Asphalt mixture performance and testing

Life optimisation tool for porous asphalt using multiscale modelling

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Abstract

With the objective of extending the service life of an porous asphalt mixture, an FE modelling approach was developed to predict the mechanical response of the mixture at the mesoscale, the scale of the aggregates, calculate the homogenous properties then evaluate the performance of the asphalt under a cyclic loading. This project is divided into 3 phases and this paper presents the results of the second phase. In the first phase, samples of asphalt mixture were scanned and a 3D realistic model was created. The model accounts for the visco-elastic response of the mortar, the adhesive zone between the aggregates and the mortar and the detailed geometry of the aggregates. The realistic model was used to characterise the asphalt mixture and identify the relevant parameters to include in the predictive model. In the second phase, a new model based on a representative volume element (RVE) has been developed. The model idealises the asphalt mixture but still accounts for the geometrical characteristics of the aggregates and the mortar. A Python script was written to automatically create the geometry and generate the mesh. The FE-RVE plug-in can then be used to calculate the homogenised properties. This allows for multiple iterations over various types of mixture in order to design a specific asphalt for each application. Finally, in the last phase of the project, a macromodel of the asphalt with multiple layers will be created using the properties obtained from the RVE model. The life of the asphalt under a representative cyclic load will be estimated using an energy based approach.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

1.1. Background

In pavement engineering the quality of asphalt pavements is often put into terms of service life. Clients formulate their demands based on the desirable service life and contractors deliver pavements with an intended service life. Research as well is aimed at doubling or increasing the service life. This doesn't come across as strange, or does it? Actually, the quantification of an asphalt pavement's service life is not (yet) possible. The need for a validated and accepted predictive model for asphalt pavements is clear. This model will help transform the present, fairly abstract term 'service life' into a quantifiable and transparent product. Fact is that currently there are no models available and when access to such a model is gained, they prove not to meet the requirements regarding output, applicability to user needs, capacity and above all user expectations.

1.2. Objective

To develop a predictive tool that can help characterize and optimize the behaviour and performance of an asphalt mixture based on the type of constituents, the mixture's volumetric design and the visco-elastic properties of the bituminous mortar.

1.3. Scope

In the Netherlands porous asphalt (PA) is the standard surface layer on national highways because of its excellent water drainage and noise absorption. Adversely, PA surface layers require more maintenance than dense layers. This is because of their relatively high void content, >20%, which leaves the mixture more susceptible to the influences of the elements. In general maintenance is performed on (porous) surface layers every 10 to 12 years, whereas the service life of binder and base courses ranges from 20 to 70 years. It was therefore chosen to develop the model for the evaluation of porous asphalt.

In addition to the porosity, multiples design parameters influence the performance of the porous asphalt such as the size, shape, types of aggregates, the mechanical properties of the mortar or the volume fraction of the various constituents [1]. Accounting for each parameter is challenging and requires characterising the mixture with a great accuracy. At the scale of a test sample, it is possible to scan the specimen, identify and measure each aggregate, evaluate the volume of mortar or void. When considering a sample of a few millimetres, the mixture can be described with a great accuracy. With a specimen of a few centimetres, the mortar, which is a mixture of bitumen and small aggregates would be consider as a homogenous material. At the scale of a motorway, it is practically impossible to obtain a detailed description of the exact constitution of the asphalt along the surface of the road.

In the first phase of the project a 3D realistic model of the asphalt mixture was created based on the 3D scans of a small sample. An illustration is presented in Figure 1. The detailed model could distinguish between aggregates and mortar. The mortar was considered as a homogeneous material. The FE model allowed the analysis of the mechanical response of the sample and the identification of the main characteristics of the mixture. From this detailed analysis, it was possible to build a simplified model that describes the asphalt mixture accurately enough to capture its mechanical response: a representative volume element (RVE).

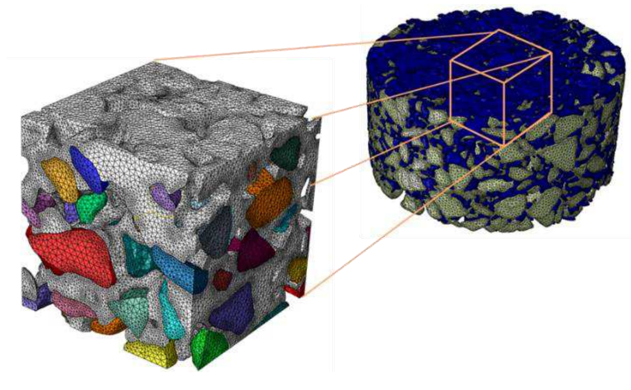


Figure 1: 3D realistic model of an asphalt mixture with 28% of void

In the second phase of the project, an RVE was created. An automatic generation of the RVE using a Python script was developed to allow for an effortless generation of multiple variations of asphalt mixture. The RVE can then be used two ways: as an optimisation tool to compare the performance of multiple mixtures at the meso-scale or as a homogenisation tool to evaluate the bulk properties of a layer of porous asphalt. Additional analyses can be performed at the macro-scale considering the additional layers that constitute the road and the complex loading applied by the vehicle tyres at the surface of the road. This paper presents the method developed in the first and second phase of the project and the results.

2. PHASE I – ANALYSIS OF A REALISTIC 3D-MODEL

In the first phase op the project a realistic model of an asphalt mixture was created. The objective of this phase mainly was to evaluate the influence of the constituent's geometry, the constituent's mechanical response and the interaction between the constituents. Firstly, a 3D geometry was made from 3D scanned data of an actual PA drilled core with a diameter of 100mm and a thickness of 50mm. From the scanned data two constituents could be identified: the aggregates and the mortar but manual work was needed to separate the aggregates from each other to create a mesh suitable for finite element analysis. Simpleware provided the 3D mesh with aggregates and mortar identified. Further work was needed to remove connections between aggregates or locally modify unsuitable mesh as illustrated in figure 2.

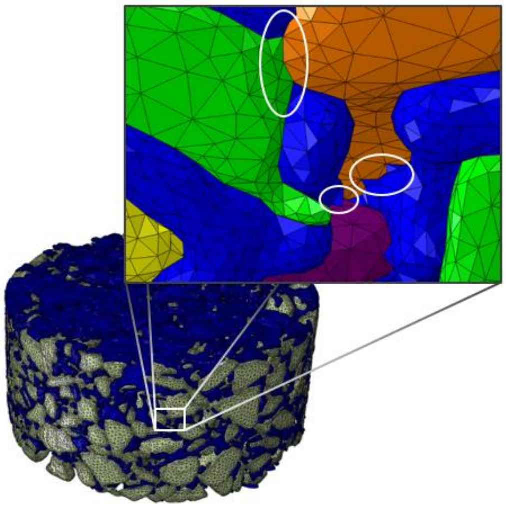


Figure 2: Cleaning up Simpleware 3D FE mesh

Subsequently, from the FE mesh a selection of 3 regions of interest was made. All three regions had the same volume but contained different volumes ratios of mortar, aggregates and voids. The ratios ranged from 29 to 33 % for voids, 25 to 37 % for mortar and 34 to 42 % for aggregates. With volume 1 an evaluation of various modelling strategies to define the interaction between aggregates and mortar were made. This interaction could be modelled either as contact surfaces or using a thin layer of elements to represent the adhesive layer. Due to the complex geometry and insufficient mesh quality, the chosen solution was to create an additional layer of element around each aggregate that would represent the adhesive (figure 3). An arbitrary thickness was defined based on experimental observations defined in the LOT report [2]. A cohesive zone model was used to describe the behaviour of the adhesive material. The model also allowed for new interactions between the mortar and the aggregates, and between aggregates through the layer of adhesive that could enter in contact with surrounding elements.

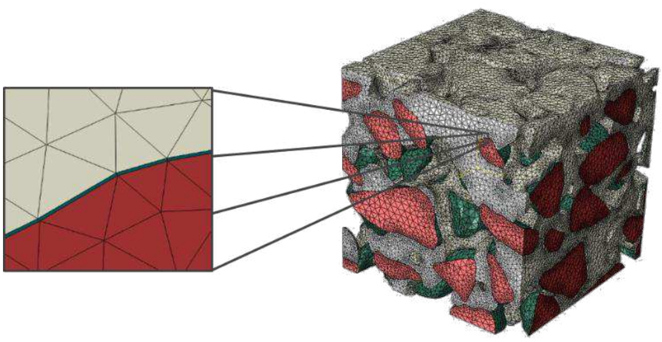


Figure 3: Additional adhesive layer

After the determination of the modelling strategy the linear visco-elastic response of the mortar, using Prony series coefficients, and the elastic response of the adhesive layer and the aggregates were defined. After applying periodic boundary conditions, the three selected volumes were then loaded by 1MPa applied in 0.1s and maintained for 50s. Comparison of the results highlighted the influence of each constituents:

- in a region with a lack of mortar, aggregates can enter into contact with each other and the stresses in the aggregates are high. Thinner layers of mortar and/or adhesive layers are under high levels of stress too.

- in a region rich in mortar, the cohesion between the constituents is better. There is less deformation and the stress is more evenly distributed.

From the analyses performed during the first phase it was concluded that the realistic model derived from 3D scan data was useful but has strong limitations:
- The time and cost for scanning of the samples are high. Additionally, recreating the 3D images then transferring the data into a finite element model is a cumbersome task as well. The realistic model does therefore not allow multiple iterations to study various types of mixtures or even variation between samples.
- The complexity of the geometry does not allow for complex material models and contact models. Computational time and cost would be prohibitive, which will lead to limit the accuracy of the modelling predictions. Realistic modelling is counter-productive: by adding more detail in the geometry, we sacrifice other important factors.

Complexity of the realistic model does not allow for further development of complex material and contact models. However, because both aspects are important a new simplified approach needed to be created. This simplified geometry needs to account for size, distribution and content of aggregates, mortar and voids. An automatic generation of a semi-random volume of asphalt would be useful to study various mixture designs. Furthermore, a simplified geometry generated by a program would allow a better control of the surface definition and the mesh quality.

3. PHASE II – RVE CREATION

The definition of an RVE is challenging when considering a random media such as the porous asphalt. The size of the RVE must be defined so that the response of the asphalt mixture can be describe accurately while keeping the computational cost to a minimum. The aim is to use the RVE model in an iterative process of optimisation.

The size of the RVE is the first parameter to be considered when analysing a new asphalt mixture. Other parameters were identified based on the results of the 3D realistic model and include:
- Geometrical parameters
- Material properties
- Contact properties (aggregate / mortar)

3.1. Geometry

The geometrical parameters needed to characterise a porous asphalt mixture are:
- The volume fraction of the constituents.
- The size of the aggregates and the size distribution.
- The thickness of the adhesive layer that describes the contact between the mortar and the aggregates.

At the meso-scale, about a few centimetres, the model can distinguish between 3 constituents: the aggregates, the mortar and the void. The mortar, a mixture of bitumen and small aggregates, is considered homogeneous. The aggregates size is usually determined using sieves of variable sizes. A cumulative size distribution of the aggregates was used to account for the aggregate size and the amount of aggregates of each category. A parametric script was written to facilitate the creation of the geometry according to the following steps:
- Creation of a cube, the size can be customised by the user.
- Automatic and random partitioning, measurement of the cells and classification as defined per user.
- Further partitioning until the cumulative size distribution of the aggregates is satisfied following the framework defined by Neumann et al [3].
- Identification of the cells that represent the aggregates – geometry is frozen for these cells.
- Further partitioning of the remaining cells to satisfy the maximum size requirement of a void defined by the user.
- Selection of the cells that represents the voids or the mortar.
- Creation of the adhesive layer that consists of additional partitions to generate a layer of cohesive elements. These elements are used to model the contact between the mortar and the aggregates. More details are available in section 3.4.

Figures 4 to 6 illustrate the steps of the geometry creation. Due to the random definition of the partitions, several iterations may be necessary to satisfy all the requirements set by the user. If the criteria are not met, such as the volume fraction of constituents or the sizes of cells, one or all steps will be repeated.

Finally, due to the large number of partitions, the mesh quality may not be satisfactory. A final step of geometry regularisation is performed to improve the mesh quality and consists of merging adjacent faces and removing unnecessary partitions of faces.

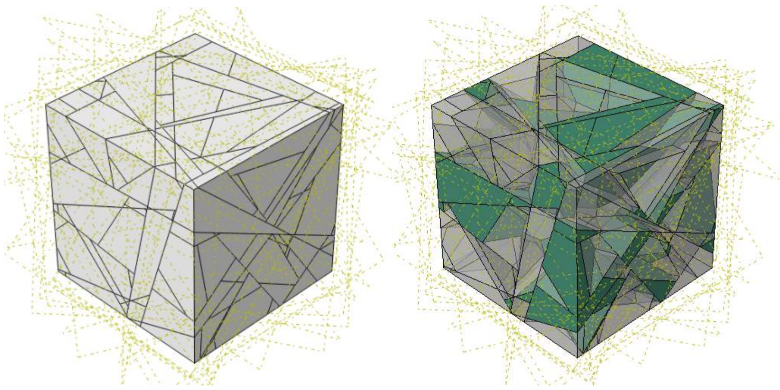


Figure 4: Automatic creation of the geometry of the RVE – step 1: partitioning and identification of the aggregates (green)

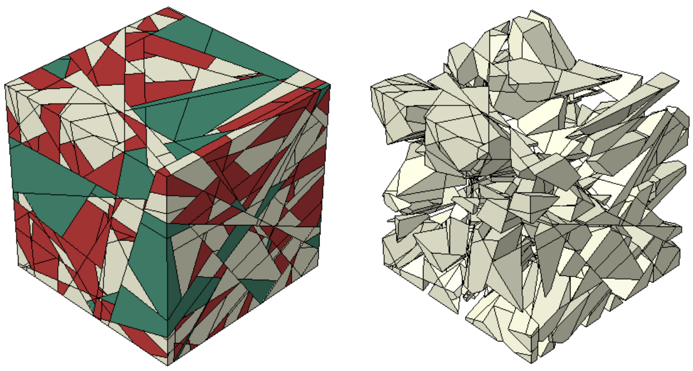


Figure 5: Automatic creation of the geometry of the RVE – step 2: further partitioning and identification of the voids (red) and mortar (grey)

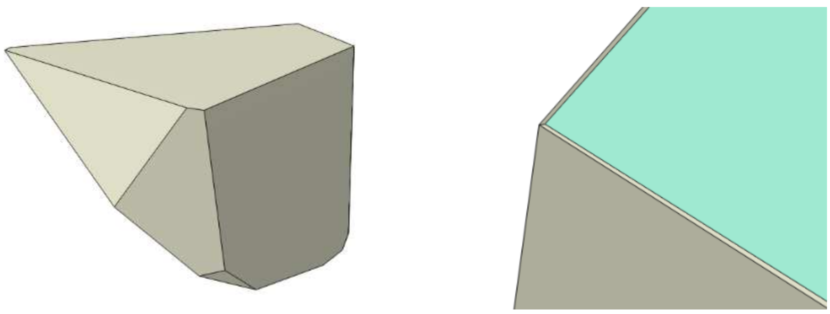


Figure 6: Automatic creation of the geometry of the RVE – step 3: final partitioning to create a thin layer of element (adhesive) around each aggregate

3.2. Material

The aggregates and the adhesive are considered elastic, the mortar is visco-elastic, defined with Prony series parameters. An example of the material properties defined for each material is presented in Table 1.

At this stage, no damage or failure model are included but an energy based law is currently being developed to describe the damage evolution in the mortar under a cyclic loading.

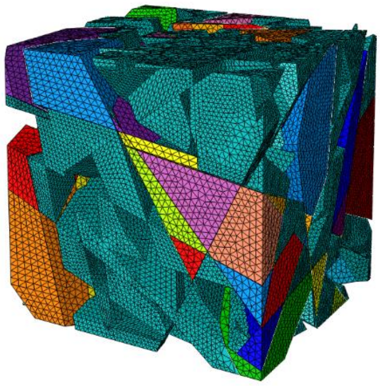
Table 1. Mechanical properties of the materials defined in the RVE model

Material	Elasticity modulus (GPa)	Poisson's ratio	Prony series coefficients	
			g_i	tau_i
Aggregate	50	0.2		
Adhesive	2.2	0.45		
Mortar	2.2 (instantaneous)	0.45	0.05	50.
			0.11	10.
			0.16	3.5
			0.65	0.25

3.3. Mesh

The script automatically generates the mesh on the mortar and each aggregate. The voids are not meshed. The mortar is meshed with tetrahedral elements, the global element size and the geometric order should be specified by the user. The aggregates can be meshed with hexahedral or tetrahedral elements, low or high order, reduced or full integration. The element size should be specified by the user. The choice will be based on a consideration between computation time and accuracy. For trial and error, a short computational time could be desirable, for which large linear elements are most useful. For end analyses that require high accuracy smaller quadratic elements are more suitable. The adhesive is meshed with one layer of cohesive elements, hexahedral or wedge elements depending on the type of the underlying elements.

An example of a meshed RVE is presented in Figure 7. The mortar and the aggregates are meshed with linear tetrahedral elements (C3D4), the element size is set to 0.75 mm for the aggregates and 0.5 for the mortar. The adhesive layer is meshed with wedge cohesive elements (COH3D6).



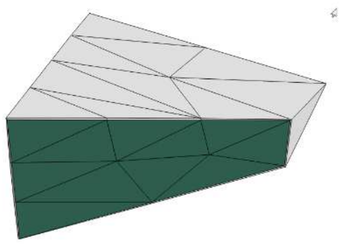


Figure 7. Mortar and aggregates meshed with C3D4 elements; adhesive layer meshed with COH3D6 elements

3.4. Interaction

The adhesive contact between the aggregates and the mortar is modelled using cohesive elements. The cohesive elements surrounding each aggregate shares nodes with the underlying elements. The external nodes of the adhesive layers are tied to the mortar and/or the adhesive layer of the neighbouring aggregates. The Python script searches for the nodes of the adhesive layers and the mortar that are within a distance defined by the user. The node sets and tie constraints are automatically created. All the nodes included as slave nodes in the tie constraints are identified so they cannot be reused when defining the boundary conditions.

3.5. Plug-in

The Python script was converted into an Abaqus/CAE plug-in. A Graphical User interface (GUI) was added to facilitate the definition of the multiple parameters as shown in Figure 8. The user can specify the following parameters:

- RVE size
- Volume fraction of constituents
- Aggregate size distributions
- Meshing parameters
- Material properties of each constituents including the adhesive
- Additional tolerances such as acceptable error on volume fraction or aggregate size

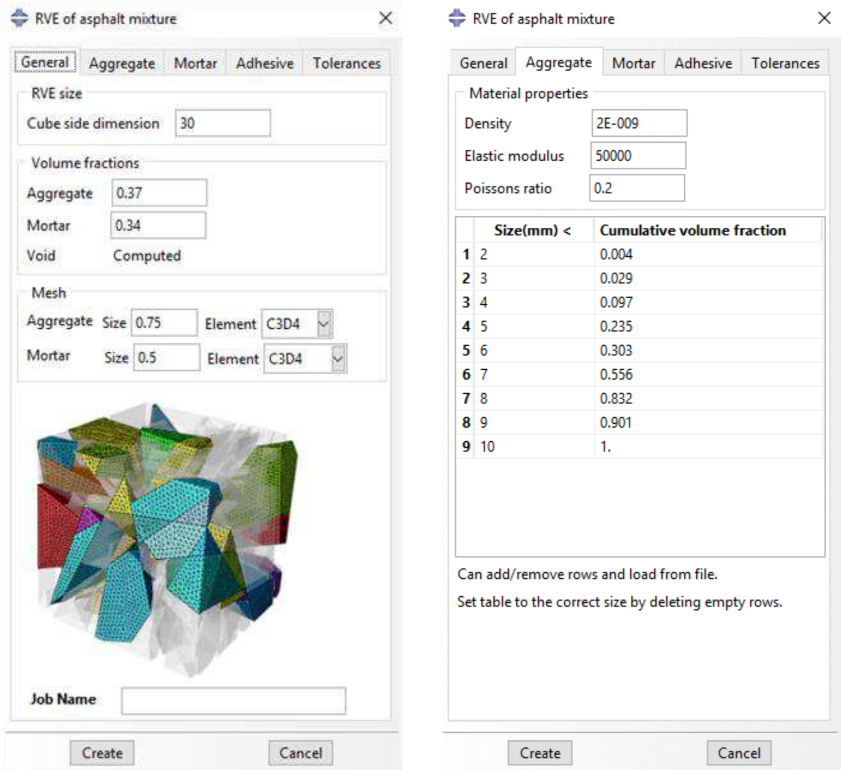


Figure 8. GUI of the RVE of asphalt mixture plug-in

4. HOMOGENISATION

The FE-RVE plug-in developed by Simulia [4] was used to define the non-periodic boundary conditions to be applied to the boundaries of the RVE then calculate the homogenised mechanical properties. The homogenised properties can then be used to define the global behaviour of the top layer of porous asphalt in a model of a road section.

4.1. Interaction

The FE-RVE plug-in automatically creates the steps and boundary conditions needed to perform the analysis. The mechanical scenario with non-periodic and strain driven boundary conditions was chosen as the RVE geometry is not periodic and contains non meshed voids. In this scenario, a uniform surface gradient boundary condition is imposed to the boundary nodes using reference points and equations relating the degrees of freedom of the boundary nodes to the degrees of freedom of the far-field reference points. 6 load cases are needed to compute the 3 Young moduli and 3 shear moduli. An illustration of the displacements applied to the RVE boundaries for each load case is presented in Figure 9.

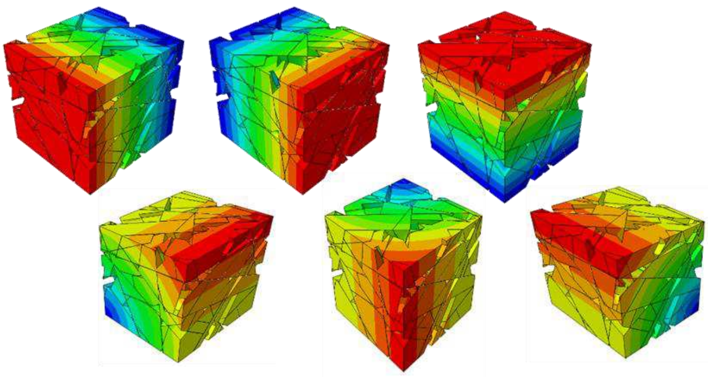


Figure 9: Uniform surface gradient BCs applied to the RVE boundaries

4.2. Homogenised properties

The homogenised mechanical properties of the asphalt mixture were calculated using the FE-RVE plug-in. The calculation was limited to the linear elastic properties. Various sets of parameters were used and multiple RVEs have been generated and analysed.

The properties obtained with the examples studied were between 250 MPa and 5000 MPa for the Young modulus and between 0.15 and 0.28 for the Poisson's ratio. The error of considering an isotropic material reached up to 30% when comparing with the anisotropic material model.

4.3. Influence of randomness

To compare the response predicted by the randomly generated RVEs, a creep test was considered. A pressure of 1 MPa was applied to the top surface of the RVE in 0.1s and maintained during 50s. 3 RVEs were generated using the same set of geometrical and material parameters. Figure 10 shows the estimated displacement of the top surface for each RVE. The instantaneous modulus varies between 1929 and 2414 MPa. The displacement after 50s varies between 0.018 and 0.028 mm.

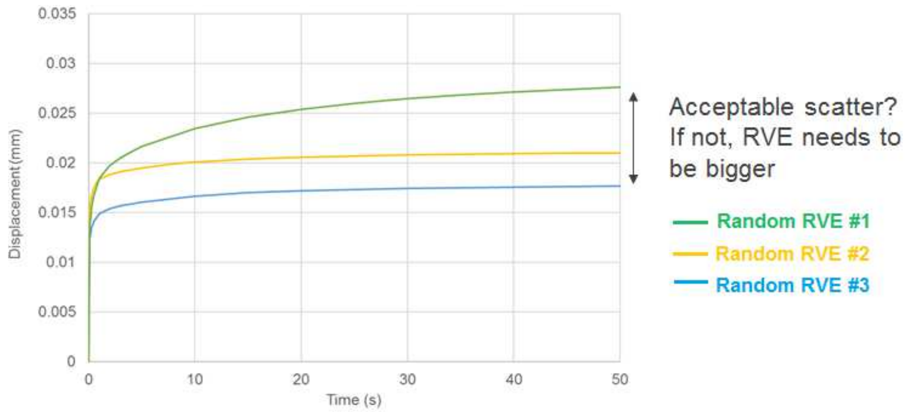


Figure 10. Creep response of 3 RVE models created with same set of parameters

5. INDIRECT TENSILE TEST

The indirect tensile test is often used to characterise a new asphalt mixture. A cylinder of asphalt is loaded in compression. Due to the geometry of the specimen, the central region is loaded in tension as shown in Figure 11. This way, it is possible to apply a repeated tensile load and evaluate the performance of a new material. Besides the evaluation of new materials this test is also useful in determining the properties of drilled cores from constructed pavements [5]. By comparing the actual performance of paved asphalt with laboratory data and model simulation more insight will be gained into the performance of asphalt mixtures.

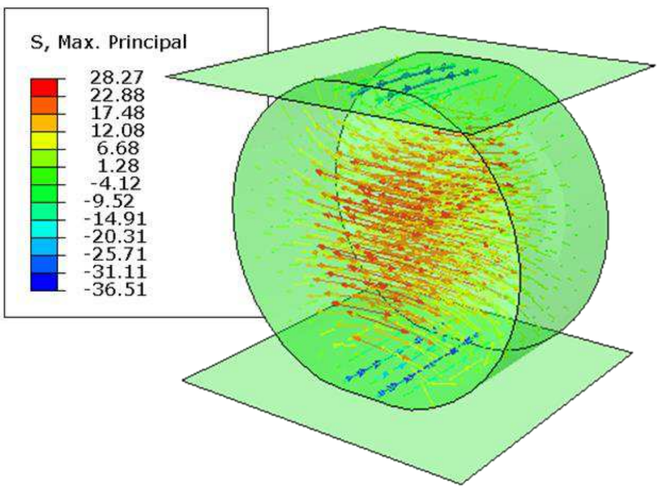


Figure 11. Indirect tensile test - tensile stress is generated in the centre of the cylinder

5.1. Model creation

Only the central region is of interest as it is where the highest level of stress is reached and where the strain is measured during the test. The model was created in two steps. First, the RVE was used to estimate the homogenised properties then it was integrated into a larger model as shown in Figure 12. The RVE represents the central region and the surrounding material is considered homogeneous. At the interface between the RVE and the homogenous material, the surfaces are tied.

The bottom plate is fixed and a compression load is applied to the top plate. An amplitude is defined so that a cyclic load is applied.

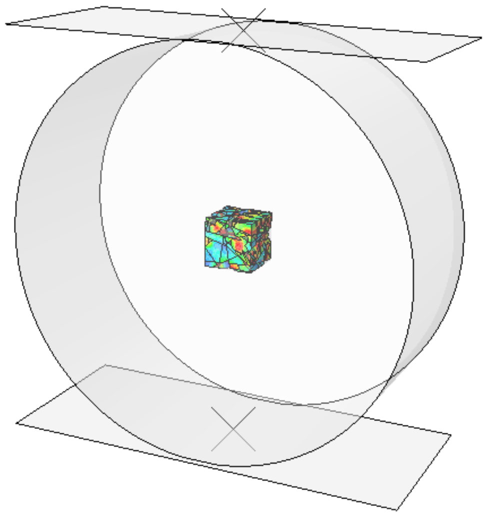


Figure 12. Indirect tensile test – RVE located in the region with highest tensile stress

5.2. Fatigue loading and perspectives

A Python script was written to automate the loading application and the analyse of the results. After one cycle, the outputs are automatically extracted and the average stress and strain in the RVE are computed. An empirical damage model is currently being developed to evaluate the damage evolution based on the local maximum strain during a cycle. If the damage has evolved, the material properties of the mortar are degraded, and a new cycle is applied. A cycle jump solution is also implemented. The law that governs the damage evolution in the mortar under a cyclic load is currently being developed. Additional tests are performed to identify the parameters of the damage evolution law.

6. DISCUSSION

6.1. RVE creation

The parametric RVE model allowed to describe the geometrical morphology of the porous asphalt mixture and multiple models could be generated easily using the plug-in. The randomly generated RVEs can be used to study the influence of any of the geometrical or material parameters. This would not be possible with scanned data and realistic 3D models. The plug-in can be used as part of an iterative process to study the mechanical behaviour of the porous asphalt and optimise the composition of the mixture.

6.2. Homogenised properties

Contrary to periodic materials, the asphalt mixture presents a random distribution of the constituents. A statistical approach may be needed to capture the global response of a random material. Based on the current results, it appears that the generated RVEs are too small to accurately capture the response of the asphalt mixture. The global behaviour was dependent on the loading direction and the creep models show a scatter in the predicted results. The size of the RVE is a fundamental parameter but it is highly dependent on the meso-structure of the material. A convergence study should be performed for each set of geometrical parameters. Another approach could be considered to improve the accuracy of the RVE predictions and consists of using multiple RVEs. Wimmer et al. [6] used 15 samples of randomly generated RVEs to obtain the homogenised properties and performed a statistical analysis. They showed that it was possible to reach convergence when calculating the elasticity coefficients. This approach may allow to consider a fixed size of RVE for any variation of the morphological properties of the mixture investigated.

6.3. Material models

The model presented in this paper accounts for the elastic properties of the aggregates and the adhesive and the linear visco-elastic properties of the mortar. An energy based damage model is currently being developed and will be implemented into the RVE model to allow for the prediction of damage in the mortar and fatigue life calculation. Further work is also needed to evaluate the global non-linear response of the asphalt mixture.

7. CONCLUSION & FURTHER DEVELOPMENTS

In this paper, a project consisting of developing an optimisation tool for fatigue life predictions of porous asphalt mixture was introduced.

The performance of the porous asphalt is driven by multiple design parameters such as the size, shape and type of aggregates, the mechanical properties of the mortar or the volume fraction of the various constituents. A parametric RVE model has been developed and implemented into an Abaqus/CAE plug-in to facilitate the generation of RVEs for porous asphalt mixture.

The RVE can then be used to compare the performance of multiple mixtures at the meso-scale or to evaluate the homogenised properties of a specific porous asphalt. Additional work is needed to ensure the convergence of the response predicted by the randomly generated RVEs. A damage model for the mortar is also being investigated to allow the prediction of damage under fatigue loading.

Finally, in the next phase of the project, additional analyses will be performed at the macro-scale considering the additional layers that constitute the road and the complex loading applied by the vehicle tyres at the surface of the road [7].

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