Simulation of Compaction in Asphaltic Mixtures, Part I: Gyratory Compactor

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Abstract

A very important phase in construction of a pavement structure is the compaction process of the asphaltic mixture. It reflects a complex mechanism where many parameters are influential. These parameters are associated with the initial air voids content in the asphaltic mixture, aggregate gradation and angularity, asphalt binder content and its viscosity, asphaltic mixture layer thickness, compaction pattern, equipment and temperature cooling rate. In general, the pavement constructors perform the most of their decision making and planning process according to their engineering judgment and monitoring of field data. Although these methods are well accepted by the road industry, still the availability of a reliable software tool to simulate the mechanical behavior of the asphaltic mixtures during compaction and foreseeing the optimum compaction pattern is highly demanded. In this work, a compaction model for asphaltic materials is developed using the finite element software package COMSOL where it receives the input parameters such as initial air void and temperature dependent properties of granular structure bounded by asphalt binder and utilizes the Solid Mechanic Module and Heat Transfer Module within a time dependent analysis to simulate the compaction process of asphaltic mixtures by gyratory compaction.

Keywords

Compaction; Finite element modelling; Asphaltic mixtures; Gyratory compactor

Introduction

Compaction of asphaltic mixtures is a complex mechanism. Many parameters influence this process through characteristics of the asphaltic mixture such as initial air voids, aggregates gradation, form and angularity, asphalt binder content and its viscosity or through the compaction operation, such as compaction equipment and pattern, layer thickness and initial temperature of the asphaltic mixture.

The pavement constructor should perceive the influence of the above mentioned parameters on the compaction procedure. Next to that, (s)he should consider various aspects such as functionality of the road, future traffic and environmental conditions to improve the quality, durability and sustainability of the asphaltic pavements as an infrastructural asset. Having insight in these influential parameters and their effects on the pavement performance can inspire the constructor to make the right decisions aiming for optimization of the compaction process.

Generally, the decision making process by the constructor is based on experts judgment or resulting from past experiences and laboratory results. Both approaches have uncertainties and will not necessarily provide the optimum solution in terms of time, money and quality. Alternatively, utilizing a model that can predict the compaction curve before construction can help the constructor to estimate the effect of each of the influential parameters on the compaction curve, [1].

The internal structure of asphaltic mixture, which refers to the arrangement of granular materials and their associated air voids, has a significant effect on the compaction process and performance of asphaltic mixture, [2]. During compaction, the granular structure rearranges internally and the air voids content among granular materials decreases. This process leads to a stiffer granular structure and a denser asphaltic mixture. With regard to the modelling aspect of the compaction process, a study through the behavior of granular materials during compaction can give a clear view of the behavior of asphaltic mixtures. However, the key role of asphalt binder in lubricating granular materials and its contribution in the stiffness of asphaltic mixture at lower temperature cannot be disregarded. As such, the compaction model is developed primarily on the basis of granular materials and adjusted subsequently to incorporate the temperature dependency of the asphalt mixture.

This paper describes the required steps and the utilized modules from COMSOL that have been employed to develop the compaction model. The paper is structured as follows: first, the Solid

Mechanics and Heat Transfer modules and their mathematical background are stated. Then, the boundary conditions, geometry and computational aspects of simulating the Superpave Gyratory Compactor (SGC) are described. Finally, the results of simulation the gyratory compactor are presented. Here the results show that the created model is capable of simulating the temperature drop and the initial and gradual compaction of the asphaltic mixture.

Compaction Process of Asphaltic Mixtures

To develop the compaction model, we started with investigating the mechanical response of granular materials. Then, we extended our attention towards the effect of asphalt binder as a lubricant and/or glue in the asphaltic mixture.

Experiments on granular materials under confinement showed the volume changes due to the mechanical load, [3]. When the load is eliminated, part of the change of volume is recoverable, though the material never reaches its initial volume. In other words, due to air void reduction, plasticity occurs. Hence, an elastoplastic model in the framework of continuum mechanics theory could be a suitable choice to simulate this phenomenon. This model should fulfil the following conditions:

- The mathematical formulation of the yield surface should result to a closed, convex and smooth surface in stress space.
- The constitutive model should be able to predict the essential performance of the granular material.
- The parameters of the model should be determined from standard test data.
- The model should consider the pressure sensitivity response of the granular materials.

The Cam-clay yield surface is a common yield surface that is being used to describe the elastoplastic behavior of granular materials and accomplishes the above conditions. As such, we utilized the Cam-clay elastoplasticity model which is a subcategory of Solid Mechanics module in COMSOL.

In addition, the Heat Transfer module was utilized to simulate the heat flux in the asphaltic material during compaction. Since the Solid Mechanics module and Heat Transfer module include different types of physics, solving them together requires a Multiphysics approach in COMSOL.

Finally, we adjusted the input parameters of the Cam-clay elastoplasticity model to make it suitable for asphaltic materials. As such, the Cam-clay model was able to simulate the stiffening of the asphaltic material due to the temperature drop (presence of asphalt binder) and the cyclic load.

Governing Equations for Cam-clay Model

The Cam-clay model was formulated by Roscoe, to simulate the light overconsolidated clays during triaxial test. This model was later modified by Roscoe and Burland and called Modified Cam-clay [4]. Both models have been developed based on critical state theory and consider strain hardening. As such, the loading and unloading of the material follows different trajectories in stress space.

According to the Solid Mechanics module in COMSOL and considering positive values for $\mathbf{p, q \text{ and } p_C}$, the yield surface for modified Cam-clay is formulated as:

$$\mathbf{F(p,q,pc) = q^2 + M^2\,(p - p_C)}, \qquad (1)$$

where M is the slope of critical state line in q-p plane and $\mathbf{p_C}$ is the hardening parameter. This parameter is the intersection point of yield cap with p axis and in soil mechanics is called preconsolidation pressure. The formulation of the yield surface in p-q space represents an elliptical surface with a cross section independent of the Lode angle, Figure 1.

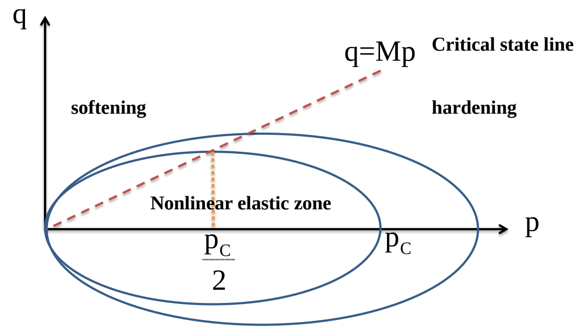

Figure 1. Cam-clay yield surface

In this model, the hardening is controlled by preconsolidation pressure $\mathbf{p_C}$ which evolves as a function of volumetric plastic strain $\boldsymbol{\varepsilon}_\mathbf{p}^\mathbf{v}$ as:

$$\mathbf{pc = pc0\ exp\ (-B_p \varepsilon_p^v)}, \qquad (2)$$

where $\mathbf{pc0}$ is the initial preconsolidation pressure and $\mathbf{B_p}$ is a parameter that depends on the initial void ratio $\mathbf{e_0}$, the swelling index $\hat{\boldsymbol{\kappa}}$ and the compression index $\hat{\boldsymbol{\lambda}}$ as:

$$\mathbf{B_p} = \frac{\mathbf{1+e_0}}{\hat{\boldsymbol{\lambda}}-\hat{\boldsymbol{\kappa}}}. \tag{3}$$

In this formulation, $\hat{\boldsymbol{\kappa}}$ is obtained as the slope of loading-unloading line and $\hat{\boldsymbol{\lambda}}$ is obtained as the slope of compression line in the $\mathbf{e-ln(p)}$ plane, Figure 2.

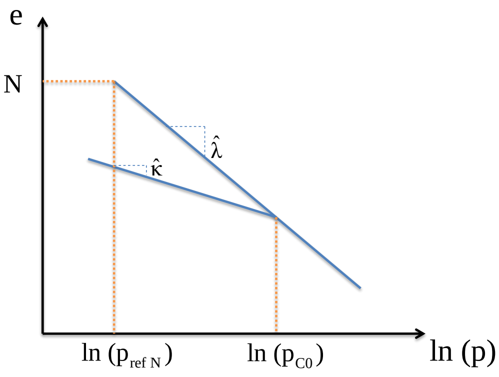

Figure 2. $e-\ln(p)$ plane, the reference void ratio N is measured at the reference pressure p_{refN}

Governing Equations for Heat Transfer

When an asphaltic mixture is placed in the gyratory mold, initially it has a very high temperature. As such, the heat will be transferred from the hot mixture to the environment.

Heat transfer in asphaltic mixture occurs by conduction (or diffusion). Conduction happens in stationary solids or liquids via a temperature gradient through diffusion. In a continuous medium, with respect to Fourier's law, the conductive heat flux q is proportional to temperature gradient $\mathbf{\nabla T}$ as following:

$$\mathbf{q = -\lambda_T \nabla T}, \tag{4}$$

where $\boldsymbol{\lambda_T}\ [\frac{W}{m}.K]$ represents the thermal conductivity of the material.

Utilizing Fourier's law and considering energy conservation law, the heat transfer via conduction can be formulated as:

$$\boldsymbol{\rho C_T \frac{\partial T}{\partial t} - \nabla(\kappa_T \nabla T) = Q}, \tag{5}$$

where $\boldsymbol{\rho}\ [\frac{\mathbf{kg}}{\mathbf{m^3}}]$ is the density, $\mathbf{C_T}\ [\frac{\mathbf{J}}{\mathbf{kg}}.\mathbf{K}]$ is the heat capacity and $\mathbf{Q}\ [\frac{\mathbf{W}}{\mathbf{m^3}}]$ is the additional heat source.

Computational Model Description

Geometry

A cylinder with dimension of 250 mm height and 150 mm radius is made in COMSOL similar to the geometry and dimensions of the gyratory compactor mold, Figure 3.

Mesh

Tetrahedral elements are used for meshing the geometry in COMSOL, Figure 3.

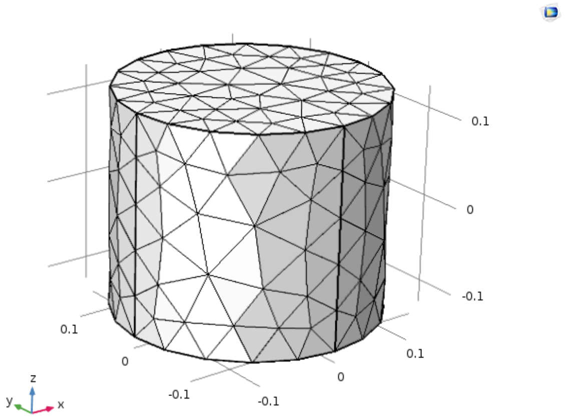

Figure 3. Mesh and geometry of the compaction model

Boundary conditions

Similar to the gyratory compactor mold, the lateral sides of the cylinder are constrained with respect to x and y axis. In addition, the bottom side of the mold follows a gyratory motion with 1.25° inclination and rotates with 30 rotations per minute. This feature is added to the boundary condition of the mold via defining a rigid body connector. The details of prescribed rotation of this connector are shown in Table 1.

Table 1. Prescribed rotation of rigid connector

Axis of rotation x	$\mathbf{sin}(\boldsymbol{\pi t})$
Axis of rotation y	$\mathbf{cos}(\boldsymbol{\pi t})$
Axis of rotation z	0
Angle of rotation	$\mathbf{1.25}^\circ$

Additionally, the heat equation accepts the heat flux as a boundary condition, where it can be formulated as:

$$-\mathbf{n}.\mathbf{q} = \mathbf{q_0}. \qquad (6)$$

In Eq. (6), q is the heat flux vector, n is the normal vector on the boundary and $\mathbf{q_0}$ is the convective heat flux, normal to the boundary. The heat flux exists due to the difference between the temperature of the environment $\boldsymbol{T_{ext}} = \mathbf{293.15}\ \boldsymbol{K}$ and the temperature of the mixture in the mold $\boldsymbol{T}[\ \boldsymbol{K}]$. In this regard, $\mathbf{q_0}$ is assumed to be equal in all directions and is obtained by the following equation:

$$\mathbf{q_0} = \boldsymbol{h}(\boldsymbol{T_{ext}} - \boldsymbol{T}), \qquad (7)$$

where h is the heat transfer coefficient.

Applied load

The top surface of the mold in the compaction model is subjected to a uniform pressure equal to 600 kPa. While, the applied pressure is constant, the gyratory motion of the bottom of the mold causes a complex type of load which is applied on the asphaltic material.

Material properties

The material properties used for the Cam-clay model is presented in Table 2 and the material properties related to heat conduction are shown in Table 3, respectively.

Table 2. Material properties related to Cam-clay model

Poisson's Ratio	$\nu = 0.35$
Density	$\rho = 2400\ [\frac{kg}{m^3}]$
Cam-clay M parameter	M =1.8
Swelling index	$\hat{\kappa} = 0.013$
Compression index	$\hat{\lambda}$ =0.032
Void ratio at reference pressure	N = 0.4
Reference pressure for the parameter N	100 $[kPa]$
Initial void ratio	$e_0 = 0.35$
Reference pressure for parameter N	$p_{refN} = 100$ [kPa]
Initial consolidation pressure	pc0 = 200 [kPa]

Table 3. Thermal properties of the asphaltic mixture

Specific heat Capacity, C_p	$1350\ [\frac{J}{kg.K}]$
Thermal conductivity, λ_T	$1.63\ [\frac{W}{m.K}]$
Heat transfer coefficient, $\boldsymbol{h}$	$76\ [\frac{W}{m^2.K}]$

The data in Table 2 are based on assumptions and the data in Table 3 are chosen according to the work of Luca and Mrawira [5]. The initial temperature of the asphaltic mixture is assumed to be $150^o\ C = 423.15\ K$.

Study

A time dependent study is considered for the simulation of compaction for a duration of 15 seconds.

Remarks

The standard Cam-clay elastoplasticity model in COMSOL cannot predict the compaction and volume reduction due to the gyratory motion and cyclic load. We have modified the formulation of the preconsolidation pressure to make the Cam-clay elastoplasticity applicable for prediction of the compaction as a consequence of both initial load and gyratory motion.

In addition, due to the temperature drop and presence of asphalt binder, the shear strength of asphaltic mixture increases during the compaction process. As such, the parameter M gradually increases. By defining a function that shows the increase of M due to temperature drop, we (i) couple the Solid Mechanics module and Heat Transfer module and (ii) consider the increase in shear strength of the asphaltic mixture.

Results

The results of the analysis for 15 seconds and the stress distribution are shown in Figure 4. As can be seen from the figure, the volume of the cylinder decreases during the compaction and plasticity occurs. A major part of this compaction is due to initial load and a minor part is due to the gyratory motion of the compactor.

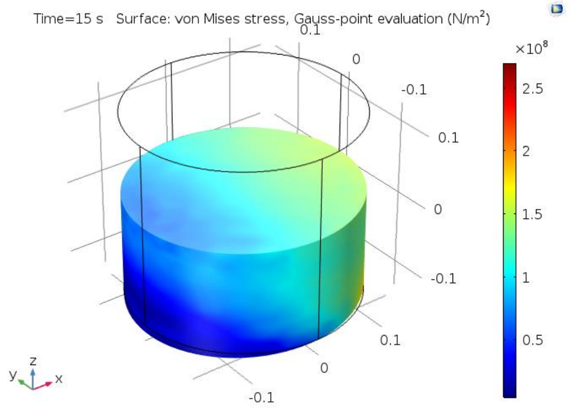

Figure 4. Von Mises stress distribution in the asphalt mixture in the mold after 15 seconds of simulation

The compaction curve is shown in Figure 5. It can be seen that initially the asphalt mixture compacts significantly and with time, the rate of the compaction decreases.

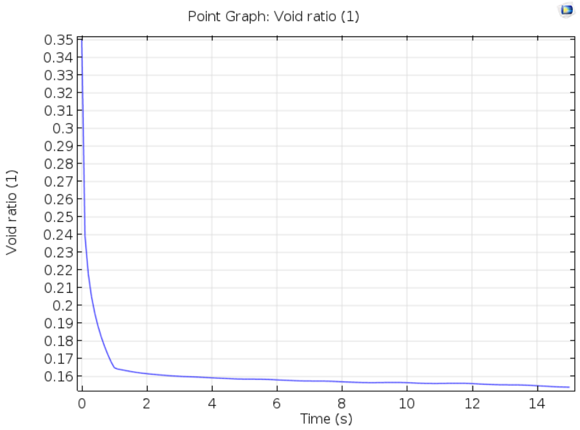

Figure 5 Compaction curve obtained from the compaction model

The results of heat transfer and temperature variation of the mold after 15 seconds are shown in Figure 6. The temperature drops faster in areas close to the boundaries of the cylinder compared to the areas close to the center of the mold.

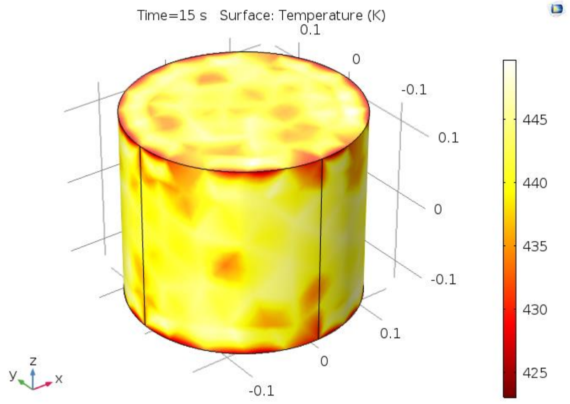

Figure 6. Temperature on the boundaries of the asphaltic mixture in the mold after 15 seconds of simulation

Conclusions

A compaction model is implemented in COMSOL by using both Solid Mechanics and Heat Transfer modules. The Cam-clay model in the Solid Mechanics module simulates the behavior of asphaltic mixtures during compaction procedure. Since some of its parameters are defined as a function of temperature, the Solid Mechanics and Heat Transfer modules are coupled together via a Multiphysics tool.

The model simulates the compaction of an asphalt concrete in gyratory compactor. The results show that the model can provide realistic results of the initial compaction and gradual compaction due to the initial load and gyratory movement of the mold, respectively.

The parameters that were used for the model should subsequently be evaluated and validated with experimental data. This is part of ongoing work and the results of the model for different types of mixtures will be published in a the future.

Due to the known variation in rearrangement of granular materials, the interaction of granular materials and asphalt binder and the temperature , the compaction of asphaltic mixture is actually a stochastic phenomenon. As such, a stochastic perspective should be considered for the model to bring into account these uncertainties.

Hence, for future work, we recommend to add a stochastic perspective to the compaction model. As such, the lower and upper bounds of the compaction range can be obtained to help in utilizing the compaction model for a broader range of materials and conditions, Figure 7.

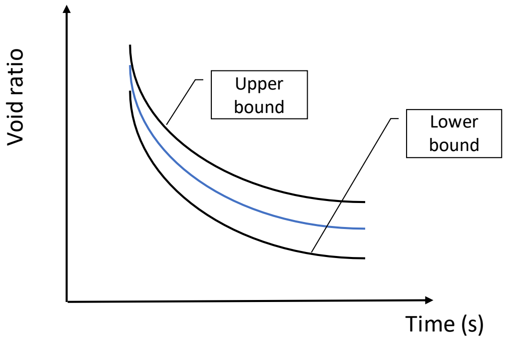

Figure 7 Stochastic model for prediction the lower and upper bounds of the compaction curve

Implementing the above perspectives will help in to develop a stochastic compaction model based on experimental data. Such a model can be used for simulation of other types of compaction methods; i.e., the slab compactor in the laboratory or field roller compactors.

Finally, the output of the compaction model will be the compaction curve/range which shows the progress of air void removal from the asphaltic mixture during the time of compaction. The pavement constructor can provide the required parameters of the model and compare the desired compaction curve with the output of the model. As such, if the difference between the two curves is significant, (s)he may adjust some of the input parameters to achieve the optimum condition. Accordingly, the best combination of input parameters promotes reliable decision makings on mixture design, equipment, compaction pattern and initial temperature of the asphaltic mixture during the compaction procedure. Subsequently, the model contributes to high quality pavements.

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