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Meso-scale finite element analysis on creep behaviour of asphalt mixture considering interface effect

X Qiu¹, S L Xiao¹, J X Xu¹, Q Yang¹ and C L Li¹

1 Road and Traffic Engineering Research Center, Zhejiang Normal University, Jinhua, 321004, China

E-mail: xqiu@zjnu.cn

Abstract. This paper investigated the creep behaviour of asphalt mixtures using a randomly generated meso-scale finite element model that takes into account the effect of asphalt-aggregate interface. Simulation analysis on the three-point bending creep tests of asphalt mixture were performed and validated. Furthermore, parameters studies were conducted to evaluate the effect of gradation and angularity of coarse aggregate, air void content, and asphalt-aggregate interface strength. The results indicated that mesostructural parameters and interface properties have an important effect on the creep behaviour of asphalt mixture. The creep performance of medium-sized asphalt mixture is better than that of fine-sized asphalt mixtures. The larger the angularity index of coarse aggregate is, the better ability asphalt mixture has to resist deformation. As to the suspended dense structure asphalt mixtures, with the increase of void ratio, the creep deformation increase gradually, and the excessive void ratio would lead to the fracture of the interface. Asphalt-aggregate interface with higher interface strength would result in better resistance to of the mixture to permanent deformation.

1. Introduction

Asphalt mixture is one of the most widely used materials in pavement construction. At meso-scale, the asphalt mixture can be regarded as a multi-phase material composed of aggregate, asphalt, air void and asphalt-aggregate interface. Among them, the asphalt-aggregate interface has a significant influence on the failure mechanisms and mechanical properties of the materials [1]. Failures often start from interface, then gradually propagate, and finally form macro cracks leading to the destruction of the asphalt mixture.

It is well known that the properties of the materials are closely related to compositions and structures. Grasping the intrinsic relationship between compositions, structures and performances is the key to understand the fundamental properties of the materials. Based on this point of view, the complex mechanical behavior of asphalt mixture at macro-scale should be the reflection of its meso-scale compositions and structures. The traditional theoretical analysis and numerical simulation often regard the asphalt mixture as a macroscopic homogeneous material, ignoring the influence of the mesoscopic components of the materials, and cannot reflect the failure process of the asphalt-aggregate interface. Therefore, it is important to create a meso-scale model to study the macro-scale performance of asphalt mixtures. Due to the anisotropy of the material, the mechanical behaviors of the asphalt mixture exhibits highly nonlinear under the action of loadings. It is not only time-consuming, laborious and expensive to study the creep behaviors of asphalt mixture only by means of laboratory experiments, but also difficult to reveal the influence law of the asphalt mixture from a perspective meso-scale analysis. With the development of numerical simulation technology and the improvement of calculation ability, more and more scholars are devoting themselves to the



numerical study of the relationship between meso-structure and macro-performance of asphalt mixture[2-4]. However, due to the complexity of structure and properties of asphalt mixture, further investigations still needed to clarify the mechanism of asphalt-aggregate interface interaction and its effect on the overall performance of the mixture. Therefore, it is an important issue to establish a more accurate and reasonable meso-mechanical model to explore the mechanical properties of asphalt mixture.

The objective of this paper is to develop a meso-scale finite element model that considers the interface effect to describe the creep behavior of asphalt mixture and to investigate the influence of factors such as gradation and angularity of coarse aggregate, air void content, and asphalt-aggregate interface parameters on the overall performance of the materials. The study would give an insight into the complex mechanical analysis of asphalt mixtures by considering the asphalt-aggregate interface effect.

2. Modeling Methodology

The AC-20 asphalt mixtures with a nominal maximum aggregate size of 19mm was prepared for materials parameters acquisition and numerical verification. The numerical simulations were conducted using the commercial finite element software ABAQUS 6.14. The model that considers each component of asphalt mixtures was established by using the random aggregate generation technique and cohesive element embedding technique, in which aggregates larger than 2.36 are classified as coarse aggregate, fine aggregates (passing 2.36 mm sieving) combined with asphalt and mineral filler are defined as asphalt mortar, and the asphalt-aggregate interface is represented by the embedded cohesive element between the coarse aggregate and asphalt mortar.

2.1 Model generation

The random aggregate generation technique was adopted to simulate the meso-structure of asphalt mixture [5]. Due to the limitation of computational resources and huge time consumption, this study used a two-dimensional model instead of a three-dimensional model. In order to simulate damages that occur in the asphalt-aggregate interface, it is necessary to embed a zero-thickness cohesive elements between the coarse aggregate and the asphalt mortar. However, it is impossible to embed the zero-thickness cohesive elements into the interface by manual operation. Alternatively, by using Python programming process on the derived ABAQUS input file that records all information of nodes, elements and sets of the model, the boundary between the coarse aggregate and asphalt mortar can be identified, and the cohesive element can be automatically embedded to simulate the interface by a series of operations. The key to embed the zero-thickness cohesive element is to split the initial mesh nodes, and then make the coordinates of the newly generated nodes equal to the original nodes, so that the thickness of the embedded cohesive element equal to zero. Another important issue is that the node numbers of newly generated cohesive elements should be arranged in counter-clockwise. Otherwise, errors will be reported during the simulation processing. The interface can be highlighted by visualizing the operation in the software as shown in figure 1.



Figure 1. Cohesive elements on the asphalt-aggreagte interface

By combining the random aggregate model with cohesive elements, the meso-scale numerical model that considers the characteristics of the coarse aggregate, asphalt mortar and asphalt-aggregate interface was obtained. The three-point bending creep test can be equivalent to a simple supported beam for numerical simulation as shown in figure 2. The size of the beam is 250mm × 35mm, and the supported beam span is 200mm. A vertical downward concentrated load is applied at the midpoint of its top surface. The global mesh size of the beam is 0.5mm. Both the coarse aggregate and the asphalt mortar are meshed using reduced integration plane strain (CPE4R) element, and the asphalt-aggregate interface is meshed with zero-thickness cohesive elements (COH2D4).

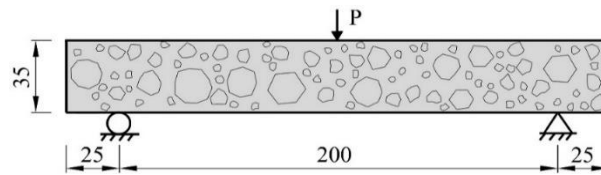


Figure 2. Model geometry and boundary conditions (dimensions in mm)

2.2 Model parameters

The coarse aggregate is considered as a linear elastic material with elastic modulus of 100 MPa and Poisson's ratio of 0.3. The asphalt mortar is defined as a viscoelastic material, and its model parameters were determined from the laboratory three-point bending beam creep test of asphalt mortar. The Burgers model was used to characterize the viscoelastic properties. And the parameters of Burgers model were transformed into the prony parameters (in table 1) for numerical simulation according to Boltzmann linear superposition principle and Laplace mathematical transformation.

Table 1. Prony parameters of asphalt mortar

Burgers model				Prony series			
E_1 (Mpa)	η_1 (MPa·s)	E_2 (MPa)	η_2 (MPa)	g_1	τ_1 (s)	g_2	τ_2 (s)
26.591	2738.247	2.978	209.793	0.9108	17.364	0.0892	2824.2

A two-parameter bilinear cohesive law was chosen to describe the behaviour of asphalt-aggregate interface. This study selected the interface properties from previous researches to realistically build the computational model. The material parameters used in this study are listed in table 2.

Table 2. Parameters of the asphalt-aggregate interface

Interface strength (MPa)	Critical fracture energy (mJ/mm ²)
0.5	1.558

2.3 Model validation

The model was established to simulate the creep behaviour of the AC-20 asphalt mixture. The simulation result was compared with the experimental result, and the correlation coefficients of the two curves was calculated. As can be seen from figure 3, the correlation coefficient between the experimental and simulation results is 0.881, indicating that the numerical model has provided a reliable solution for the simulation of creep behaviour of asphalt mixture. The two curves are basically the same at the initial creep stage, and gradually begin to differ after 100s. Finally, the two curves tend to be consistent. The differences may due to simplification of the aggregate distribution by the random aggregate model. In addition, the numerical simulation is a two dimension model, while the real state is a complex three-dimension structure, which may cause some difference in the simulation results.

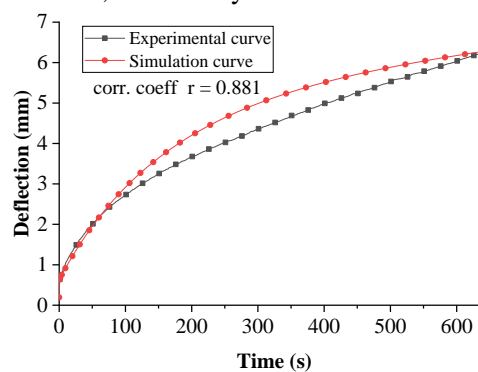


Figure 3. Comparison between the simulation curve and experimental curve

The SDEG (scalar stiffness degradation) is defined in Abaqus filed output, which represents damage status of interface elements adopted in cohesive element. When the interface stress reach to its

maximum strength, the SDEG value begins to be greater than 0. And when the interface is completely damaged, the SDEG value reaches 1. In order to better characterize the cracking phenomenon of the interface, the coarse aggregate is hidden in the visualization operation. The distribution SDEG contours is shown in figure 4, where the red part indicates that the asphalt-aggregate interface has completely cracked. It shows that the location of the complete failures of the interface are mainly near the coarse aggregate with larger particle size near the middle of the specimen.

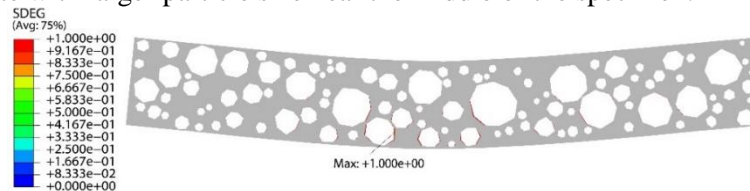


Figure 4. SDEG contours of the AC-20 asphalt mixture

According to the creep deformation curve, the finite element simulation can reflect the three-point bending creep behavior of asphalt mixture, reflecting a good agreement with the experimental results. At the same time, the cohesive zone model adopted in this paper can better reflect the failure characteristics of interface damage and provide a basis for further meso-mechanical analysis of asphalt mixture.

3. Results and analysis

3.1 Effect of coarse aggregate gradation

In order to study the effect of aggregate gradation on the creep behaviours of asphalt mixture, three types of gradations including AC-13, AC-16 and AC-20 were generated, as shown in figure 5. Median recommended aggregate gradations were chosen for each type of asphalt mixture in accordance with the Chinese specification JTG F40-2004.

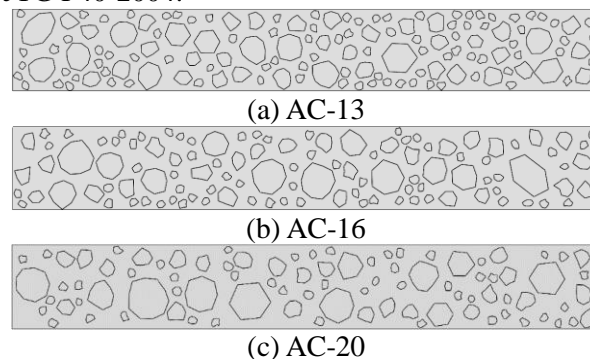


Figure 5. Numerical specimens with different gradations

Figure 6 shows the deflection versus time curves for different aggregate gradations. Deflection reflects the creep deformation of specimens over time, and it can be divided into elastic deformation and viscoplastic deformation. The elastic deformation can be restored, while some viscoplastic deformation cannot be restored, thus becoming the permanent deformation. The smaller the deflection is, the greater the resistance the asphalt mixture has to permanent deformation. As can be seen, AC-13 asphalt mixture has the largest deflection, followed by AC-20, and the smallest is AC-16. Therefore, the creep performance of medium-sized graded asphalt mixture (AC-16 and AC-20) is better than that of fine-sized graded asphalt mixture (AC-13), and the creep performance of AC-16 is better than that of AC-20. This indicates that under the condition of guaranteeing aggregate skeleton, appropriately reducing the content of coarse aggregate can avoid the problems of compaction difficult and void fraction caused by the large size of coarse aggregate, thus improving anti-deformation ability of asphalt mixture.

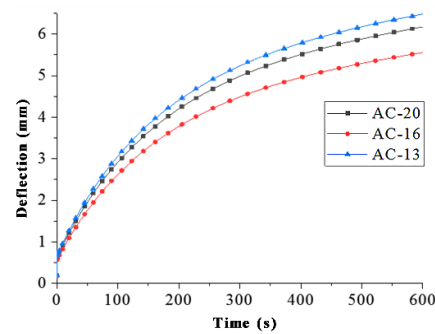


Figure 6. Creep curves under different aggregate gradations

3.2 Effect of coarse aggregate angularity

In order to investigate the influence of aggregate irregularity on creep behavior of asphalt mixture, the angularity index (AI) was selected as the control factor, which can be calculated as in equation (1). Different shapes of the aggregate with various angularity indexes were considered to generate numerical specimens. When the aggregate is irregular, the angular index is greater than 1. Angularity indexes for different shapes of the aggregate are shown in table 3.

$$AI = \frac{C^2}{4\pi S} \quad (1)$$

Where,

- C — Perimeter of coarse aggregate (mm),
- S — Area of coarse aggregate (mm²).

Table 3. Angularity index of coarse aggregates with different shapes

	Circle	Square	Hexagon	Octagon	Decagon
Angularity index	1	1.273	1.103	1.055	1.033

Figure 7 shows the creep results of the asphalt mixtures under different aggregate angular indexes. It can be seen from the figure that the deflection of the mixture decreases with the increase of angularity indexes. The creep deformation at the angularity index of 1.273 is 15.8 % lower than that of angularity index of 1.000. A more irregular aggregate can result in more per unit contact areas (length) between the asphalt and aggregate, hence a better mechanical interlocking, physical adhesion and chemical bonding will be obtained, thus enhancing the overall strength of the material. This means that improving the angularity of coarse aggregate can greatly enhance the deformation resistance of asphalt mixture. Therefore, choosing crushed stone has a better creep performance than that of pebble stone.

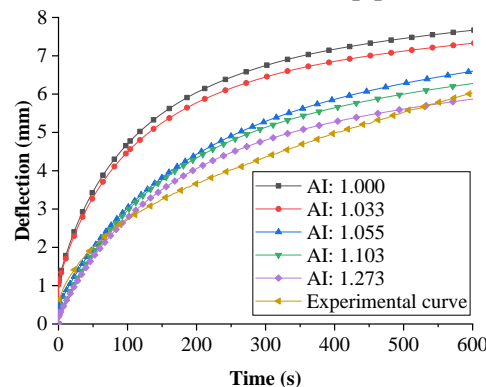


Figure 7. Creep curves under different angularity indices of aggregate

3.3 Effect of air void content

In order to investigate the effect of air voids on the creep behaviour of asphalt mixture, air void content varies from 1% to 4% were discussed. It should be noted that too fine a mesh will lead to high computational cost and convergence problems. The air void is reasonably assumed as random polygon shape with an equivalent diameter of 1mm in the numerical model.

Figure 8 shows the results of creep tests under different air void contents. As the air void content increases, the deflection increased, which means that the ability to resist deformation is decreased. This may be due to the fact that the air void in the model can be regarded as a material like asphalt mortar but without bonding strength and cannot withstand any stress, so the overall strength of the asphalt mortar is reduced, and the creep deformation is increased. That is, at a larger void content, asphalt mixture is more prone to yield compression deformation, resulting in rutting problem, especially under high temperature conditions.

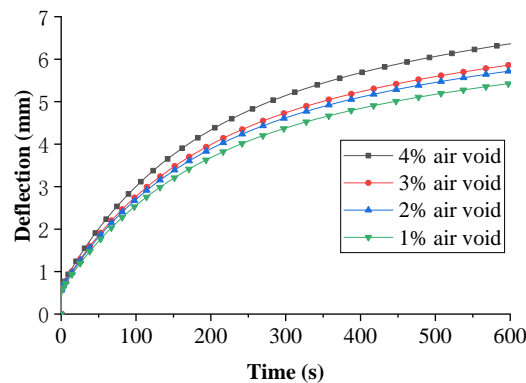


Figure 8. Creep curves under different air void contents

At the same time, part of the air voids that near aggregate correspond to some initial crack at the interface, which may easily lead to the development of the cracks, as shown in the lower left corner of figure 9. In case of large air void content, voids may be linked together with the increase of deformation, as shown in right lower corner of figure 9, which may cause the expansion of the micro-cracks of the asphalt-aggregate interface and eventually lead to the macro-cracks of asphalt mixture. Therefore, it is necessary to control the air void content of asphalt mixture to ensure its durability and stability.

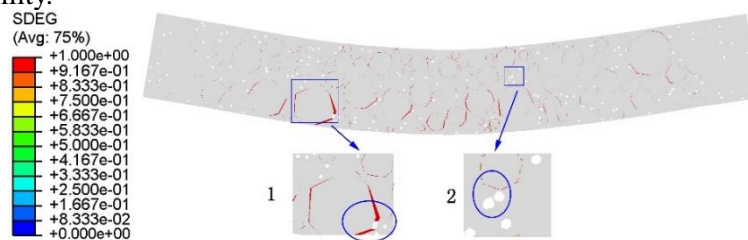


Figure 9. Adverse effects of voids in the specimen

3.4 Effect of asphalt-aggregate interface strength

The asphalt-aggregate interface is the weakest link in the overall strength of asphalt mixture. Keeping the fracture energy of the interface unchanged, various of interface bonding strength including 0.1 MPa, 0.3 MPa, 3 MPa, 10 MPa and 1000 MPa were chosen to further investigate the creep properties of the asphalt mixtures.

Figure 10 shows the creep curves of asphalt mixture under different interface strength. As can be seen, with the increase of interface strength, the deflection decreases gradually, which indicates that if the bonding strength between aggregate and asphalt is improved, the creep deformation of asphalt mixture under will be reduced and the ability to resist permanent deformation can be enhanced. When the interface strength range from 0.3MPa to 0.8 MPa, the numerical results are closed to the experimental results by the end of the creep tests. While the interface strength is 1000 MPa which is far greater than the actual interface strength, the deflection shows the lowest value at 3.5mm at the end

of the creep test. Interface with a strength of 1000 MPa can be considered as completely bonded interface, or perfect interface. However, the aggregate is more commonly surrounded by a weak interface due to the surface texture of the aggregate and the difficulty in fully mixing and compaction of asphalt mixture [6]. Therefore, interface effect cannot be neglected when establish a numerical simulation to study the macro-mechanical behaviour of asphalt mixture.

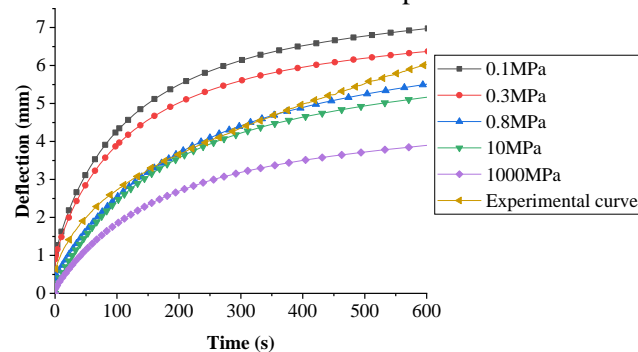


Figure 10. Creep curves under different interface strength

4. Conclusions

The following major findings were achieved from this study.

(1) The creep property of medium-sized asphalt mixture is better than that of fine-sized asphalt mixture. Reducing the content of coarse aggregate to a certain degree can avoid the problem of compaction difficult, thus improving the ability of an asphalt mixture to resist permanent deformation.

(2) The greater angularity index of coarse aggregate, the longer the perimeter per unit area, and the larger the area (length) of asphalt in contact with aggregate, which implies more microtextural features and stronger mechanical interlocking between the asphalt and the aggregate. Therefore, a better ability to resist deformation is obtained.

(3) For the suspend-dense mixtures, with the increase of air void content, a larger energy dissipation and creep deformation was obtained, which indicates that the fracture performance of the asphalt-aggregate interface and the resistance to deformation is reduced.

(4) The asphalt-aggregate interface has a significant effect on the overall behavior of asphalt mixture. The greater bonding strength the interface has, the stronger the resistance the mixture has to permanent deformation.

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