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Predicting the rutting behaviour of natural fibre-reinforced cold mix asphalt using the finite element method

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Abstract:

This paper describes the development of a three-dimensional (3-D), finite element model (FEM) of flexible pavements made with cold mix asphalt (CMA), which has itself been reinforced with two different natural fibres: jute and coir. A 3-D finite element model was employed to predict the viscoelastic response of flexible CMA pavements when subjected to multiple axle loads, different bituminous material properties, tire speeds and temperatures. The analysis was conducted by the finite element computer package ABAQUS/STANDARD. The pavements were subject to cyclic and static loading conditions to test for permanent deformation (rutting). The accuracy of the developed model was validated by comparing the predicted results with those measured in the lab. Reinforced and unreinforced CMA mixture models were simulated in this research. The results indicate that the CMA mixtures reinforced with natural fibres, are effective in mitigating permanent deformation (rutting). These reinforcing materials can extend the service life of flexible pavements.

Keywords: 3-D model; ABAQUS; enhancement; flexible pavements; mechanical properties; permanent deformation; simulation.

1. Introduction

Due to increases in traffic volume, specifically heavy trucks, in terms of numbers of vehicles and high tyre pressures, above average demands are being placed on existing road pavements. Both horizontal and vertical stresses induced between pavement layers, result in permanent deformation (rutting) and crack formation [1]. Rutting is one of the main distresses that frequently occurs in flexible pavement overlays [2] which can be constructed using hot mix asphalt (HMA), warm mix asphalt (WMA) or cold mix asphalt (CMA). Cold mix asphalt is defined as bituminous materials which are prepared at ambient temperature by emulsifying the asphalt in water before blending with the aggregates. CMA has a number of benefits over HMA, but the main difference lies in the fact that CMA does not require any heating as it can be manufactured, laid and compacted without heating. In addition, CMA can offer the following advantages:

- CMA is not dependent upon warm weather.
- It can be mixed on site or off site.
- Eco-friendly option during all production processes made from water-based materials at ambient temperatures, which reduces emissions, energy consumption and toxic fumes.
- Cost-effective solution for paving or repairing rural roads that are nowhere near a hot mix plant, as minimal material and transportation costs required where CMA used in remote areas.

Although CMA provides both economic and environmental benefits in terms of removing the need for heating large amounts of aggregate [3, 4], it is rarely used due to its weak early strength, long curing time, high air voids and poor mechanical properties [4].

Reinforcing HMA and CMA with fibres can improve strength, bonding and durability [5-7]. Currently, natural and synthetic fibres are used as a reinforcing material in asphalt mixtures because of their high stiffness and strength properties, and are considered the most appropriate reinforcing materials [1]. A variety of experimental research has been conducted to evaluate the effect of natural and synthetic fibres on the mechanical behaviour of bituminous mixtures in terms of hot mix asphalt. The results of these studies indicate that these fibres have a positive impact on the performance of bituminous mixtures [8-11], the performance of reinforced mixtures mainly affected by fibre length, content, type, diameter and surface texture [9, 12]. In consequence, in this research, several parameters pertaining to fibres; type, length and content, were considered and optimized when said fibres were added to CMA mixtures. Two different natural fibre types, jute and coir with 14 mm optimum fibre length and 0.35% fibre content, were used to improve the performance of the CMA mixtures [13].

In countries where high temperatures are the norm, pavement rutting is the major distress encountered in flexible pavements and considered to be one of the more complex issues in pavement structure [14]. It occurs due to the accumulation of permanent deformation on the pavement surface underneath the path of repeated wheel loadings. Such accumulated permanent deformation has been attributed to different variables including temperature, traffic volume, wheel load and repetition, tyre pressure, material properties and bituminous layer thickness [15]. Flexible pavement design methods are based on linear elastic calculations, however, new pavement design techniques are required to account for undesirable environmental conditions and heavy loading, these being common sources of rutting [16]. However, given that flexible pavements are subjected to different loading and environmental conditions which impact on their performance, it is somewhat surprising that the impact of these aspects has not been fully simulated to date [16]. With specific reference to repeated loading, there is no technique currently available to investigate rutting on CMA pavements and no model available to predict permanent deformation for such pavements.

This research aims to predict the rutting behaviour of CMA mixtures reinforced with natural fibres. The Finite Element Method (FEM) is used to carry out the numerical analysis for this model. In finite element modelling, bituminous laboratory samples are tested to obtain the material properties that are required for the development of the viscoelastic model [17]. The rutting analysis is performed utilizing ABAQUS software.

Different techniques are available to predict rutting in bituminous mixtures such as finite difference methods [18], analytical methods [19], multilayer elastic theory [20], hybrid methods [21] and finite element methods [22, 23]. FEM has been used for bituminous materials but it does depend on experimental data as input. Allou, et al. [24] developed a 3-D linear viscoelastic model to characterize the dynamic modulus and Poisson's ratio of bituminous mixtures. Pérez, et al. [25] developed a 3-D finite element model to evaluate the response of rural road pavements when recycled in situ, using bitumen with two different added materials: 75% natural aggregate and 25% reclaimed asphalt pavement, with and without 1% cement. Gu, et al. [26] evaluated the mitigation effect of geogrid-reinforced flexible pavements on rutting damage using a finite element model. The results showed that reinforced pavements have much better rutting resistance than unreinforced pavements.

The primary objectives of this study are to develop a 3-D finite element model to simulate the laboratory testing of CMA mixtures' wheel tracking tests for rutting and to relate the test results to the properties of the mixtures. This viscoelastic model was employed to assess loading time, strain, temperature and the properties of the mixture materials, to evaluate the behaviour of the CMA pavements.

2. Viscoelasticity of cold mix asphalt

Viscoelasticity is the property of a material that performs both viscous and elastic behaviours when subjected to deformation [27]. Viscous materials can resist shear stresses and show linear strain patterns over time when loading is applied. Elastic materials strain instantaneously on loading, returning back to their original state without permanent deformation when the load is released. Asphalt mixtures have elements of both these characteristics and present time-rate dependent behaviour. They are considered viscoelastic materials when the deformation is small [28]. Bitumen is typically a viscous material when mixed with elastic aggregate to produce asphalt mixtures, hence viscoelasticity is expected. Viscosity can be represented by a dashpot, following the equation:

$$\sigma(t) = \eta \frac{d\varepsilon(t)}{dt} \quad (1)$$

where $\sigma(t)$ and $\varepsilon(t)$ are stress and strain, respectively, and η is the viscosity. Elasticity can be represented by a spring, which follows the equations:

$$\sigma(t) = E\varepsilon(t) \quad (2)$$

$$\varepsilon(t) = D\sigma(t) \quad (3)$$

where E and D are the modulus and compliance of elasticity, respectively.

Different combinations of dashpots and springs represent a variety of viscoelastic models. For instance, the Maxwell model consists of one dashpot and one spring in series (Figure 1a), while the Kelvin-Voigt model consists of one dashpot and one spring in parallel (Figure 1b). After application of a single load, instantaneous and retarded elastic strains predominate and the viscous strain is negligible. However, under multiple load applications, the accumulation of viscous strain is the cause of permanent deformation [27]. Huang [27] suggested that a single Kelvin model is not adequate enough to cover the long period of time over which retarded strain takes place, and that a number of Kelvin models may be needed. In consequence, to describe the isotropic viscoelastic behaviour of bituminous mixtures, a generalized model has been used in this study. This model consists of one Maxwell model and two Kelvin models connected in a series as shown in Figure 1c. The total strain at time *t* of the generalized model is given as follows [29]:

$$D(t) = \frac{\sigma}{E_{o}}\left(1+\frac{t}{T_{o}}\right)+\sum_{i=1}^{N}\frac{\sigma}{E_{i}}\left(1-e^{-\frac{t}{T_{i}}}\right) \tag{4}$$

where *D(t)* is the creep compliance; E_o the initial elastic modulus at time zero; T_o the relaxation time; *t* the loading time; T_i the retardation time ($T_i = \eta / E$); E_i the elastic modulus at any time and *N* the number of Kelvin models in the Prony series model. This equation is also known as a Prony series expansion.

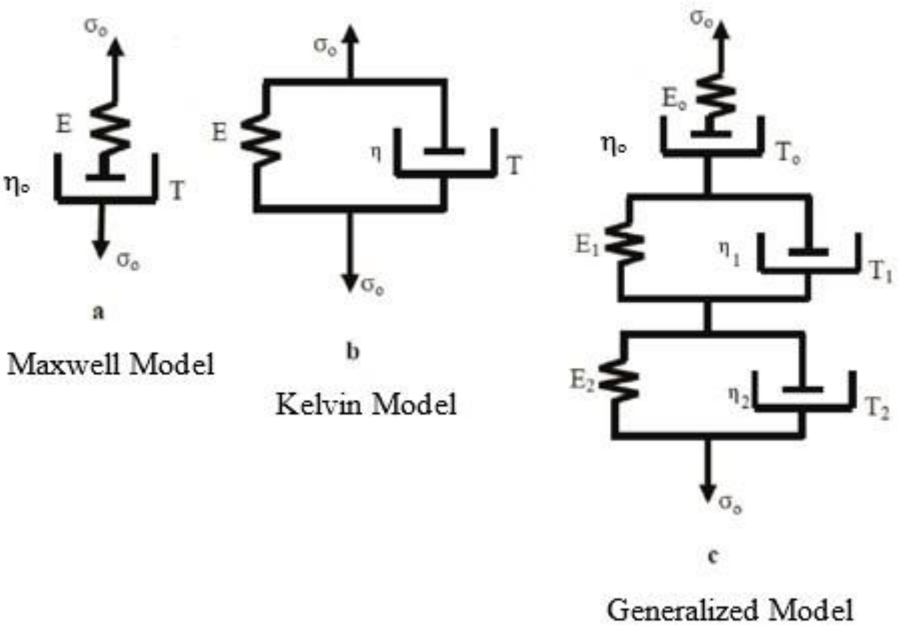


Figure 1. Mechanical models for viscoelastic materials

The phenomenon of permanent deformation (rutting) can be evaluated by carrying out creep and relaxation tests [30]. Both creep compliance *D(t)* and relaxation modulus *E(t)* are required to develop a viscoelastic model; creep compliance is required to predict deformation and the relaxation modulus to determine pseudo strain. In this study, Prony series coefficients have been fitted to experimental data to represent the viscoelastic (time-dependent) properties of the bituminous mixtures. The experimental data were obtained from creep and relaxation tests for reinforced and unreinforced cold mix asphalt mixtures.

The creep and relaxation test for asphalt mixtures, a typical strain-time curve, can be divided into three distinct strain stages: decelerated creep, the first stage where the strain rate decreases; standard creep, the second stage with a constant strain rate and accelerated creep, the third stage which sees an increase in strain rate. These three stages of asphalt mixture behaviour are shown in Figure 2. The total strain in asphalt mixtures usually consists of four constituents: (1) recoverable elastic strain which is time-independent; (2) recoverable viscoelastic strain which is time-dependent; (3) irrecoverable plastic strain which is time-independent, and (4) irrecoverable viscoplastic strain which is time-dependent. During recovery time, elastic strain is instantaneously recovered de-formation while delayed recovered deformation is viscoelastic strain. Viscoelastic strain needs adequate time to fully recover. Permanent strain is the combination of both plastic and viscoplastic strains.

The objective of this study is to investigate a viscoelastic model that can entirely characterize the first two stages of creep deformation behaviour, for both reinforced and conventional cold mix asphalt mixtures, through a series of creep and relaxation tests.

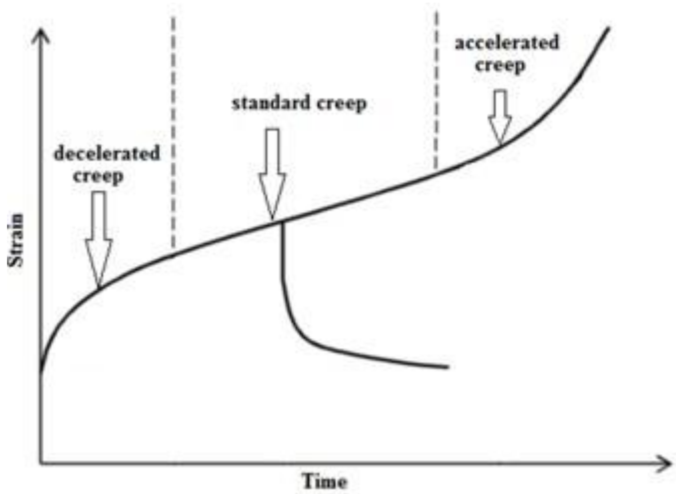


Figure 2. Creep and relaxation behaviour at constant stress

3. Experimental methods

3.1 Materials

The conventional (CON) cold mix asphalt (CMA) mixture was made of aggregates of gradation 14 mm, a close-graded surface course, in according with the European Committee for Standardization-part 1 [31], as presented in Table 1. Based on the British Standard [31], the selected aggregate is one of the most common aggregate used in the production of asphalt and it is considered hard, durable, clean, have suitable shape, provide a level of skid resistance and resist permanent deformation. In addition, this selection was in order to ensure an appropriate interlock between the particles in the mixtures. Cationic, slow-setting (B3), bituminous emulsion with 50% bitumen content (C50B3), was used as the binding agent for the aggregates. The supplier of this emulsion (Jobling Purser, Newcastle, UK) has used another commercial name as a cold asphalt binder (CAB 50) and it is based on a 40/60 penetration grade base bitumen. Table 2 shows the properties of the selected bitumen emulsion. Two types of natural fibres were used as reinforcement materials; jute (JUT) and coir (COI) fibres. According to the laboratory results, the reinforced mixtures were made with the optimum fibre content and length, 0.35% and 14 mm, respectively.

Table 1. Selected mix gradation

Sieve size (mm)	14	10	6.3	2	1	0.063
Passing (%)	100	80	55	28	20	6

Table 2. Properties of (CAB 50) bitumen emulsion

Property	Value	Standard
Type	Cationic	
Appearance	Black to dark brown liquid	
Breaking behaviour	110-195	EN 13075-1
Base bitumen Penetration (0.1 mm)	50	EN 1426
Softening Point (°C)	50	EN 1427
Bitumen content, (%)	50	EN 1428
Viscosity (2mm at 40°C)	15-70	EN 12846
PH	5	
Boiling point, (°C)	100	
Adhesiveness	≥ 90%	EN13614
Relative density at 15 °C, (g/ml)	1.05	
Particle surface electric charge	positive	EN 1430
Density (g/cm³)	1.016	

3.2 Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus test (ITSM), is a non-destructive test mainly used to evaluate the stiffness modulus of asphalt mixtures (see Figure 3a). ITSM at 20°C has been used to optimize the length of the fibres and the fibre and emulsion content. Four different testing temperatures, 5°C, 20°C, 45°C and 60°C, were used to assess the susceptibility to temperature of the mixtures. This test is carried out in accordance with the European Committee for Standardization, part 26 [32].

a b c

Figure 3. Laboratory equipment

3.3 Creep and relaxation test

The creep test at 5°C, 20°C, 45°C and 60°C, was used to study the influence of reinforced and unreinforced mixtures on creep performance to assess their viscoelastic properties (Figure 3b).

The test was conducted under 0.1 MPa stress in accordance with the European Committee for Standardization, part 25 [33].

3.4 Wheel track test

The laboratory wheel track test was used for the asphalt mixtures to assess resistance to rutting of hot and cold mix asphalt mixtures [34, 35], following the European Committee for Standardization, part 22 [36]. This test is used to validate the model results in terms of rut depth and deformation shape (Figure 3c). Prior to carrying out the tests, the loose bituminous mixtures were mixed and compacted in a steel mould under a steel roller compactor, resulting in a solid slab measuring 400 mm (length) × 305 mm (width) × 50 mm (thickness). The specimens then were kept in the mould for 24 hours at room temperature (20°C). Following this, the slabs were cured for 14 days, inside a ventilated oven at 40°C, to achieve full curing [34]. This curing temperature is significant as it needs to be less than the bitumen softening point (50°C) and thus prevent the bitumen from ageing [34]. Slab specimens were tested to measure rut depth in both the reinforced and conventional cold mix asphalts (close-graded surface course). Wheel track testing was conducted at 45°C and 60°C, under application of 700 kPa stress. Three slabs of each mixture type were tracked using the wheel tester.

4. Fibres optimisation

The Indirect Tensile Stiffness modulus is regarded as key when evaluating the effect of different fibre lengths and contents on CMA mixture performance, taking into account the effect of curing time and condition. Figure 4 shows that ITSM initially increases then decreases, with increasing fibre content, for all fibre lengths and types. The CMA mixture reinforced with 0.35% fibre content by weight of dry aggregate, had a higher ITSM than the other mixtures for all fibre lengths. This is in agreement with other researchers Chen, et al. [9] and Xu, et al. [37] who recommend that the optimum fibre content should be between 0.3% and 0.4%, based on the results from similar tests. 14 mm long fibres, cured for 2 days, developed the ITSM of the reinforced CMA mixtures to the maximum value. This indicates that the reinforced mixture with 14 mm fibre length and 0.35% content adheres well to the bitumen [1]. According to Liu, et al. [38], short fibres (10 mm) cannot properly reinforce mixtures that have a larger size of aggregate (maximum 14 mm) while long fibres (longer than the maximum size of the aggregate) can lead to loss in mixture strength because these fibres tend to lump together during the mixing process. The results found here were similar to those found in the literature [39]. Because of the use of an appropriate length of fibre (14 mm in this research), the placement and distribution of this fibre in the bituminous mixture, produced enhanced interlocking between the fibre and the paste, hence the lateral strain was delayed and the mixture strength improved [40].

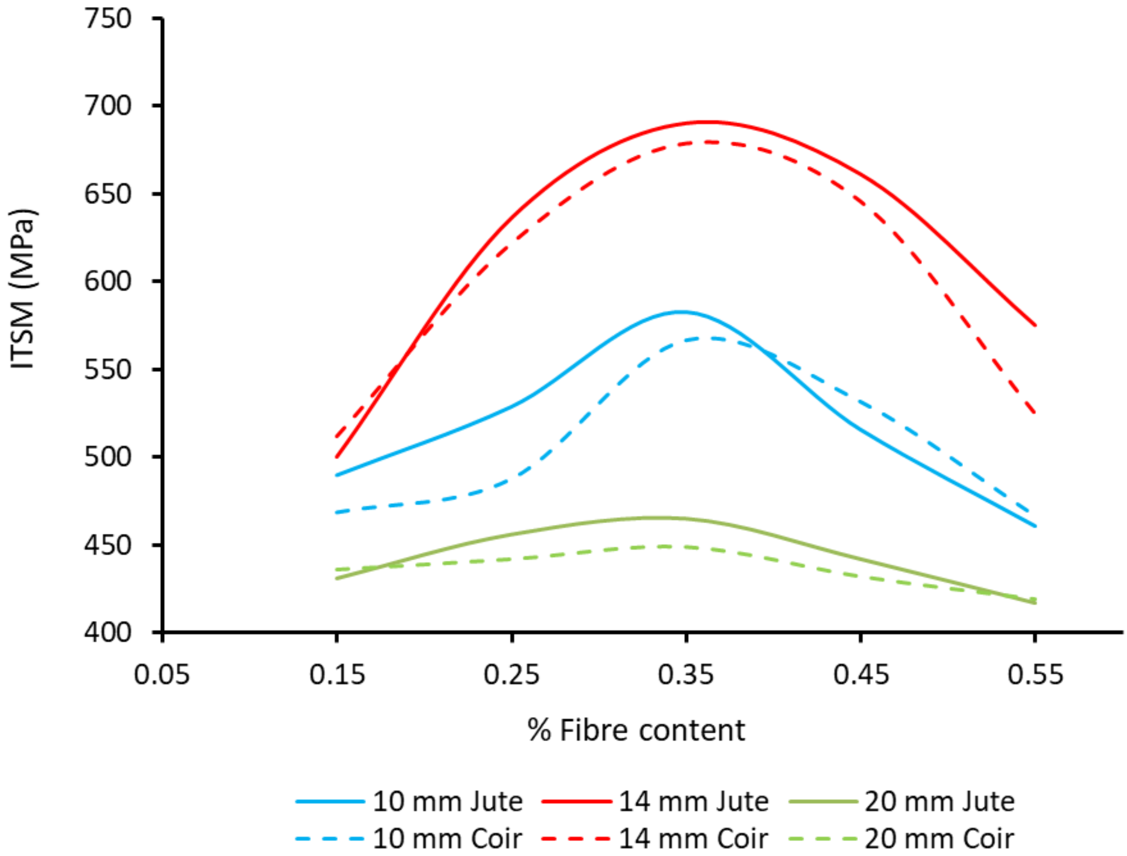


Figure 4. Fibre optimisation at 20 °C after 2 days

5. Finite element model development

Different techniques are available to predict flexible pavement deformation such as multilayer elastic theory, boundary element methods, analytical methods, hybrid methods, finite difference methods and finite element methods (FEM) [14]. FEM has been used successfully for flexible pavement performance analysis and has been found suitable for application to the complex behaviour of composite pavement materials. Furthermore, using three-dimensional (3D) finite element models can solve the problems that cannot be solved by two-dimensional (2D) models under repeated loading. Therefore, in this study, a 3D finite element model has been adopted for analysis to simulate the natural fibre reinforced CMA mixtures. This model includes consideration of viscoelastic pavement properties and moving load applications to accurately characterize the time, rate and temperature dependent responses of the bituminous layer.

The commercial finite element software ABAQUS was used to build this model to evaluate the changes in pavement response properties. This program has been widely used in other research to model hot mix asphalt pavements systems because this type of model can include consideration of the behaviour of viscoelastic materials under repeated loadings: to date this same model has not been applied to CMAs.

5.1 Model geometry, boundary conditions and meshing.

Depending on the nature of the finite element analysis, it is essential to find suitable dimension, mesh and boundary conditions for the model to be analysed. Therefore, to optimize computation times and provide results comparable to the experimental data, the number of trials, mesh size and density, number of elements and suitable dimensions were determined.

The geometry of the FEM is based on a section (a slab) of a wheel tracking test. The surface of the pavement is assumed to be symmetrical (x and y-axes), therefore, a quarter of the model is used to reduce the cost of the analysis [24, 25, 41]. The model geometry consists of a bituminous layer with a depth of 5 cm, length and width of 20 and 15.25 cm, respectively, positioned over a fixed steel plate. The model boundary conditions were selected to exert a significant influence on the predicted response of the pavement. These boundaries are applied to the all the edges, or faces, of the structural pavement geometric model to control displacement in a horizontal direction on the vertical edge, perpendicular to the layer surface. Thus, the bottom of the layer moves in all directions, while the horizontal and vertical deflections can be predicted in all other planes.

An 8-node brick element was used for the generation of the mesh. In order to determine a suitable size of element to ensure the desired degree of accuracy for the developed model, different mesh densities were applied. It can be seen from Figure 5 that the densest mesh was used in the areas under, and near to, the load applications, whilst relatively coarser meshes were employed further away from the loading area, in both directions. A mesh sensitivity analysis was conducted to determine the optimum element size for the fine mesh. According to this analysis, the smallest element length is 1.5 mm. The finite element mesh contains 58548 C3D8R (Continuum 3-Dimensional 8 node elements with reduced integration) brick elements and 64890 nodes.

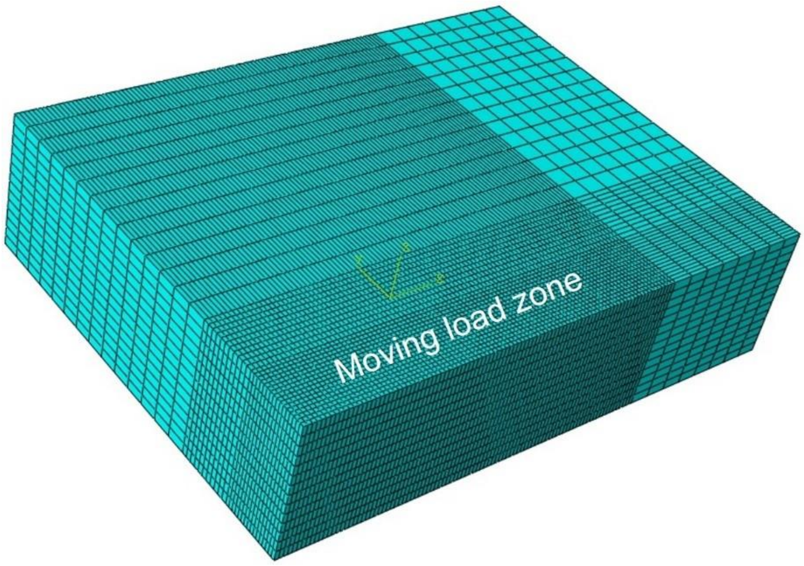


Figure 5. 3-D finite element mesh for pavement simulation

5.2 Loading configuration

The wheel tracking test results were used to validate the model while wheel loading was used to investigate pavement response. The viscoelastic effect of the bituminous layer is an essential facet regarding the analysis of flexible pavements in terms of CMA. For that reason, in the FEM, it is important to consider time and loading rate dependency in addition to temperature. In order to properly characterize these factors, cyclic and static loadings were applied to the surface of the finite elements, seen as a small rectangle which represents a tyre footprint. [42]. This load transfers to the pavement surface through contact pressure between the tyre and pavement surface. The contact pressure is equal to the tyre pressure on the road surface [43]. A total of 700 kPa pressure loads were applied and distributed uniformly over the contact area, to simulate the load of a wheel tracking test with a speed of 0.6 km/h, as shown in Figure 6. This pressure is applied repeatedly to the pavement surface over many cycles. During each cycle (1.44 s), the load is applied for 0.18 s to simulate a vehicle speed of about 0.6 km/h. The load is then removed for 1.26 s as schematically shown in Figure 7. A relatively high temperature (60°C) was used to examine the effect of high temperature on the flexible pavements.

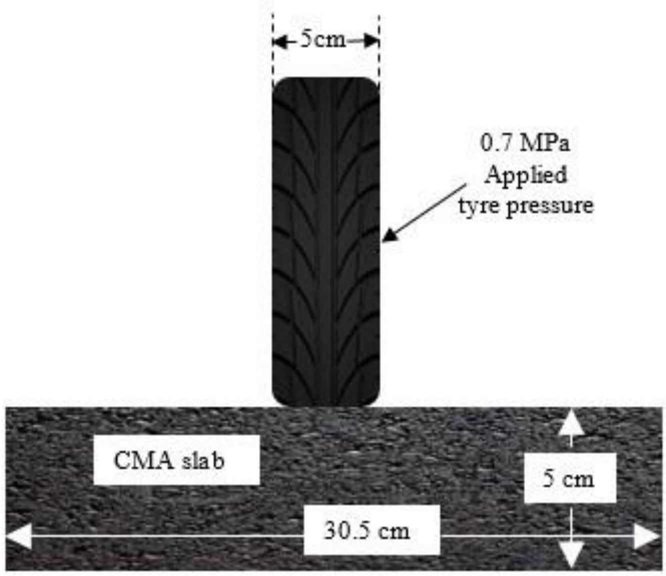


Figure 6. Dimensional cross-section of slab modelling

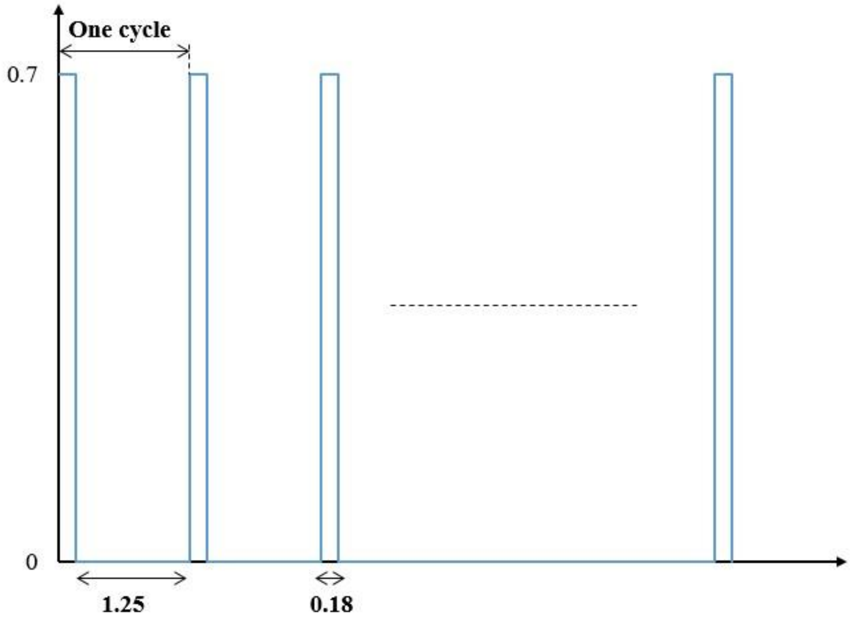


Figure 7. Schematic of the applied repeated loading

5.3 Material characterization

The ABAQUS software used in this research has the capacity to analyse complex time and rate dependent, viscoelastic problems. For the viscoelastic analysis of bituminous materials, shear *G(t)* and/or bulk *K(t)* moduli are required in most finite element modelling as viscoelastic material property inputs. These properties can be calculated (using equation 4) from the creep test at certain temperature using the Prony series. This is a mechanical representation of the viscoelastic material behaviour of flexible pavements [44]. Flexible pavement material is homogeneous and isotropic and the Poisson's ratio does not change with time [45]. Poisson's ratio has therefore been considered a constant (0.35). This the most suitable assumption for bituminous mixtures as it provides reasonable and accurate time and rate dependent responses of viscoelastic materials [46]. Elastic modulus of different CMA mixtures at different temperatures were measured using ITSM test. The Prony series parameters and moduli of elasticity were successfully calculated based on the experimental results, as given in Table 3, after 14 days of curing time.

Table 3. Elastic and viscoelastic properties of different CMA mixtures at different temperatures

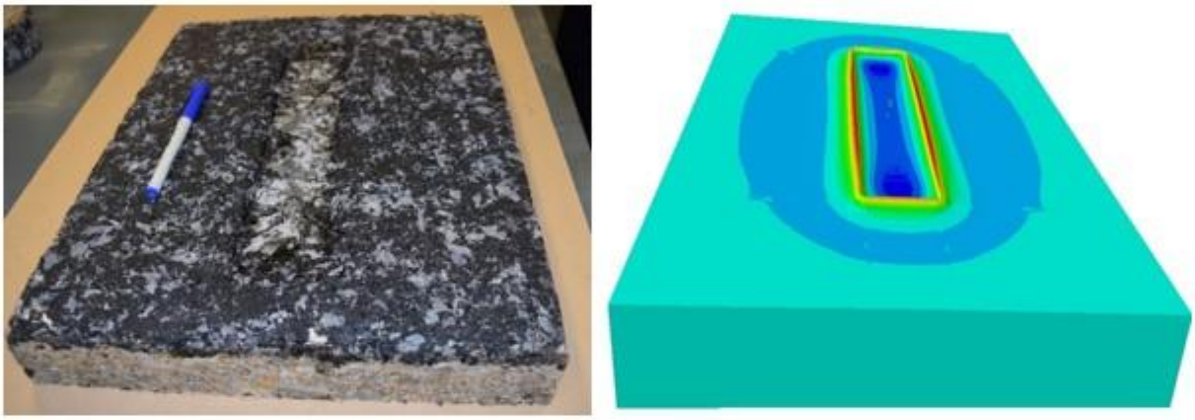
		Viscoelastic material coefficients					
		Temperatures (°C)					
		60			45		
		D_i (1/kPa)			D_i (1/kPa)		
i	τ_i (s)	CON	JUT	COI	CON	JUT	COI
1	0.1	6.91×10^{-6}	4.86×10^{-6}	4.65×10^{-6}	1.14×10^{-5}	2.75×10^{-6}	2.69×10^{-5}
2	1	6.12×10^{-5}	3.36×10^{-5}	4.41×10^{-5}	1.90×10^{-5}	2.14×10^{-5}	4.05×10^{-5}
3	10	1.54×10^{-4}	8.52×10^{-5}	1.04×10^{-4}	4.08×10^{-5}	6.71×10^{-5}	8.03×10^{-5}
4	100	2.09×10^{-4}	1.39×10^{-4}	1.27×10^{-4}	7.43×10^{-5}	8.67×10^{-5}	1.31×10^{-4}
5	1000	2.62×10^{-4}	1.74×10^{-4}	1.42×10^{-4}	1.08×10^{-4}	1.15×10^{-4}	1.72×10^{-4}
Modulus of elasticity E (MPa)		35	311	255	100	417	324

		Viscoelastic material coefficients					
		Temperatures (°C)					
		20			5		
		D_i (1/kPa)			D_i (1/kPa)		
i	τ_i (s)	CON	JUT	COI	CON	JUT	COI
1	0.1	3.66×10^{-6}	1.10×10^{-6}	6.30×10^{-6}	8.81×10^{-6}	7.68×10^{-6}	9.11×10^{-6}
2	1	5.18×10^{-6}	1.52×10^{-6}	1.69×10^{-5}	7.24×10^{-5}	4.34×10^{-5}	5.53×10^{-5}
3	10	3.90×10^{-5}	3.05×10^{-5}	3.69×10^{-5}	9.63×10^{-5}	6.02×10^{-5}	8.78×10^{-5}
4	100	5.67×10^{-5}	5.08×10^{-5}	5.16×10^{-5}	5.16×10^{-4}	9.79×10^{-5}	4.33×10^{-4}
5	1000	7.40×10^{-5}	5.21×10^{-5}	6.28×10^{-5}	8.25×10^{-4}	2.95×10^{-4}	8.19×10^{-4}
Modulus of elasticity E (MPa)		464	1021	890	581	1876	1634

6. Results and Discussion

6.1 Model validation

The responses of the CMA, predicted by the viscoelastic model developed for two different natural fibres, were validated against those from the wheel tracking tests. The wheel tracking tests were conducted for CMA mixtures, with and without fibres, to calculate rutting at the surface of the bituminous layer. Transverse surface permanent deformation was calculated after 3472 load applications. A similar set of experiments were conducted using the finite element model to compare the actual measurements of rutting (permanent deformation) with the rutting values obtained from the model. The magnitude of permanent deformation at the surface of the CMA layer, is the most significant factor characterizing the rutting performance of flexible pavements. Rutting transfer functions are the functions of shear and tensile strain at the surface of the bituminous layer, under applied wheel loads. It is therefore imperative to accurately predict deformation response characteristics at the surface of the CMA layer for more appropriate evaluation of pavement rutting. The CMA mixtures were conducted at 45°C and 60°C during the wheel tracking tests. Based on the comparison of time-deformation, peak deformation and transverse surface deformation, it can be seen that the FEM-simulated-CMA response is close to the lab response, as shown in Figure 8. Therefore, it can be claimed that the model is validated and ready for further parametric study.

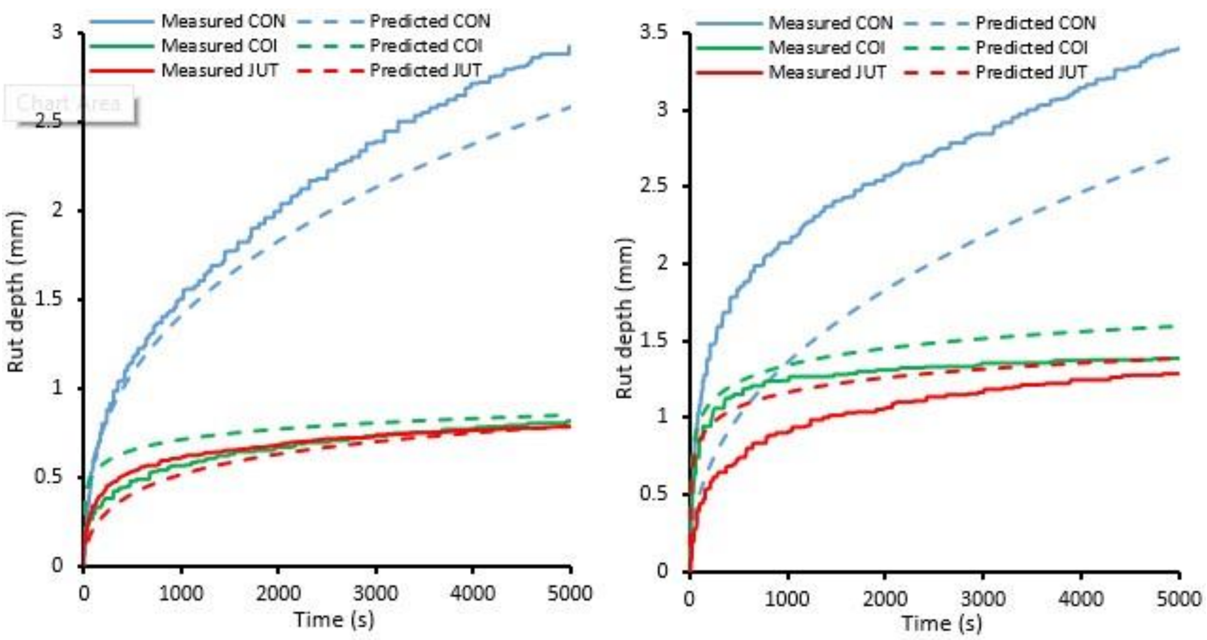


a b

Figure 8. Deformed shape of conventional CMA at 45°C (a) measured, and (b) predicted

6.2 Rutting in cold mix asphalt mixtures

Figure 9 shows the rutting measured on the surface of the CMA layer, under the centre of the moving wheel path, and those predicted by the viscoelastic model for both reinforced (by jute and coir fibres) and conventional (no treatment) mixtures, at two different temperatures (45°C and 60°C). The predicted rutting matches well with the measured ruts, even though some variations were observed (between the predicted and measured rutting) between mixture types and temperature. This small vibration between the predicted and measured rutting is because of the model assumes that the material properties are uniform and homogenous, whilst in reality the mixtures include some voids and different aggregate interlocks. Also, in reality, the temperature and viscosity of the mixtures can not be distributed equally for the whole mixture and this can not be modelled because of the difficulty of setting different temperatures and viscosities for each particles of the mixture. However, these discrepancies do not affect the validation of the FE model. It is interesting to note the distinctive difference in the rutting due to the different fibres used. The measured and predicted permanent deformation of the bituminous layer that occurs along the moving area under the wheel path, is calculated as the average deformation along, and under, the wheel path. The results clearly show that the CMA with jute and coir fibres induces reduced rutting on the bituminous surface layer, this positively affecting the rutting resistance of flexible pavements.



a b

Figure 9. Predicted vs. measured rutting at the top of the pavements (a) at 45°C and (b) 60°C

The permanent deformation of the different CMA mixes, after 3472 cycles (about 5000 s), are illustrated in Figure 10. The results of the equivalent static loading condition (5000 s loading) on the same model, are also presented in Figure 11. Both different loading conditions were performed following the same order of permanent deformation resistance; the CMA mixtures reinforced with jute, have the smallest rut depth followed by the coir fibre mix. The conventional CMA mixtures have the maximum rut depth. The permanent deformation found in the static loading condition is greater than that of the cyclic loading condition for all mixture types because there is no rest interval to let mixtures recover (viscoelastic properties) in the static loading condition.

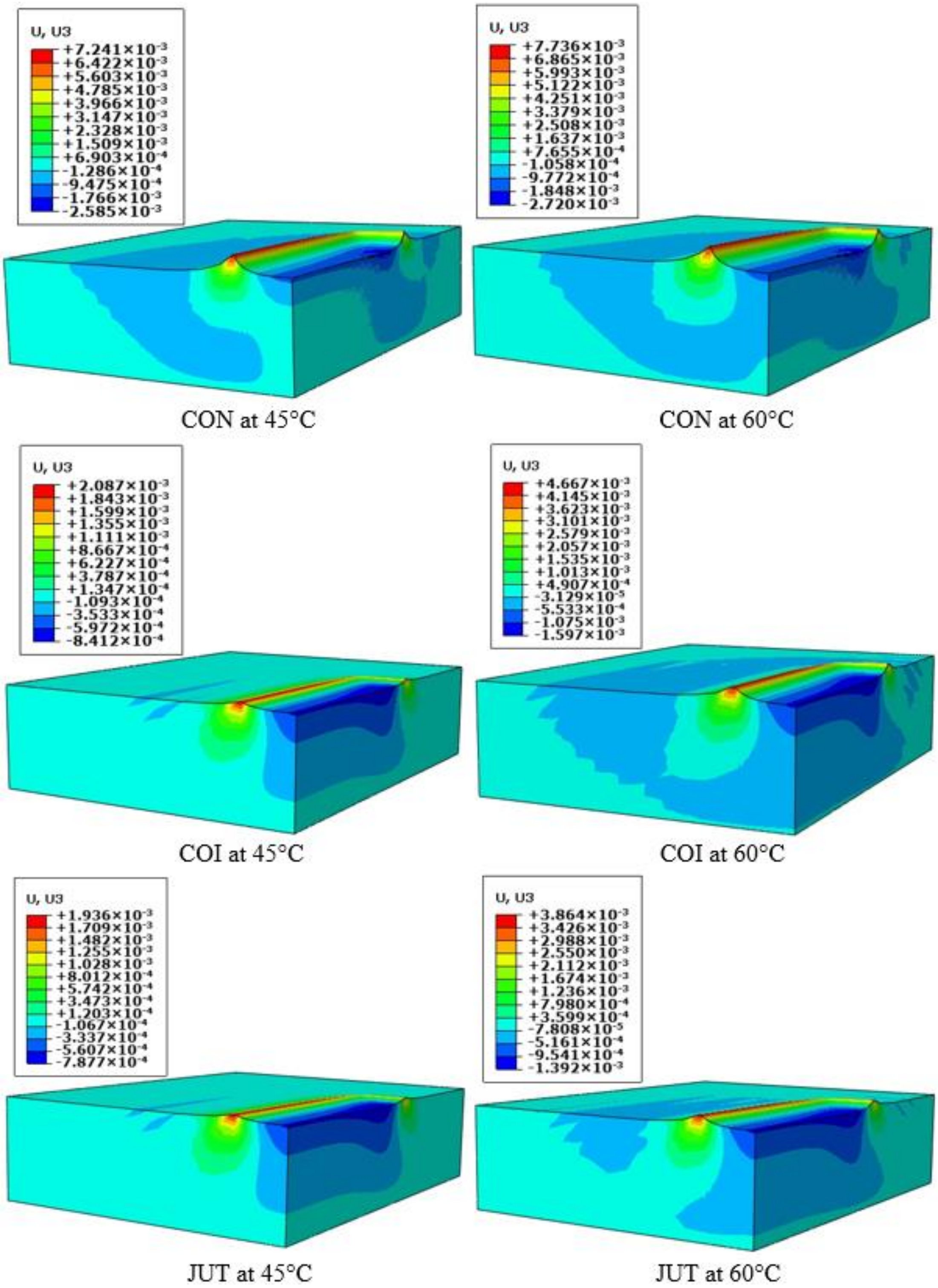


Figure 10. Permanent deformation for cyclic loading at 45°C and 60°C

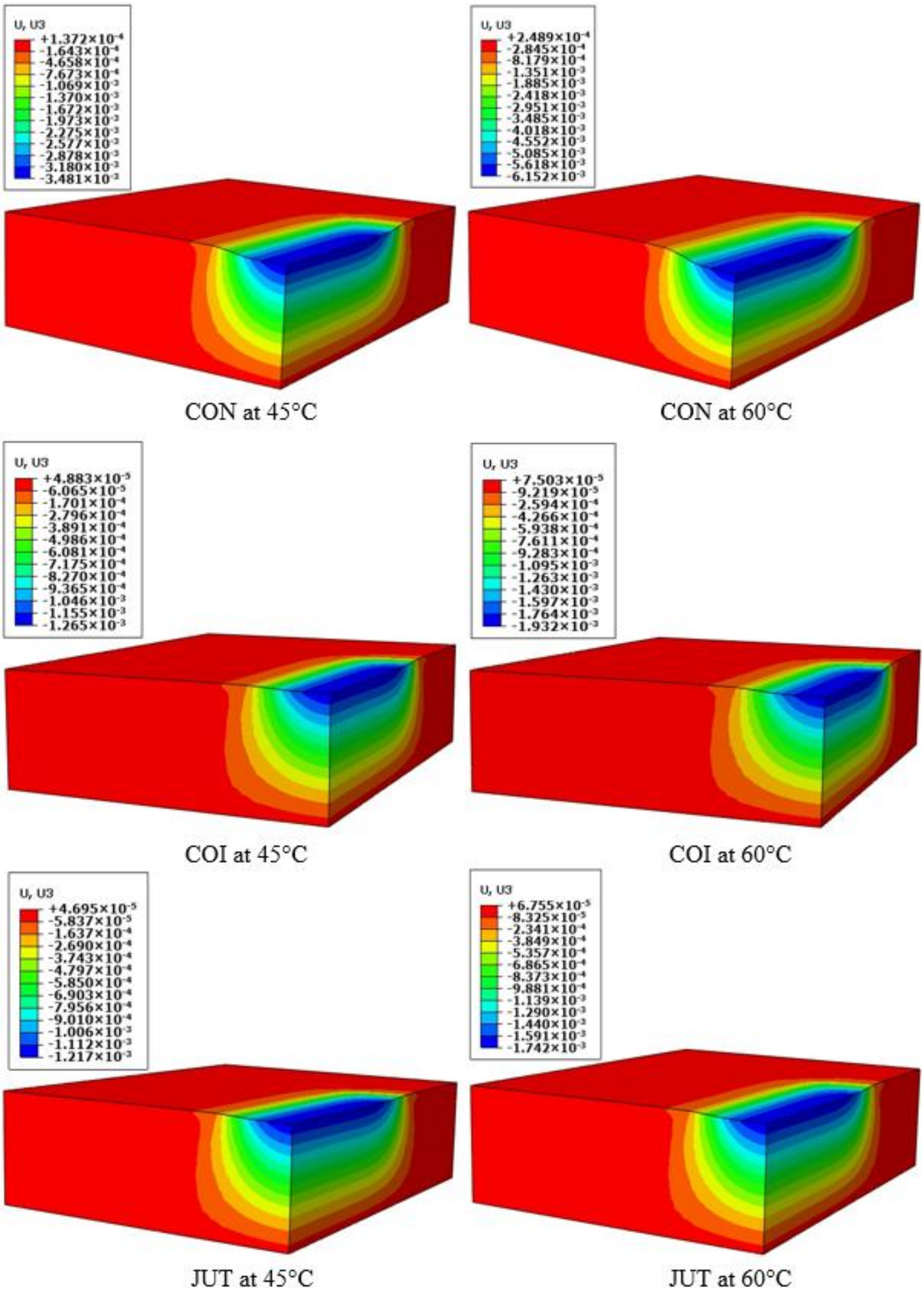


Figure 11. Permanent deformation for static loading at 45°C and 60°C

Because the elastic modulus of conventional CMA is less than the modulus of the reinforced CMA mixtures, its rut depth is greater. The elastic modulus and viscoelastic properties of different CMA mixtures (as shown in Table 3) have a significant effect on rut depth.

6.3 Sensitivity analysis

After the rutting analysis and validation of the model, a sensitivity analysis was performed to investigate the effect of different factors on flexible pavements response, dependent on mixture type.

6.3.1 Temperature attributes

The permanent deformation of flexible pavements is closely related to pavement temperature as variation in temperature effects stiffness modulus and shear stress. Rutting resistance increases when the pavement temperature is low (around 0°C) because of the high stiffness of asphalt pavements [47]. The variation in pavement rutting for different temperatures (20°C and 5°C) is shown in Figure 12. As expected from the model, the CMA mixtures at low temperatures, show lower permanent deformation than at high temperatures. Given there is a significant effect of temperature on rutting, design procedures and analysis should include actual pavement temperatures.

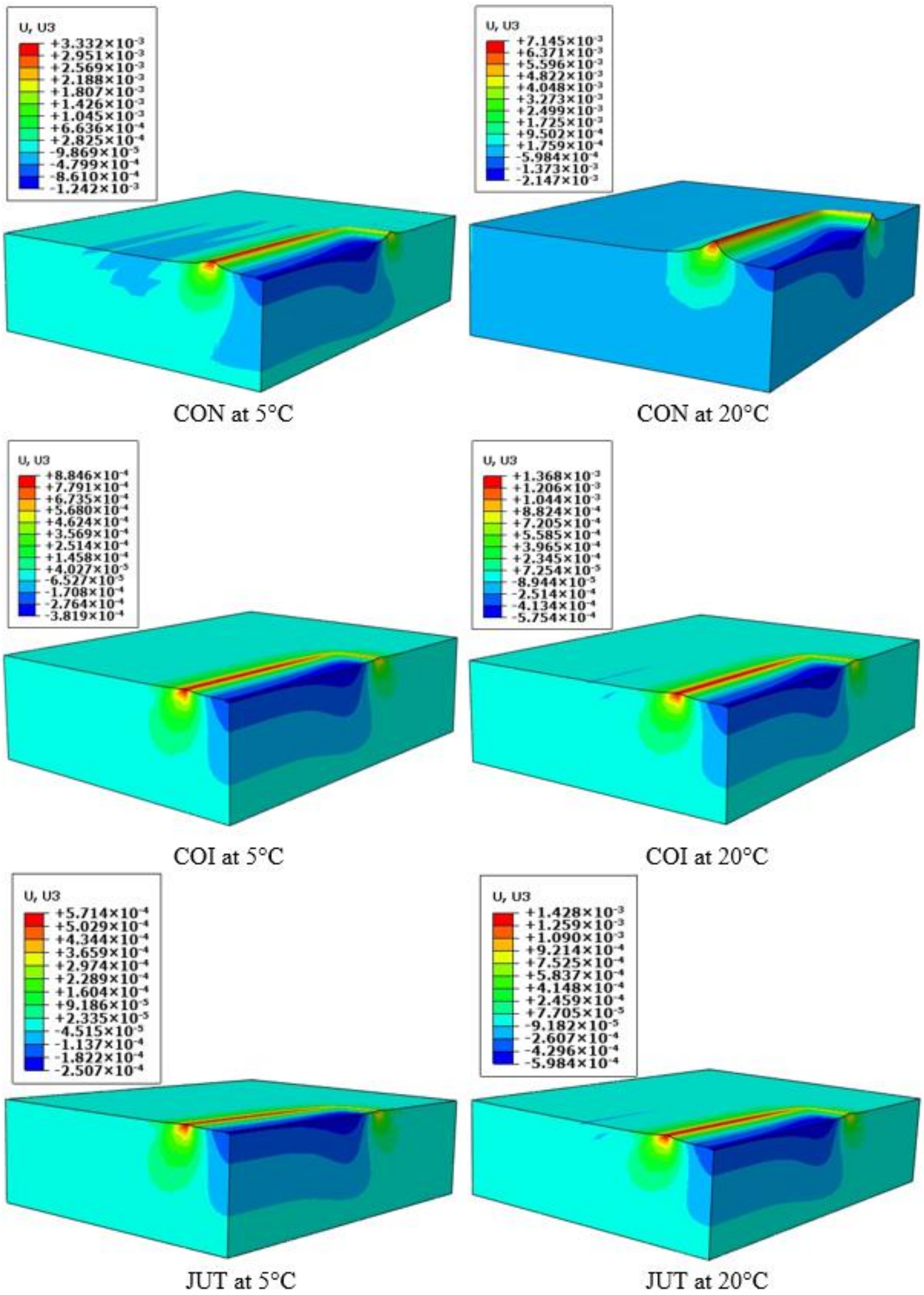


Figure 12. Permanent deformation for cyclic loading at 5°C and 20°C

6.3.2 Load and vehicle speed attributes

Zhi, et al. [48] stated that static loads are more damaging to asphalt pavements than moving loads. A comparison was carried out, using this model, on the effect of different traffic speeds

(5, 30 and 60 Km/h) on reinforced and unreinforced CMA. Cumulative pavement rutting on the top of the asphalt layer at 30 km/h, is significantly less than that at 5 km/h. The rutting variation between 30 km/h and 60 km/h is relatively small, as shown in Table 4. The loading time for each cycle (1.44 s), is dependent on vehicle speed. It is 0.0216 s at 5 km/h, 0.0036 s at 30 km/h and 0.0018 s at 60 km/h.

Table 4. Maximum rut depth for different vehicle speeds after 5000 s.

Temperature (°C)	Vehicle speed (km/h)	Max. rut depth (mm)		
		CON	COI	JUT
60	5	2.75	1.31	1.25
	30	1.22	0.79	0.68
	60	0.98	0.60	0.55
45	5	2.20	0.72	0.63
	30	0.87	0.44	0.38
	60	0.66	0.38	0.32
20	5	1.63	0.48	0.41
	30	0.57	0.31	0.21
	60	0.51	0.28	0.18
5	5	0.74	0.26	0.20
	30	0.29	0.12	0.09
	60	0.26	0.10	0.07

7. Conclusion

This research presents a viscoelastic model for asphalt pavements, using a cold mix asphalt subjected to static and multiple-axle loads. This model was developed using the Prony series parameter properties of CMA mixtures to simulate a laboratory wheel-tracking test. In order to compare numerical predictions to laboratory measured rut depth values, reinforced and unreinforced CMA mixtures were also tested in the laboratory. A good level of agreement was obtained between the predicted rutting and experimental results, measured on the surface of the bituminous pavements. The validated model was used to evaluate the permanent deformation of different CMA mixtures, subjected to different tyre speeds and temperatures.

Based on laboratory tests and FEM analyses, some important observations and conclusions can be made:

- The generalized model can be used effectively to analyse the rutting characteristics in CMA mixtures. The viscoelastic parameters of the generalized model fit with the procedure described in this research.
- According to the results, the developed model can accurately predict the rutting behaviour of reinforced and unreinforced CMA mixtures, under different stresses and temperatures.
- Tyre speed, temperature, loading and bituminous material properties have an effect on the depth of rutting of CMA mixtures.
- FEM analysis indicates that at high temperatures and static loading conditions, maximum rutting depth occurs.
- The results show that jute and coir fibres have positive effects on the mechanical behaviour of CMA mixtures.

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