \rho n\frac{\partial S}{\partial p}\frac{\partial p}{\partial t} + \rho S\,\mathrm{div}\left(n\mathbf{v}_c\right)\end{gathered} \tag{9}$$

The mass conservation rule postulates that the rate of decrease of a mass in a region is equal to the net transfer out of the region [3]. By applying this rule to the solid components of the asphalt, using the divergence theorem, it follows that:

$$\frac{\partial(1-n)}{\partial t} = -\mathrm{div}\left[(1-n)\,\mathbf{v}_c\right] \tag{10}$$

which can be rewritten as:

$$\frac{\partial n}{\partial t} + \mathrm{div}\left(n\mathbf{v}_c\right) = \mathrm{div}\,\mathbf{v}_c \tag{11}$$

Furthermore, the flux of solid velocity is the divergence of $\mathbf{v}_c$:

$$\alpha \frac{\partial p}{\partial t} = \mathrm{div}\, \mathbf{v}_c \tag{12}$$

where α is the consolidation coefficient of the material.

By substituting (11) and(12) into (9) and replacing $\frac{\partial \rho}{\partial p} = \rho c_f$ and $nS = \theta$ the equation for the flow of water through the pores of an asphalt mix is obtained as:

$$\begin{aligned} &\mathrm{div}\left[\frac{\rho \mathbf{k}}{\mu}(\mathrm{grad}\Phi)\right] = \\ &\theta \frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} + \rho n \frac{\partial S}{\partial p}\frac{\partial p}{\partial t} + \theta \rho \left(c_f + \frac{\alpha}{n}\right)\frac{\partial p}{\partial t} \end{aligned} \tag{13}$$

where c_f is the compressibility of the water and θ is the moisture content.

Derivation of the Transport Equations

The fundamental processes of advection, diffusion, dispersion and desorption that occur in an asphalt mix are simulated by the transport equations. On the basis of the mass balance principle it holds:

$$\frac{D}{Dt}\int_V (\theta C_d + \rho_b C_a)\, dv = -\int_\Gamma \mathbf{n}(\mathbf{v} C_d)\, d\Gamma - \int_\Gamma \mathbf{n}\mathbf{J}\, d\Gamma \tag{14}$$

where C_d, C_a, ρ_b and $\mathbf{v}$ are the dissolved concentration, the adsorbed concentration, the bulk density and Darcy's velocity, respectively. $\mathbf{J}$ is the surface flux with respect to the fluid velocity.

By applying the Reynold's transport theorem and the divergence theorem, (14) can be rewritten in differential form:

$$\begin{aligned} &\frac{\partial (\theta C_d + \rho_b C_a)}{\partial t} + \mathrm{grad}(\theta C_d + \rho_b C_a)\mathbf{v}_c + (\theta C_d + \rho_b C_a)\mathrm{div}\, \mathbf{v}_c = \\ &-\mathrm{div}(\mathbf{v} C_d) - \mathrm{div}\, \mathbf{J} \end{aligned} \tag{15}$$

By substituting (12) into (15) and by neglecting the second term of (15):

$$\frac{\partial\left(\theta C_d + \rho_b C_a\right)}{\partial t} + \alpha\left(\theta C_d + \rho_b C_a\right)\frac{\partial p}{\partial t} = -\mathrm{div}\left(\mathbf{v} C_d\right) - \mathrm{div}\,\mathbf{J} \tag{16}$$

The surface flux $\mathbf{J}$ is postulated to be proportional to the gradient of C_d [4] as

$$\mathbf{J} = -\theta \mathbf{D} \cdot \mathrm{grad}\, C_d \tag{17}$$

where $\mathbf{D}$ is the diffusion/dispersion coefficient tensor.

Simulation of Desorption of Mastic from Asphalt Mixes

Simulations are made of an impermeable aggregate covered with a mastic film, embedded in a mastic layer from one side and exposed to a steady field of water flow of 0.5 m/hour, Figure 1.

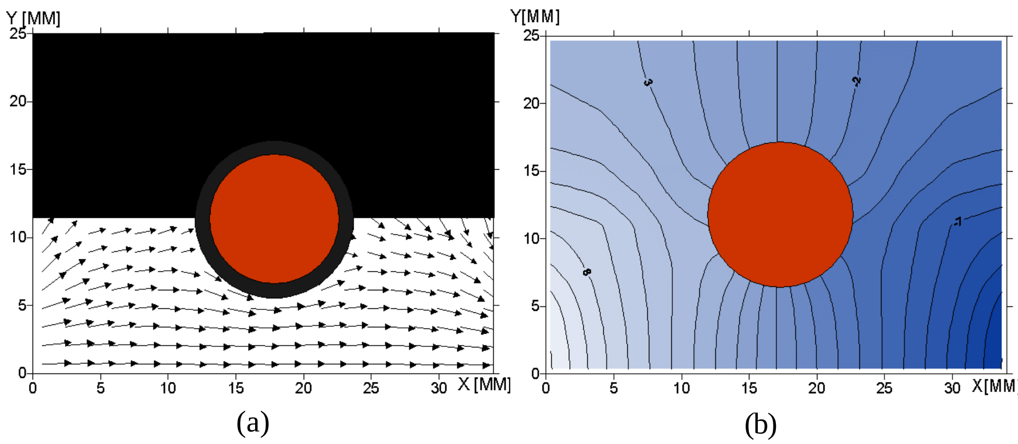

Figure 1:(a) Direction of the flow field around an embedded aggregate
(b) Distribution of the water pressure field around an embedded aggregate

The current simulations are meant to show the phenomena of diffusion of water through the mastic film and desorption of the mastic from an asphalt mix due to water infiltration. For these simulations the mastic has been assigned assumed coefficients for the distribution, the diffusion and the dispersion. The simulations should be looked upon as qualitative only. Laboratory experiments are currently being organized to provide actual values for these coefficients.

The simulations indicate that a relatively thick film (ratio of mastic film thickness to aggregate diameter t/D=0.3) shows a clear gradient in desorption of the mastic film over the thickness, Figure 2. The mastic particles at the outside surface of the film tend to be washed off faster than the mastic particles that are closer to the aggregate. A thinner film (t/D=0.03) gives, for the same set of parameters, a more uniform desorption development.

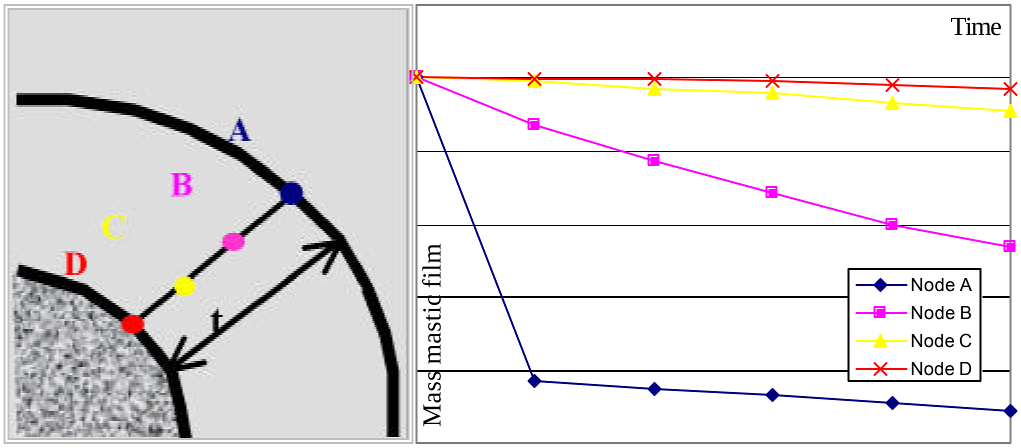

Figure 2: Rate of washing off of mastic surrounding an aggregate. For a ratio of mastic film thickness to aggregate diameter t/D= 0.3.

Conclusions

By varying the material parameters of the different components in the asphalt mix, by incorporating the characteristics of the bond between the aggregates and the mastic and by simulating different 3D geometries, insight shall be gained towards the development of ravelling damage in open graded asphaltic mixes, and its prevention.

References

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