Chapter 2

Stresses and Strains Distribution of a Developed Cold Bituminous Emulsion Mixture Using Finite Element Analysis

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Additional information is available at the end of the chapter

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Abstract

Cold bitumen emulsion mixtures (CBEMs) offer an energy-efficient, sustainable and cost-effective alternative to conventional hot asphalt mixtures, as no heating is required to produce the CBEMs. The enhancement of flexible pavements performance by modifying asphalt mixture has been considered valuable. This is due to the undesirable environmental conditions and heavy loads that will cause unsatisfactory performance of conventional mixtures. Empirical methods using layers with elastic response have been largely used to design such mixtures. Currently fast and powerful design techniques are used to reduce the limitation in determining stresses, strains and displacement in flexible pavements analysis. This research presents a simple and more practicable design procedure of CBEM and discusses limitations of this design. Also, present the properties and characteristics of modified CBEMs for surface course mixture using glass fibre as a reinforcing material. In addition, a three-dimensional (3D) finite element analysis (FEA) simulation for the prediction of pavement mechanical behaviour and performance is carried out using ABAQUS software in which element types, model dimensions and meshing have been taken to achieve appropriate accuracy and convergence.

Keywords: ABAQUS, cold bitumen emulsion mixture, design procedure, emulsion, finite element analysis

1. Introduction

In recent years, demand on road transport networks around the world has developed increasingly in terms of traffic volume, and axle loads also have increased significantly in terms of traffic load. Subsequently, road pavement structures are deteriorating due to structural failure leading to a need to construct new roads or overlay the old one. These include the use of hot mix asphalt (HMA) for constructing and laying, which is manufactured and laid at elevated temperatures [1]. The construction industry of road pavements has paid increasing attention to the improvement and utilization of cold bitumen emulsion mixture (CBEM) for pavement construction, which uses bitumen emulsion instead of hot bitumen. However, current technology solely allows such mixtures to be utilized for particular applications in certain situations such as low to medium traffic volume, roads in remote areas and for small-scale jobs such as reinstatement works [2]. Therefore, the regular employment of CBEMs makes necessary the investigation of their performance, taking into account that there is no internationally accepted mix design available for these materials at present [3]. The performance of CBEMs was investigated through laboratory results originally designed for HMA and properly modified in order to consider the specific properties of such mixtures [4]. CBEM has been considered an inferior mix compared to HMA for the last several years, mainly in terms of its mechanical properties, the extended curing period required to achieve an optimal performance and its weak early life strength [5]. Several researches have been conducted by Chevron Research Company in California that full curing time of CBEMs on site may occur between 2 months and 2 years depending on weather condition [6]. This cold process has been extensively made for many years in several countries such as the United States of America, Australia, France, Belgium, Brazil and those in Scandinavia. In the United Kingdom, the development of CBEM technology is only recently being brought forward [7].

Modification of asphalt mixtures is one of the most important and significant way to improve the performance of these mixes especially if these mixtures do not meet the traffic volume, climatic changes and pavement structure specifications [8]. Cement is widely used in cold mix asphalt and its role has been investigated in several studies. Ordinary Portland Cement (OPC) can considerably develop the early life stiffness modulus, increase the durability and decrease the permanent deformation (rutting) of the asphalt mixtures. Brown and Needham [9] and Al-Hdabi et al. [10] showed that the use of OPC to modify cold asphalt mixtures has improved the mechanical properties such as fatigue strength, permanent deformation resistance and stiffness modulus. Also, Schimdt et al. [11] indicated that when cement was mixed with the aggregate at the time the heated asphalt was combined, the mixes cured faster, and resilient modulus (Mr) developed rapidly. Al-Hdabi et al. [12] carried out some laboratory tests on the cold-rolled asphalt (CRA) mechanical properties and water sensitivity by performing the cement as a replacement material for the waste bottom ash (WBA) and conventional filler. The results showed an important enhancement in the CRA mechanical properties such as water sensitivity, stiffness modulus and uniaxial creep.

In addition, there is a valuable method to predict flexible pavement deformations by using finite element model. The most common approach of predicting flexible pavement response to the applied loads is usually the multi-layer elastic theory, which was originally established for two-layered linear elastic response. This method has been successfully developed to a wide range of pavement problems and is now considered the traditional approach in

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determining pavement responses to vehicular loading [13]. Several computer softwares have been used to calculate pavement stresses, strains and deflections of layered structures. Although this way has a number of assumptions that may be questionable, the simplicity of the multi-layer analysis is generally thought to justify the uncertainty of the results. However, the effect of the assumptions is usually considered to evaluate pavement responses under loads (i.e. uniform pressure distribution, circular contact area, and linear elastic response of pavement materials).

The design methods were developed by different organizations for the calculation of the necessary pavement thicknesses [14]. Finite element techniques developed thereafter for the determination of the stresses and the strains in the flexible pavements. During the development of the finite element techniques, a significant progression in the simulation of the flexible pavements has been noticed. Several models of finite element have been created for simulating the flexible pavement behaviour. The main advantage of these methods is the evaluation of the pavement deformations and the stress distributions in the flexible pavement layers.

2. Advantages of CBEM

CBEM is a mixture of unheated aggregate and emulsion, and it has been claimed that there are obvious variations between cold and hot mix asphalt. The main difference is that the emulsion and aggregates are mixed together at ambient temperature without heating in terms of cold mix, and at high temperature (138–160°C) to mix the binder and aggregates in terms of hot mix. The following advantages could be offered when CBEM is used as a paving mixture [15]:

- Aggregate, asphalt and filler heating will be eliminated.
- It requires less energy consumption and has lower environmental impact.
- Economical.
- Suitable in all conditions.
- Ease of construction.

3. CBEM's materials

The selection of the cold bituminous emulsion mixture to be used in this research is based on two requirements: first, material availability for producing laboratory test samples and second, full-scale tests to carry out with controlled environment and loading conditions. Since the objectives of this research were to present a simple and more practicable design procedure, enough material needs to be available for producing laboratory samples for the mixture properties.

3.1. Mineral aggregate

There are different kinds of mineral aggregates that can be utilized in bituminous mixtures. The aggregate used in this research is crushed granite from Bardon Quarry and one type of aggregate gradation: close graded surface course is used. The aggregates are washed, dried, riffled and bagged with the sieve analysis achieved in according to BS EN 933-1 [16]. Gradation of 14 mm close graded surface course is used in this research.

3.2. Mineral filler

The filler has an important effect on the properties of bituminous mixtures. The amount of filler utilized is varied and depended on the gradation and type of mixture. Typically, in a close graded surface course mixture, the content of filler can be 6% of the total weight of the aggregate and range between 6 and 12% in other mixtures such as stone mastic asphalt. In this research, limestone dust was used.

3.3. Bitumen

Bitumen acts as a binding agent to the aggregates, fillers and additives in the mixtures. A cationic slow-setting bituminous emulsion: (C50B3) as it is based on 40–60 penetration is selected for the cold mix to ensure high adhesion between aggregate particles.

3.4. Glass fibre

Glass fibre was used in this study and presented interesting properties as a reinforcing material. It is both strong and flexible. It is thermally and chemically stable at bituminous mixture temperatures. It is not affected by de-icing salt, petroleum or bitumen. Glass fibre has the Young's modulus almost 20 times higher than typical bituminous modulus at around 20°C [17] and has a high tensile strength.

4. CBEM's design procedure

CBEM is defined as bituminous materials which are prepared at ambient temperature by emulsifying the asphalt in water before blending with the aggregates. Many different parameters effect cold mix asphalt properties, such as aggregate source, curing time and condition, emulsion selection and initial emulsion content, optimum pre-wetting water content and optimum moisture content at compaction and residual asphalt content [18].

In spite of several procedures of CBEMs mix design, there is no design that is globally acceptable. Asphalt Institute [19] has proposed some procedures for designing CBEMs and most of these are based on the procedures that were developed by the American Asphalt Institute, with some improvements. Asphalt Cold Manual MS-14 [19] introduced two approaches for designing CBEMs: Modified Hveem and Marshall methods for emulsified asphalt-aggregate cold mixture design. The Marshall method is used in this research with some modifications (indirect tensile stiffness modulus is used instead of Marshall stability). This is discussed as follows.

4.1. Aggregate gradation selection

Several aggregate properties such as shape, type, specific gravity for coarse and fine aggregate, and filler type and percentage are considered the main factors for aggregate gradation selection. 14 mm aggregate maximum size (AMS) and asphalt concrete close graded surface course were used as the aggregate gradation in this report. **Table 1** shows the selected aggregate gradation which has the grading curve shown in **Figure 1**. Physical properties of the aggregate are given in **Table 2**.

4.2. Emulsion selection

The selection of the emulsion depends on the selected aggregate type and gradation and emulsion ability to coat the aggregate. In this research, cationic slow-setting bituminous emulsion (C50B3) was used in order to identify the optimal emulsion content [20]. Cold asphalt binder (CAB 50), as it is based on a 40/60 penetration grade bitumen, is selected for the cold mix in this research.

4.3. Determination of initial emulsion content

The following empirical equation is suggested by MS-14 to calculate the approximate initial residual bitumen content into CBEMs:

$$P = (0.05A + 0.1B + 0.5C) \times (0.7) \tag{1}$$

where P is the percent of initial residual bitumen content by weight of total dry aggregate, A is the percent of aggregate retained on sieve 2.36 mm, B is the percent of aggregate passing sieve 2.36 mm and retained on sieve 0.075 mm and C is the percent of aggregate passing sieve 0.075 mm.

Sieve Size (mm)	% Passing (Specification limits)	% Passing (Mid of the Specification)
14	100	100
10	77-83	80
6.3	52-58	55
2	25-31	28
1	14-26	20
0.063	6	6

Table 1. The selected aggregate (14 mm AMS).

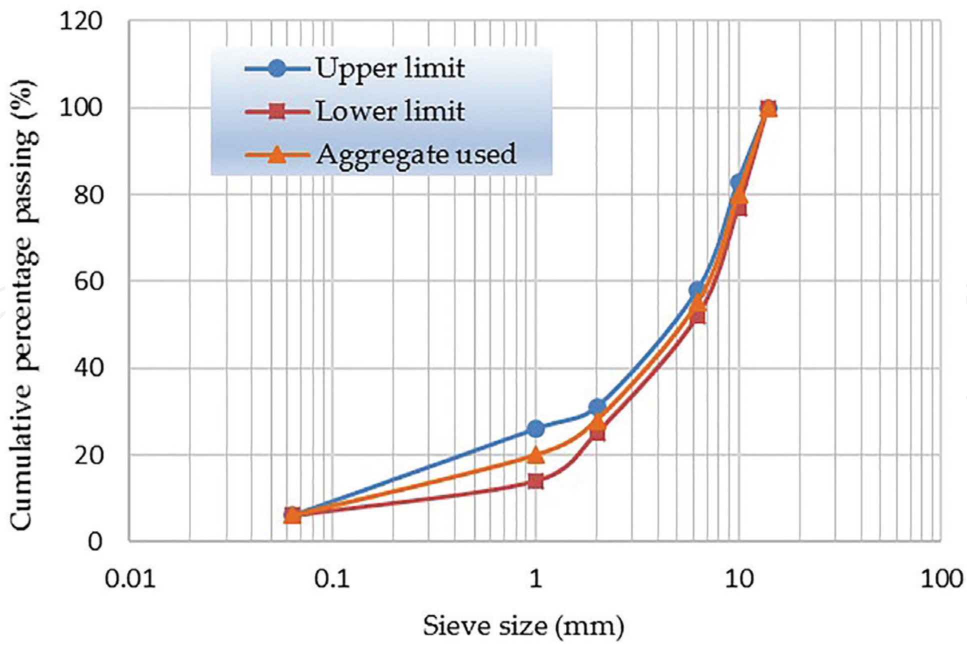

Figure 1. Gradation of close-graded surface course 14 mm AMS.

Properties	Value	
	Course Aggregate	Fine Aggregate
Bulk specific gravity (g/cm³)	100	100
Apparent specific gravity (g/cm³)	77-83	80
Water absorption (%)	52-58	55

Table 2. Physical properties of the aggregate.

The initial emulsion content could be found by dividing *P* by the percentage of bitumen content in the emulsion.

According to the aggregate gradation selection and by application of Eq. (1) the initial residual emulsion content is ($P = 6.16\%$) of the aggregate weight. Due to the variation between American and British sieve opening, little estimation happened during this calculation. The base bitumen content in the emulsion is 50%, thus:

$$\text{Initial emulsion content } (EIC) = 6.16/0.50 = 12.32\,\% \text{ of aggregate weight} \quad (2)$$

4.4. Determination of optimum pre-wetting water content (coating test)

Using IEC in coating test must be conducted after mixing all of the dry aggregate batches and filler, and pre-wetted with different amount of water. Five percentages of pre-wetted water content (2.5, 3, 3.5, 4 and 4.5%) of total aggregate were investigated to obtain the

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lowest percentage which ensures the highest coating. One minute of mixing time is sufficient to mix aggregate with water. Emulsion is added afterwards and blended for about 2–3 min until even coating is obtained. New batch of aggregate will be prepared with an additional increment water of 0.5 percent by weight of dry aggregate. The optimum pre-wetting water content (OPWwc) is that mixture gives the best bitumen coating on the aggregates surface (in which the mixture is not too sloppy or too stiff). The coating degree has not to be less than 50% by visual observation. Three percent was selected to be OPWwc by visibility judgment as shown in the **Figure 2**.

4.5. Determination of optimum water content at compaction

Water amount percentage during specimens' compaction is very critical. A high percentage of water, dissipated compaction effort, low density and undesirable mechanical properties are expected. On the other hand, low workability, density and mechanical properties result in low water content. Therefore, optimization of water content during compaction will enhance the desired mixture properties. According to MS-14, different water contents during compaction

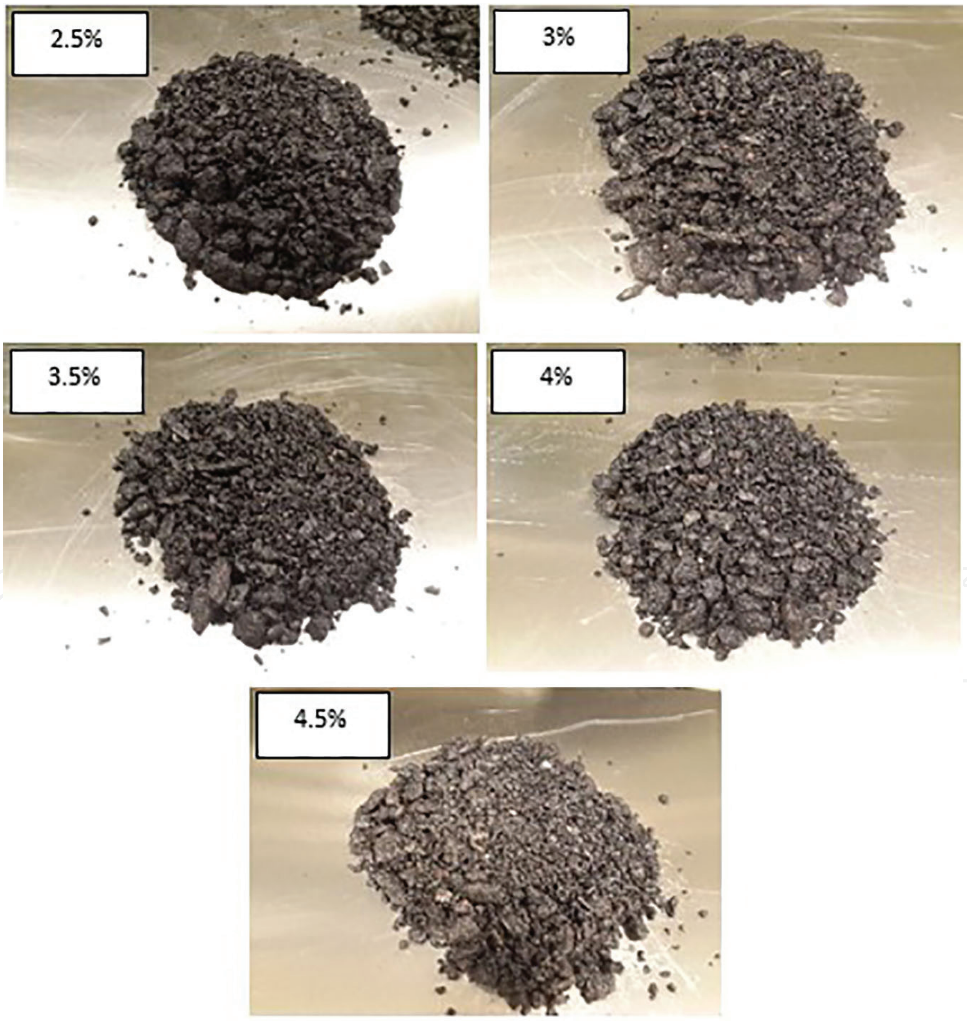

Figure 2. Percent of pre-wetting water content.

(the loose mixtures were compacted at *OPWwc* and at different water content during compaction with 1% steps by air drying) were performed as Marshall specimens. This stage gives the optimum water content at compaction at which the dry density of the sample is a maximum.

Initial emulsion content (*EIC*) = 12.32%.

Optimum pre-wetting water content (*OPWwc*) = 3%.

Total liquid content at compaction is 15.32%.

To find the optimum total liquid content at compaction, five percentages of total liquid content were investigated (15.32, 14.32, 13.32, 12.32 and 11.32%). The water content of each mixture was calculated after leaving the loose mixtures for different periods to reduce the total liquid content. Then, Marshall Hammer was performed to compact the mixtures; 50 blows were applied on each face. **Figure 3** shows that the 12.32% total liquid content gives maximum dry density. The result for each point represents the average of results of three specimens.

4.6. Determination of optimum emulsion content

Different emulsion content above and below the calculated initial emulsion content was used to prepare the Marshall samples, where the total liquid content remained same (15.32%). Indirect Tensile Stiffness Modulus (*ITSM*) test was used to determine the optimum residual emulsion content, which was observed to be 6.2% of aggregate weight (12.4% emulsion content) for soaked samples, while *ITSM* decreased with increase in residual bitumen content for dry samples, as shown in **Figure 4**. However, 12.4% emulsion content was adopted to be the optimum emulsion content because of the wet condition in the governing situation.

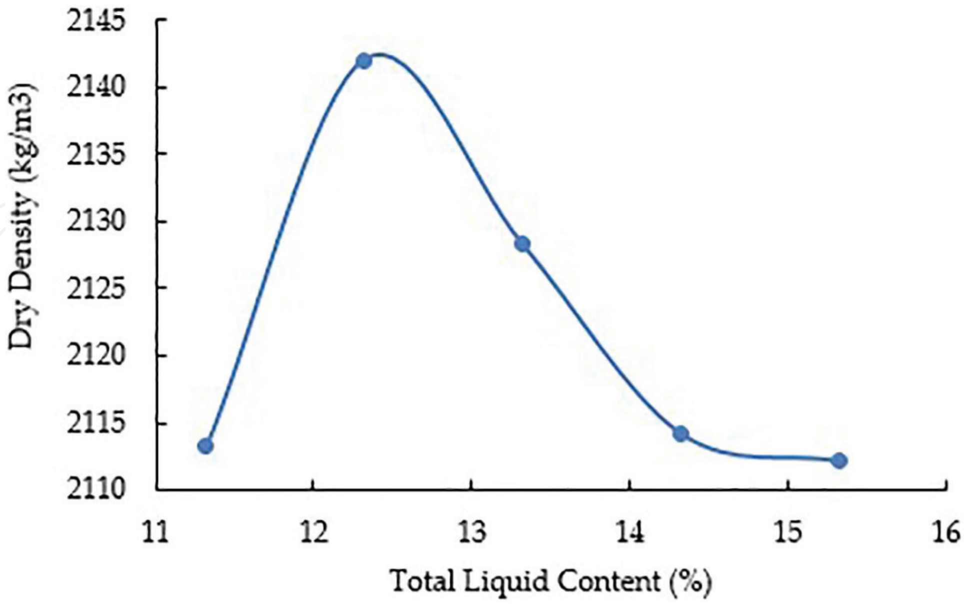

Figure 3. Optimum liquid content (%).

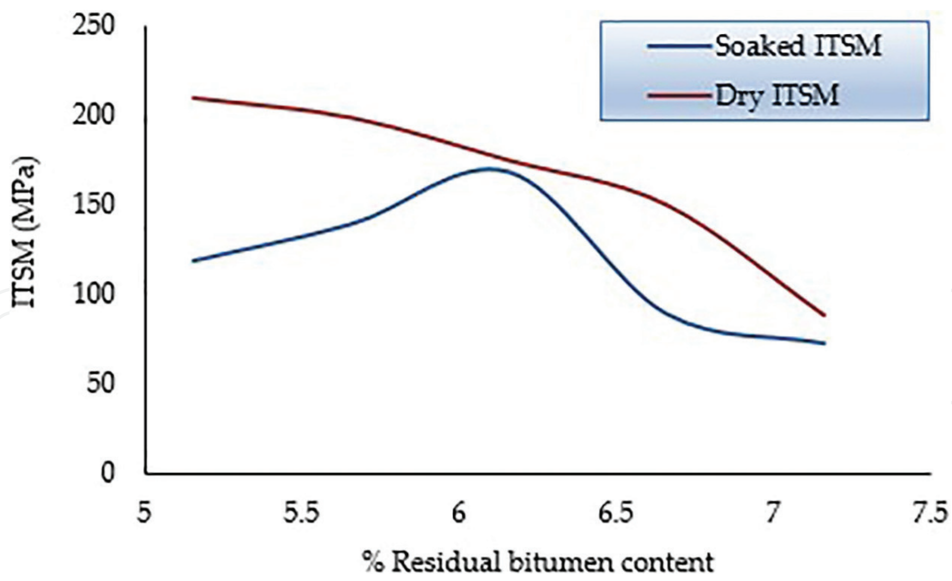

Figure 4. Optimum emulsion content.

5. Experimental program

5.1. Samples preparation

Incorporation of the glass fibre into the bituminous mixture was achieved through partial substitution of the conventional aggregate with different percentages by total weight of aggregate. In order to find the optimum content and length of the fibres, CBEMs were treated according to fibre weight with 0.15, 0.25, 0.35, 0.45 and 0.55% of the total aggregate weight and 10, 14 and 20 mm long. The testing results supported that 0.35% fibre content and 14 mm long gave the best results in term of Indirect Tensile Stiffness Modulus (ITSM). Compaction was carried out by means of a Marshall hammer with 50 blows applied to each face of the specimen.

The materials were blended together in a Hobart mixer. The aggregate together with the fibres and the pre-wetting water content were added and mixed for 1 min at low speed. After that, bitumen emulsion was added progressively throughout the next 30 s of mixing, and the mixing was continued for the next 2 min at the same speed. In addition, the samples were mixed and placed in the mould, and then directly compacted with 100 blows of the Marshall hammer, 50 on each side of the specimens by using standard Marshall Hammer (impact compactor).

The samples were left at lab temperature (20 ± 1°C), while they were still inside the moulds for 24 h; this represents the first stage for specimen's condition according to the procedure adopted by the Asphalt Institute. After that, all the samples were extruded from the moulds and kept in the lab for the different curing periods (1, 3, 7, 14 and 28 days).

5.2. Indirect tensile stiffness modulus (ITSM)

The ITSM test is a non-destructive test used mainly to evaluate the stiffness modulus of hot mixes. ITSM at 20°C was used to obtain the optimum emulsion content. Different testing temperatures, 5, 20, 40 and 60°C, were used to assess the temperature susceptibility of the mixtures. This test was carried out as per BS EN 12697-26 [21] using the Cooper Research Technology HYD 25 testing apparatus as shown below in **Figure 5**.

5.3. Creep and relaxation test

The creep test at different temperatures (5, 20, 40 and 60°C) was used to obtain the viscoelastic properties of CBEMs. The test was conducted under 0.1 MPa in accordance with BS EN 12697–25 [22] as shown in **Figure 6**.

5.4. Wheel tracking test

The laboratory wheel tracking test, which is shown in **Figure 7**, was used for asphalt mixtures in terms of rutting resistance in accordance with the European Committee for Standardization [23]. This test is used to validate the model results in terms of rut depth and deformation shape. Slab specimens with 400 mm × 305 mm × 50 mm dimensions were prepared to measure rut depth in reinforced and conventional cold mix asphalt (close graded surface course). In this study, the wheel track testing was conducted at different temperatures 45 and 60°C under application of 700 kPa stress.

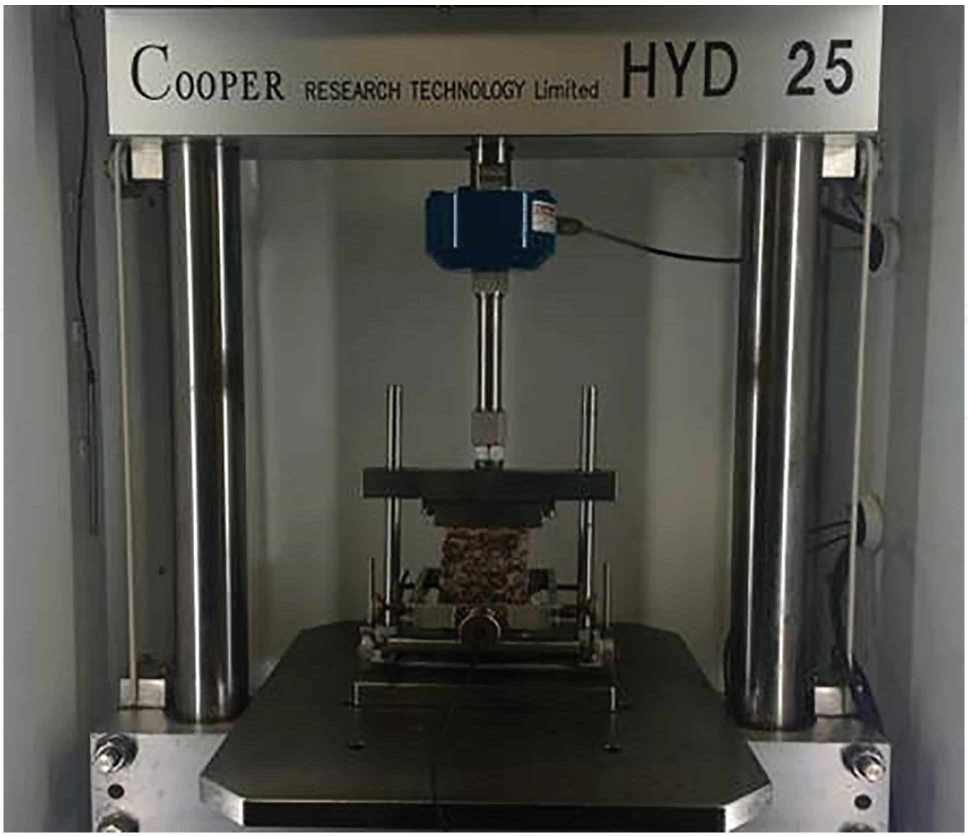

Figure 5. ITSM apparatus machine.

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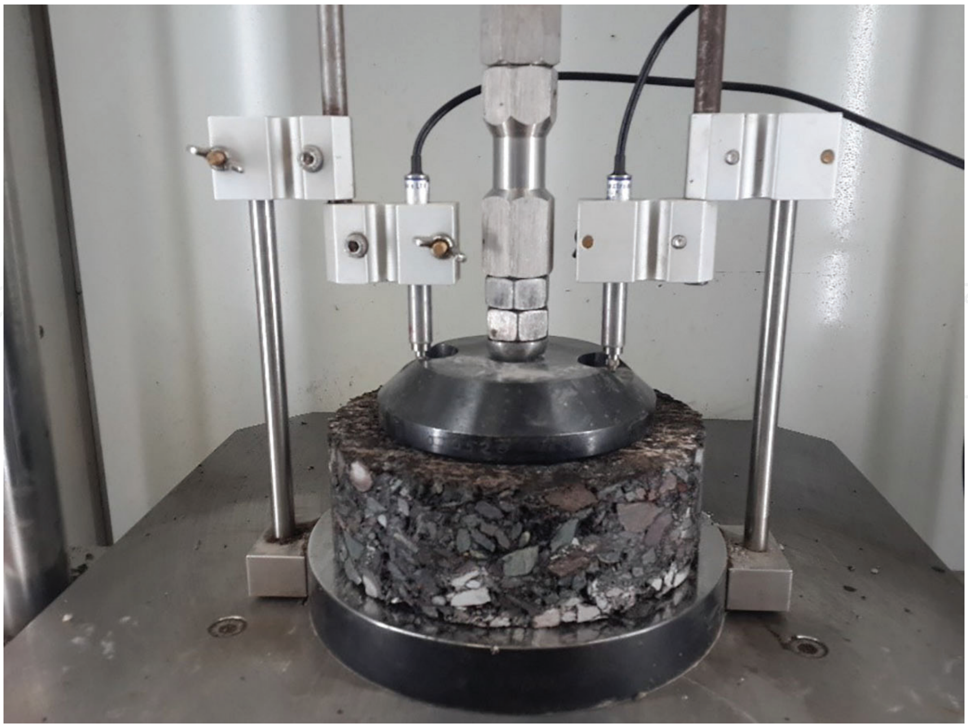

Figure 6. Creep test set–up.

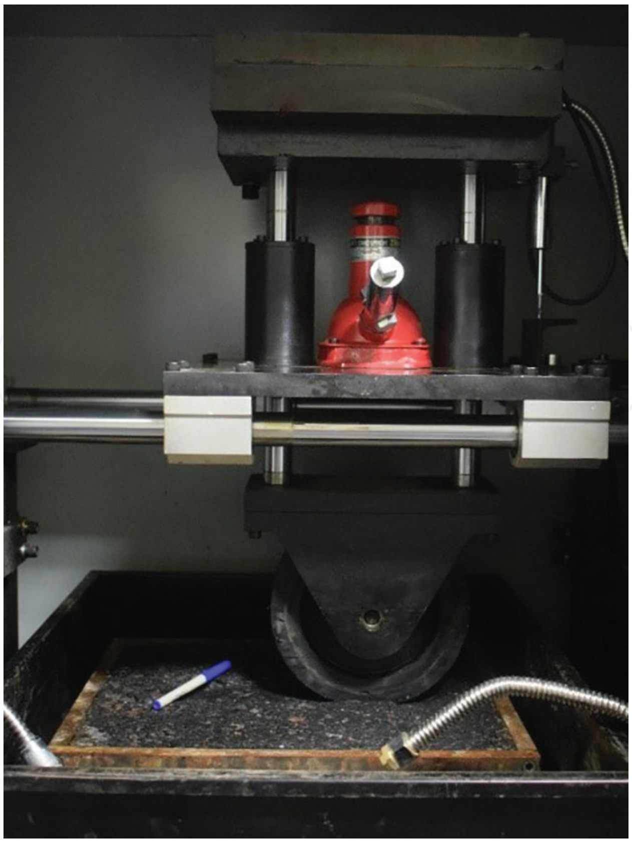

Figure 7. Wheel tracking test.

6. Finite element modelling

Road pavement design requires choosing appropriate materials, and a structure can resist repeated loading and climate changes during a long time period without need to maintenance. Pavement construction materials, which have complex behaviour, require advanced constitutive models that are able of controlling these complexities. Economic and efficient pavement system for modelling complex behaviour of materials is the finite element method. It is a versatile analysis technique and has the ability to model two- and three-dimensional geometric designs, linear and nonlinear material properties, elastic, plastic and viscous behaviours, and other complex features. However, in finite element analysis simulation, applying large number of loads requires significant computational effort. Nevertheless, finite element analysis can extend understanding behaviour and performance of pavement and pavement's material; also, it give insights into critical positions in the road pavement structure.

The viscoelastic model development and validation of this research are implemented in ABAQUS, which is a commercial finite element package widely used in pavement engineering analysis. This software is capable of solving simple and complicated problems using linear and nonlinear analysis. Pavement deformation analysis in road pavement is easy to find by using simple tool in ABAQUS under moving and static loads. The advantages of using such software for this application are validated, mature, well-documented, and its ability to visualize the results after the analysis is completed. In addition, ABAQUS's library has many material models, which can be used to simulate every pavement layers such as linear elastic, viscoelastic, elastoplastic and viscoelastoplastic. In this research, the model was developed as viscoelastic, and the load is a static.

6.1. Materials model

To define the response of the pavement materials, viscoelastic behaviour was used. For obtaining this purpose according to the materials consist of the pavement structure (**Figure 8**),

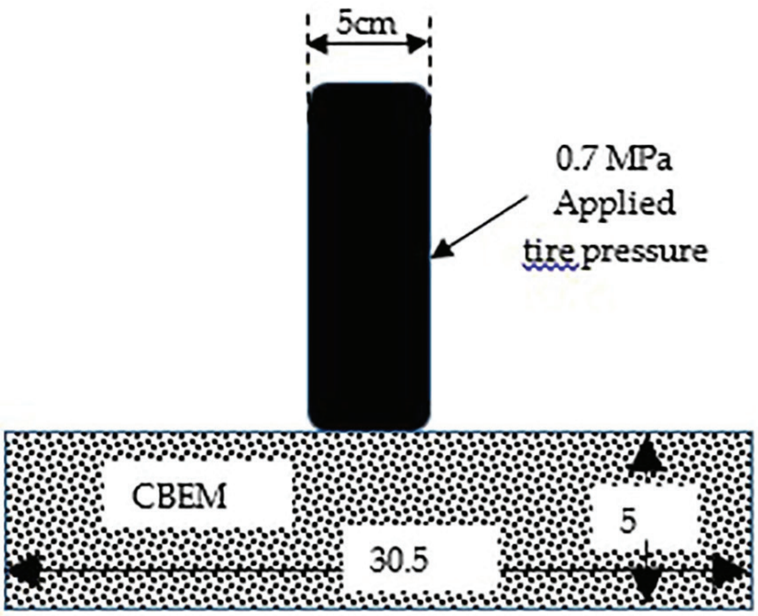

Figure 8. CBEM slab modelling for the evaluation of mixtures.

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		Viscoelastic material coefficients							
		Temperatures (°C)							
		60		45		20		5	
		D_i (1/kPa)		D_i (1/kPa)		D_i (1/kPa)		D_i (1/kPa)	
i	τ_i (s)	CON	GLS	CON	GLS	CON	GLS	CON	GLS
1	0.1	6.91E-06	4.65E-06	1.14E-05	3.24E-06	3.66E-06	2.87E-06	8.81E-06	2.68E-06
2	1	6.12E-05	4.41E-05	1.90E-05	2.47E-05	5.18E-06	1.63E-06	7.24E-05	1.22E-05
3	10	1.54E-04	1.04E-04	4.08E-05	7.08E-05	3.90E-05	3.24E-05	9.63E-05	2.28E-05
4	100	2.09E-04	1.27E-04	7.43E-05	9.85E-05	5.67E-05	7.07E-05	5.16E-04	5.19E-05
5	1000	2.62E-04	1.42E-04	1.08E-04	1.29E-04	7.40E-05	1.15E-04	8.25E-04	1.02E-04
Modulus of elasticity E (MPa)		35	491	100	501	464	1152	581	1827

Table 3. Elastic and viscoelastic properties of reinforced and unreinforced CBEMs at different temperatures.

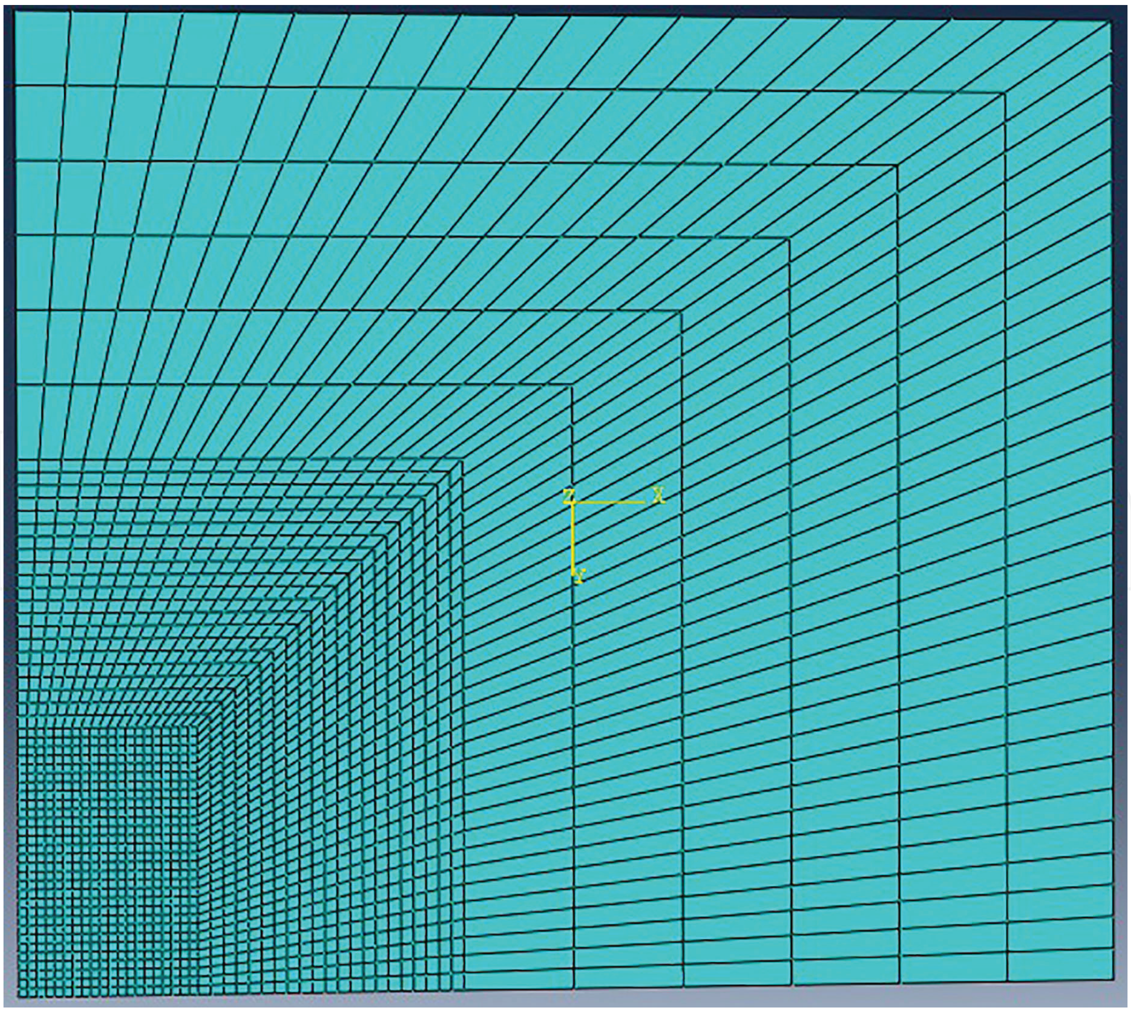

Figure 9. The final mesh of the top surface layer.

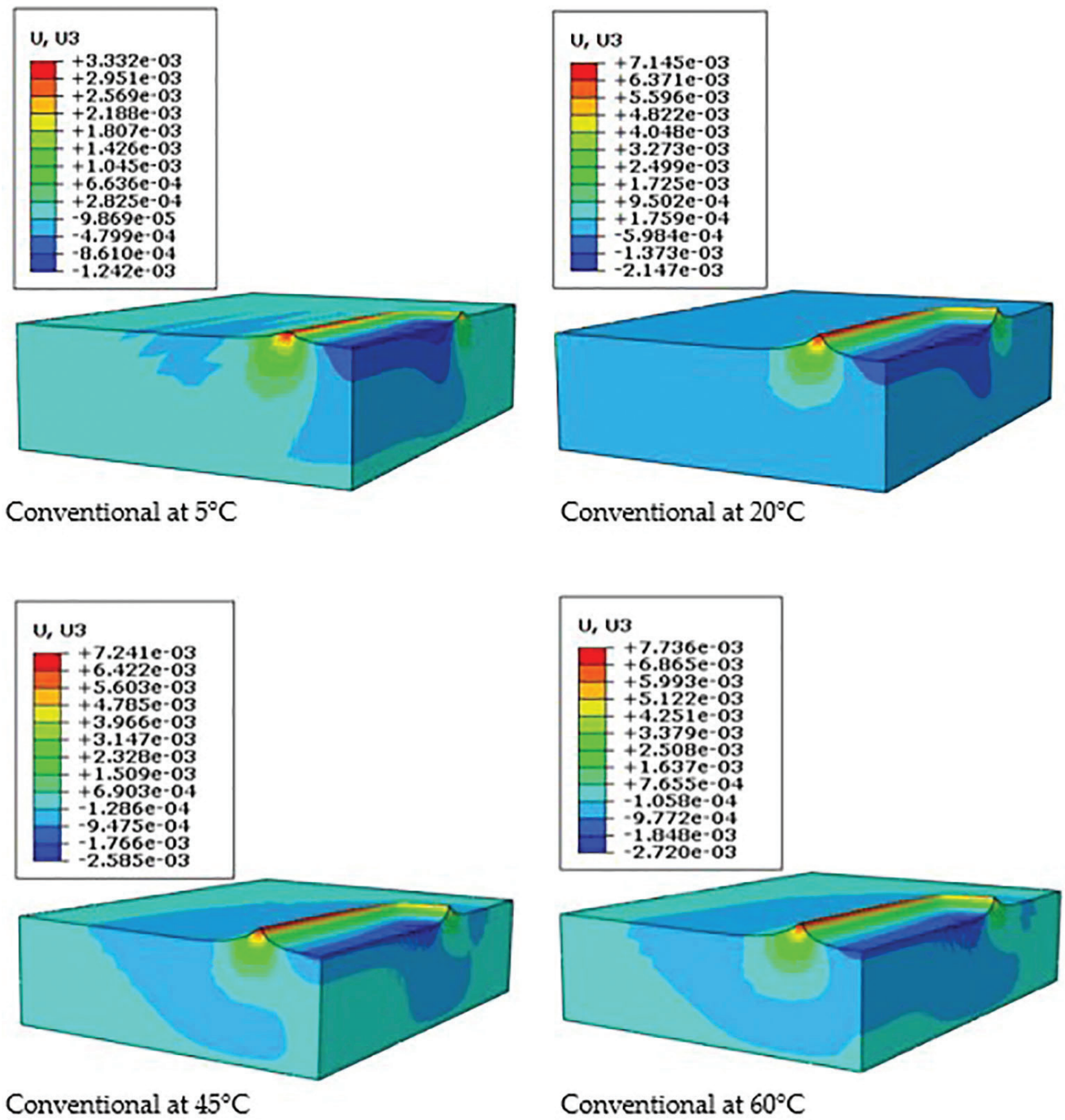

Figure 10. Predicted rutting of conventional CBEMs.

all pavement material behaviours are modelled to be homogeneous isotropic responded to the applied load as a moving load. Experimental tests are carried out on CBEMs after 14 days of curing to obtain elastic and viscoelastic properties of CBEMs as shown in **Table 3**.

6.2. Element type and mesh

The pavement structure was meshed using an 8-node continuum linear brick reduced integration element (C3D8R element). Under the loading area of the model, stress concentrations are applied and, therefore, fine mesh must be used for obtaining results as shown in **Figure 9**.

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The large size of the elements in the model is 0.075 m, and in the loading area is 0.0015 m (fine mesh under loading area and coarse mesh far from it). The total number of elements is 46,800, and the mesh convergence study is achieved to find this optimum number of elements.

6.3. Loading and boundary condition

Symmetric boundary condition was performed in simulation, and the bottom of the layer was assumed to be fixed with no displacement in horizontal and vertical directions representing a very stiff layer (encastre). For simplify simulation, the tire and contact between tire and pavement structure are neglected, and uniform pressure as a surface load is defined as tire loading.

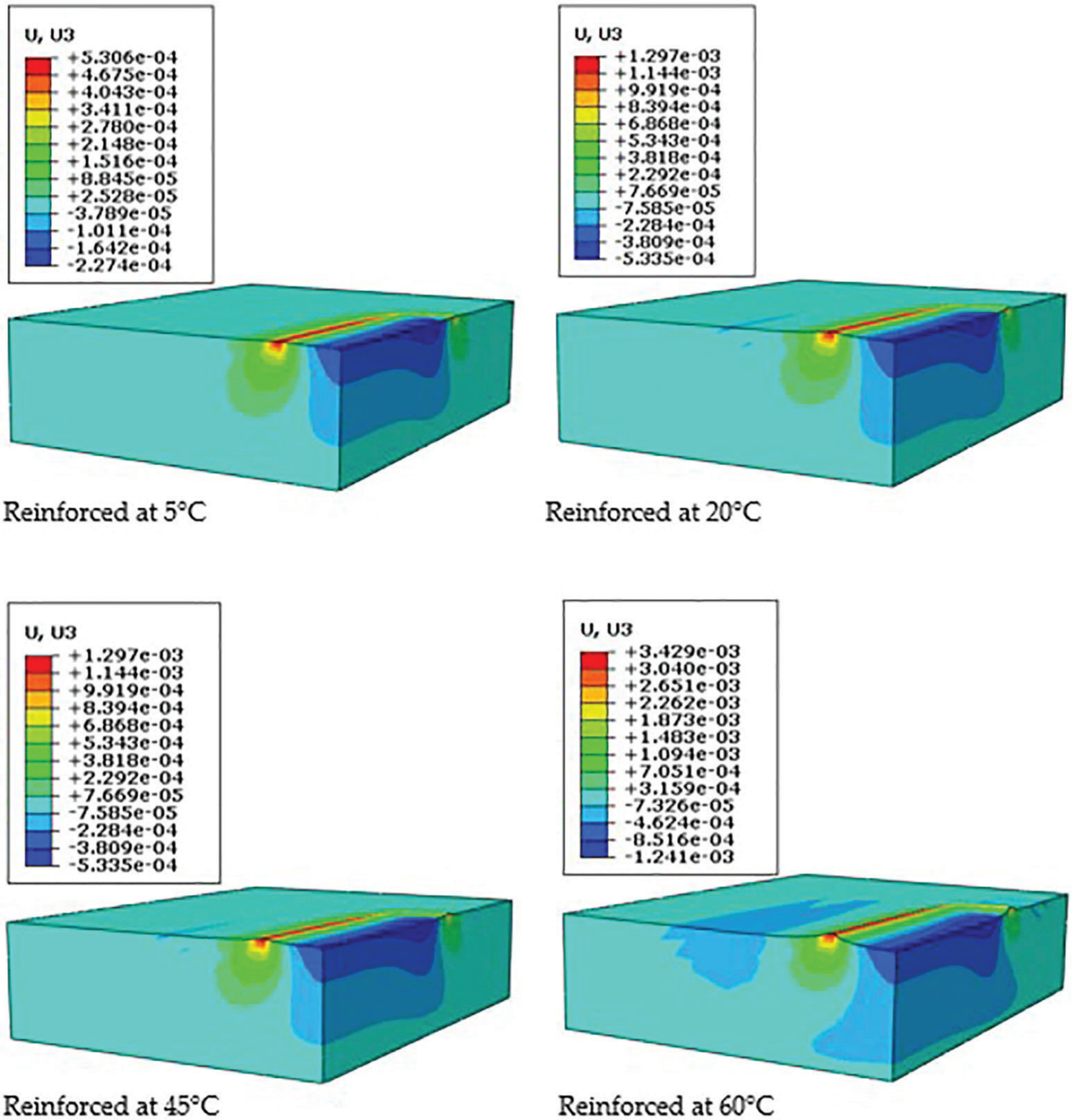

Figure 11. Predicted rutting of reinforced CBEMs.

6.4. Results and discussion

Figures 10 and **11** present predicted rutting for conventional and reinforced CBEMs at different temperatures. The model shows that increasing temperature increases the rut depth at the final state of 5000 wheel repetitions. It can be seen that the rutting (deformation) under the load is deeper than other areas. Moreover, after 5000 loading cycles, the rutting accumulated on the reinforced slab samples has a high potential to minimize pavement rutting in comparison with unreinforced samples. The rutting accumulation still keeps increasing with increasing temperatures. These results indicate that the bituminous material reaches the second stage of creep earlier as temperature increases. In addition, there are some predicted heaves located besides of the load edges.

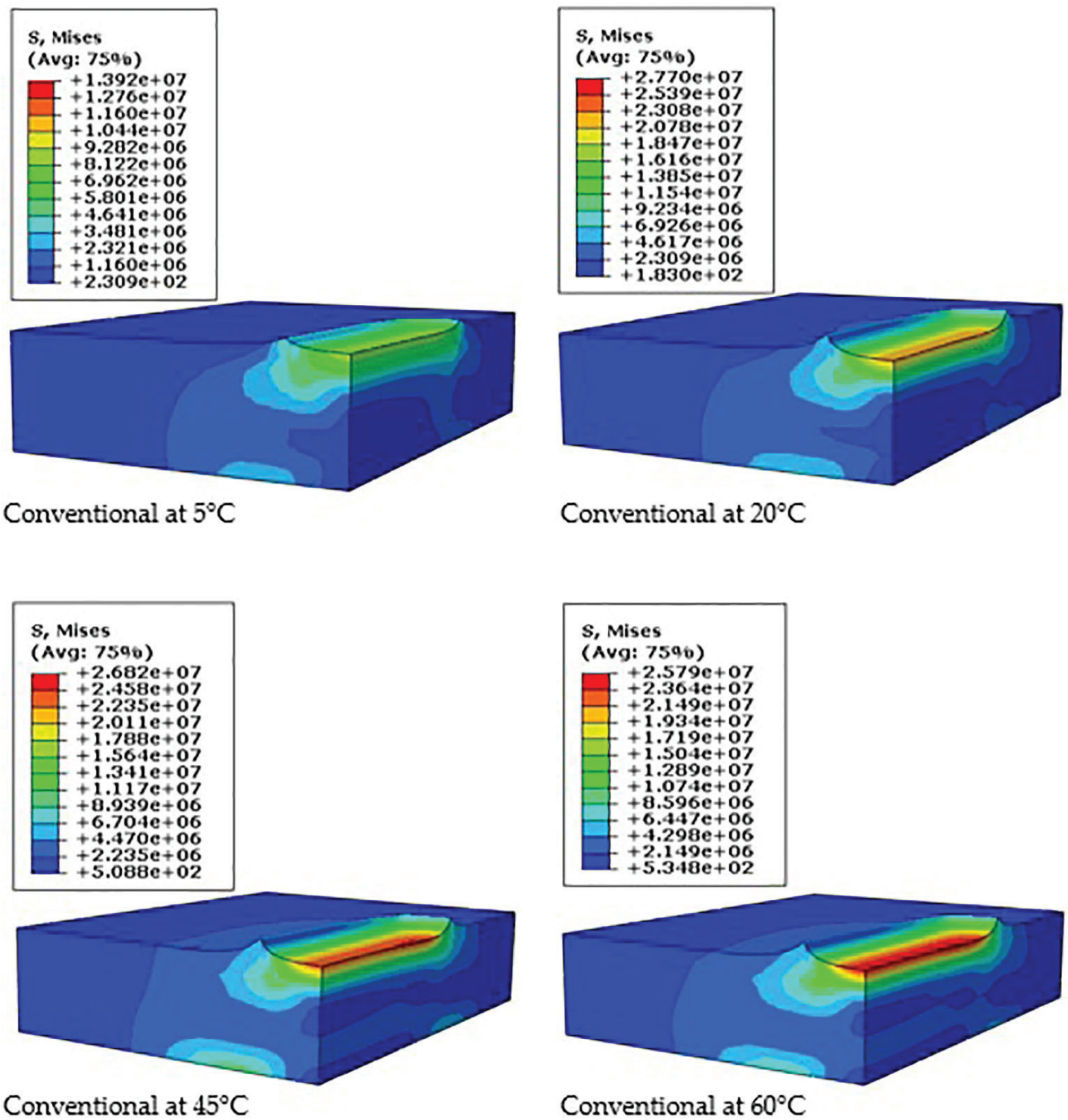

Figure 12. Predicted stress of conventional CBEMs.

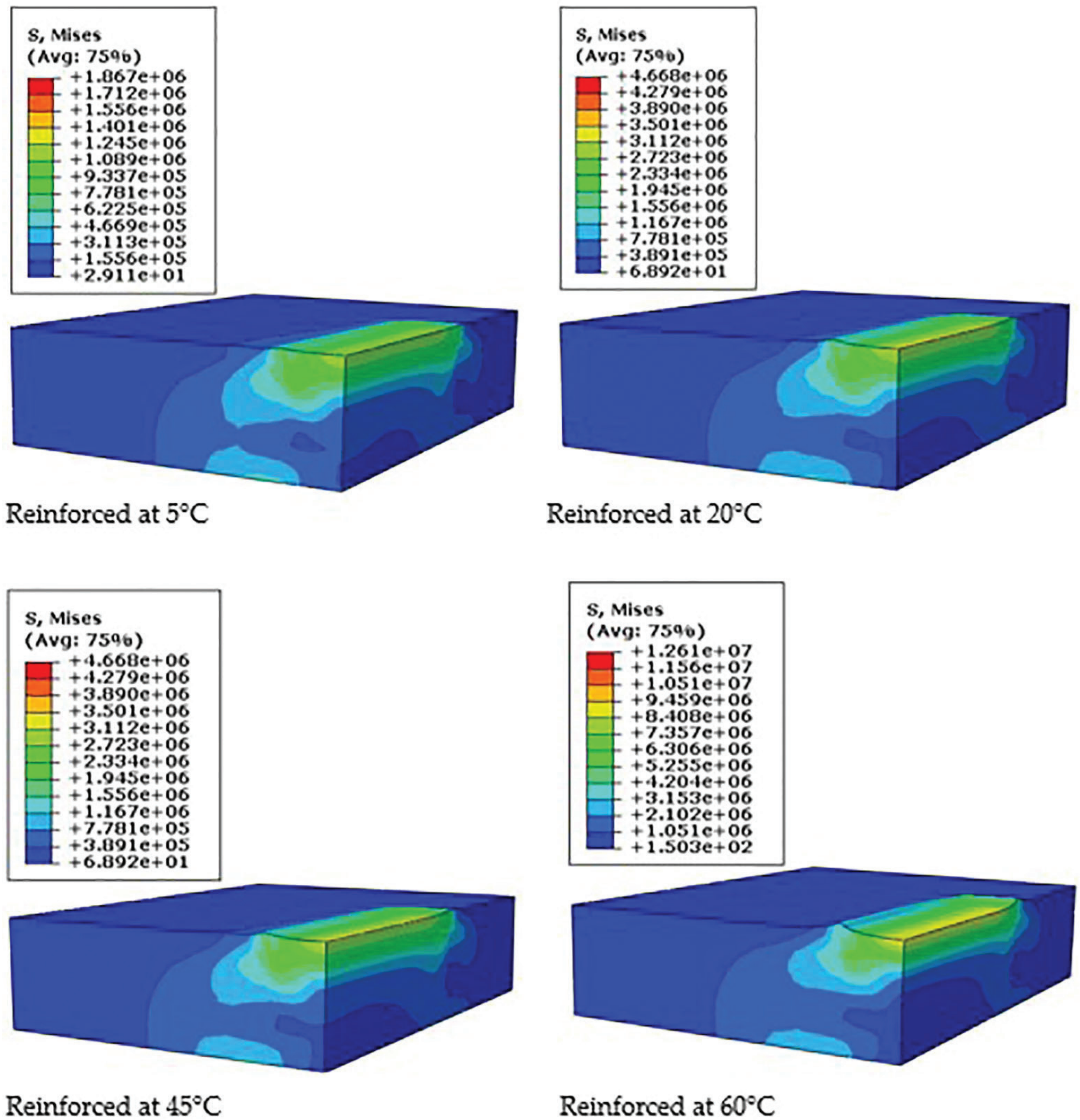

Figure 13. Predicted stress of reinforced CBEMs.

The results of this model and the distributions of the stresses in the reinforced and unreinforced CBEM slabs are presented in **Figures 12** and **13**. These figures show the results obtained by the model after 5000 s of cyclic load application at different temperatures. The extreme values of the stresses appear on the top of the CBEM slabs under the load.

7. Conclusion

The aim of this research was to predict rutting performance of glass-fibre reinforced and conventional cold bitumen emulsion mixtures (CBEMs). To achieve this goal, the ABAQUS finite element method is performed for simulation of the CBEMs accelerated rutting performance in the wheel-tracking test. Three-dimensional viscoelastic model is used in simulation, and some conclusions can be drawn:

- Results show that there is a good relationship between the rutting predicted in the finite element modelling and the rutting measured in the wheel-tracking test.
- According to obtained results, the provided model can properly predict rutting behaviour of reinforced CBEMs in different temperatures.
- Compared with the conventional model, the reinforced model shows a lower rutting for the testing condition ranges of temperatures given in this research.
- Results show that glass fibre has positive effects on mechanical behaviour of CBEM.

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