Creative Construction Conference 2016

Rutting Prediction of a Reinforced Cold Bituminous Emulsion Mixture Using Finite Element Modelling

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Abstract

A three-dimensional (3D) finite element (FE) model of a reinforced cold bituminous emulsion mixture (CBEM) was built in order to investigate the effect of static wheel load on rutting formation and flexible pavement response. This model has been developed to represent a four-layer pavement structure with elastic responses and to simulate the mechanical behaviour and pavement performance under static load condition. Also, it is focused on the prediction of the contribution of glass fibre (as a reinforcement material) in the surface course to develop the tensile and shear strength of flexible pavement. Preparation and validation of the model were carried out in the pavement laboratory using experimental data. In this research, finite element analyses have been conducted using ABAQUS software in which model dimensions, element types and meshing strategies are taken to achieve a desired degree of accuracy and convergence of the developed model. In addition, this developed model has been applied to CBEMs to investigate the effects of glass fibre on the performance of a reinforced pavement surface layer, as well as to study the effects of this fibre to minimize the vertical surface deflection, and horizontal and vertical displacements for the various courses. Finally, the FE model is capable of predicting surface damage to flexible pavement and its partial recovery after application of load. The results demonstrate the capability of the model in simulating the effect of fibre on vertical surface deflection (rutting), horizontal and vertical displacements in CBEM.

Keywords: ABAQUS, cold bitumen emulsion mixtures, rutting, three-dimensional finite element

1. Introduction

Permanent deformation (rutting) is one of the main important and significant damages encountered in flexible pavement, Permanent deformation (rutting) is one of the main important and significant damages encountered in flexible pavement, especially in the countries that have high temperature during the summer seasons. In all flexible pavement layers, the accumulation of permanent deformation under the effect of traffic loading causes rutting. Rut depth and width are mainly affected by structural properties of the pavement layers such as layers thickness, material quality, traffic loads and temperature [1]. The ability of rutting or permanent deformation prediction in flexible pavement is an essential part of pavement design. Therefore, some simplification hypotheses are often performed for analysis and design such as the elastic behaviour of pavement material and isotropic nature. The basic hypotheses of multi-layer pavement system include [2]:

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- Flexible pavement layers are homogeneous and isotropic.
- Materials behaviour is elastic and linear.
- Materials are massless.
- Layer thickness is limited.
- Load is uniformly distributed over a rectangular contact area.

Boundary conditions were considered that the contact between two layers is identical for both layers in term of shear tension, vertical tension, vertical and radial displacements.

Some diagrams and tables have determined stress, strain and displacement in multi-layer system after proposing these equations [3]. Finite element analysis is a numerical method to solve these equations.

The research objective is to develop a finite element model for an existing flexible pavement. This model would be capable of predicting the stress and strain responses of the elastic pavement and the output of the model is the prediction of permanent deformation (rutting).

2. Classical rutting prediction approach

Classic attempts to model rutting analysis are concentrated on protecting the under layers. At the top of the subgrade layer, the vertical stress and strain are limited to control the permanent deformation of the whole pavement structure and also restricted the tensile stress and strain at the bottom of the lowest bituminous layer to control fatigue cracks [4]. A classic model of rutting prediction utilized in road pavement analysis is given in [4] :

$$N_f = 1.077 \times 10^{18} \, (10^{-6} \div \varepsilon_v)^{4.4843} \tag{1}$$

Where:
Nf : applied load (kN).
εv : vertical compressive strain at the top of subgrade layer.

Nowadays, comprehensive researches have been carried out using different laboratory test methods such as wheel tracking test, creep test, complex (dynamic) modulus test and triaxial test, combined with contributions from investigations of pavement field rutting [4]. It was noticed that rutting failure was not solely occurring in subgrade layer or other under layers but also can be as a result of bituminous mixture problems. Consequently, it has become obvious that in accurate road pavement design procedure, the cumulative permanent deformation in all pavement layers must be considered.

Three model types have been used to compute permanent deformation in flexible pavement: empirical, mechanistic empirical and fully mechanistic. The empirical model is the simplest mathematical form fitted to controlled field data depending on regression equations. Properties of materials and site conditions are not included in this type of modelling whilst specific applications, for instance performance predictions in system of road pavement management are commonly used. The main purpose of this model is to evaluate future performance based only on the recorded deformation history.

The mechanistic empirical model is designed based on a combination of predictions of simple mechanistic response (usually using theory of elasticity) with empirical equations which are calibrated by experimental tests. The computed mechanistic response is utilized as input in the empirical model to predict actual performance, such as rutting and cracking. The effect of traffic loading and environmental conditions can be involved. Throughout application, the model mechanistic response is obtained during a pavement structural analysis. The linear elastic theory is usually used for its formulation and fast computer analysis.

Fully mechanistic models to compute or predict permanent deformation also use a structural analysis program to show the effect of the stresses and strains in the road pavement structure due to the influence of loading time (frequency) and temperature. The different characteristics of material behaviour are represented using constitutive models to directly predict rutting, cracking and other types of damage. With the most important points of these models, the effect of various load conditions, for example loading time, value and temperature can be simply evaluated and incorporated into these models. Because of capabilities of mechanistic models to predict road pavement distresses, there is no need for empirical functions. However, constitutive mechanistic models are complex and have some difficulties in calibration and execution. Very limited researches have been carried out to fulfil mechanistic models to predict behaviour of asphalt mixtures.

3. Materials and methods

3.1. *Materials*

The materials used in this research work are briefly introduced as follows:

3.1.1. Aggregate

A crushed granite aggregate both coarse and fine aggregate was used in this research which is normally used to produce Asphalt Concrete hot mix. The main properties of the aggregate together with the traditional mineral filler (limestone) used are presented in Table 1. The aggregate grading was asphalt concrete close graded surface course which is a prominent type of asphalt surface layer material, as shown in Figure 1 of mixtures (cold and hot) which are in accordance with BS EN 13108-1[5].

Table 1. Physical properties of the aggregate.

Properties	Value
Coarse aggregate:	
Bulk specific gravity (g/cm3)	2.78
Apparent specific gravity (g/cm3)	2.83
Water absorption (%)	0.6
Fine aggregate:	
Bulk specific gravity (g/cm3)	2.68
Apparent specific gravity (g/cm3)	2.71
Water absorption (%)	1.5

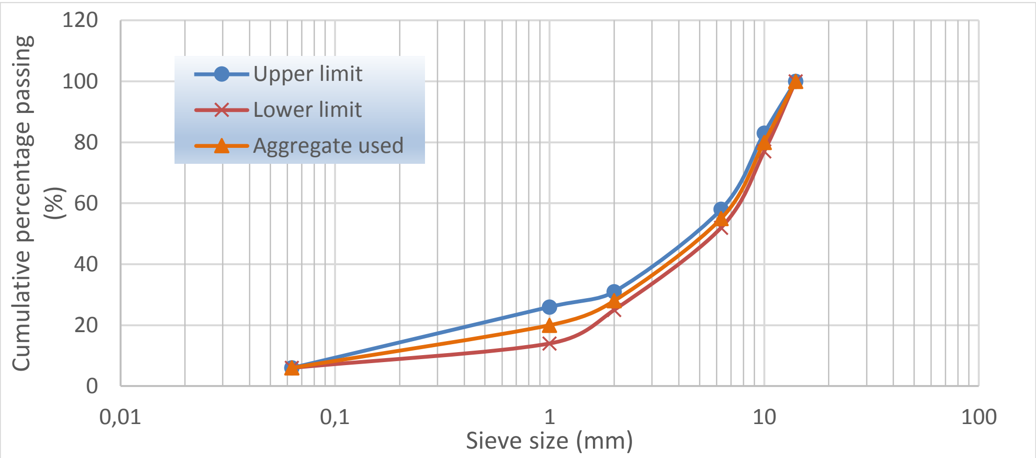

Figure 1. 14mm close graded surface course.

3.1.2. Bitumen emulsion and bitumen

A slow-setting cationic emulsion (cold asphalt binder (CAB50)) that contains 50% residual bitumen of 50/70 pen grade based bitumen was used throughout this study for the cold mixtures as its properties are shown in Table 2. This bitumen emulsion was chosen to obtain high adhesion between aggregate particles.

Table 2. Properties of (CAB50) bitumen emulsion.

Description	(CAB) bitumen emulsion
Type	Cationic
Appearance	Black to dark brown liquid
Base bitumen	50/70 pen
Bitumen content	50 %
Boiling point, ºC	100 ºC
Relative density at 15 ºC, g/ml	1.05

3.1.3. Filler and fibre

One filler type was used in this study, traditional mineral filler. Glass fibre was used in this study and it presents interesting properties as a reinforcing material. It is both strong and flexible. It is thermally and chemically stable at bituminous mixture temperatures of 200°C. It is not affected by de-icing salt, petroleum or bitumen. Glass fibre has a Young's modulus almost 20 times higher than typical bituminous modulus at around 20°C [6] and has a high tensile strength.

3.2. *Sample preparation and conditioning*

The design procedure followed the method adopted by the Asphalt Institute, (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design (MS-14), 1989) for designing the cold asphalt mixtures. Incorporation of the fibre was achieved through partial substitution of the conventional aggregate. Glass fibre as a reinforcement material was the material that was added to the mixture. In order to find the optimum content and length of the glass fibre, cold bituminous emulsion mixtures (CBEMs) were treated according to fibre weight with 0.25, 0.35 and 0.50% of 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. Cold mixtures are evolutional in nature, where the mixtures' strength characteristics are very sensitive to curing time and temperature.

3.3. *Method*

The fundamental test that was used is the Indirect Tensile Stiffness Modulus (ITSM): The test was conducted in accordance with BS EN 12697-26 [7], using Cooper Research Technology HYD 25 testing apparatus. The test conditions are as in Table 3.

Table 3. ITSM Test Conditions.

item	range
Specimen diameter mm	100 ± 3
Rise time	124 ± 4 ms
Transient peak horizontal deformation	5 µm
Loading time	3-300 s
Poisson's ratio	0.35
No. of conditioning plus	5
No. of test plus	5
Test temperature °C	20 ± 0.5
Specimen thickness mm	63± 3
compaction	Marshall 50×2
Specimen temp. conditioning	4hr before testing

4. Finite element modeling

After designing the conventional and reinforced CBEMs, stiffness modulus tests were carried out at two and seven days curing time as shown in Table 4.

Table 4. ITSM of the conventional mix.

Curing time (days)	ITSM (MPa)	
	Conventional	Reinforced
2	278	723
7	366	1060

4.1. *Model geometry*

The flexible pavement geometric model is created by using discrete parts which each part represent one structural pavement layer in the ABAQUS solid modeler. The geometric model is constructed in three dimensions (3D) finite element with a single axle which is assumed symmetrical on the surface of pavement in traffic direction. Model dimensions are used to avoid any edge effect errors, while having acceptable limits of elements' size.

Pavement cross-section is shown in Figure 2, four types of layers: cold bituminous emulsion mixture as a surface course, granular base, granular subbase and subgrade are performed to simulate the road pavement structure. All layers have the same shape to keep the nodes continuity between successive layers.

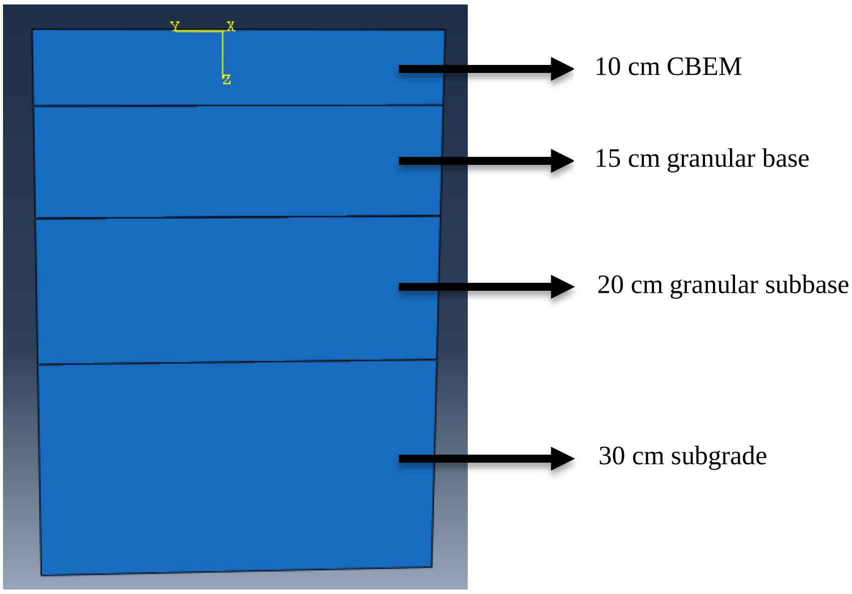

Figure 2 Pavement cross-section.

4.2. *Boundary condition*

Boundary conditions are employed to all edges or faces of the structural pavement geometric model to control displacement in the horizontal direction on the vertical edge which is perpendicular to the layer surface. The last layer (subgrade) modelling is assumed to be fixed with no displacement in horizontal and vertical directions representing a very stiff layer (encastre). The geometric model is symmetrical on x and y axes, therefore, quarter of the model is taken and the load is applied as shown in Figure 3.

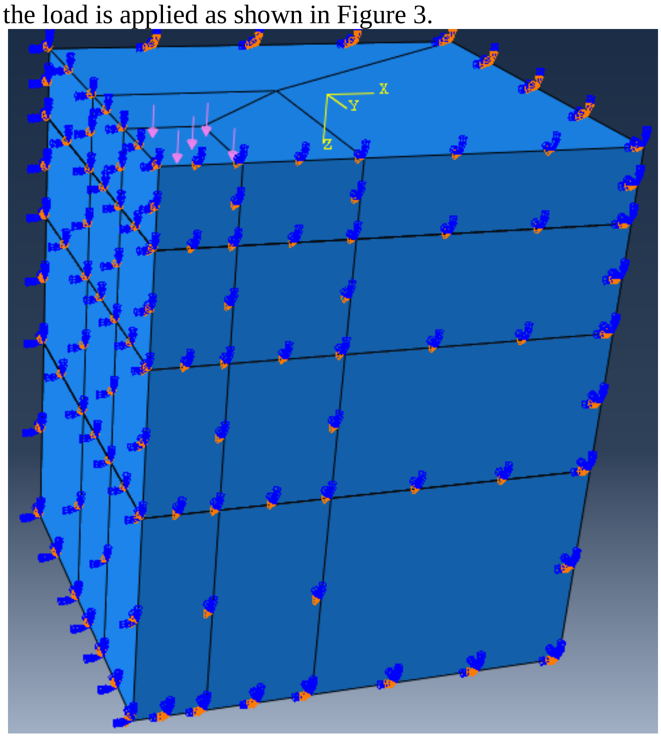

Figure 3. Boundary condition and load.

4.3. *Meshing and element definition*

The meshing process divides the body into many finite elements jointed at shared nodes. The accuracy of results depends on the density of the elements in a known area of the body. For instance, high density is preferred around the loading area and underneath the wheel path in the case of simulating a flexible pavement subjected to a tyre load, to improve the level of accuracy. However, computational time will be longer if more elements are there. It is significant to restrict the number of finite elements. In order to obtain asuitable mesh size, several iterations of finite element analyses are ideally performed with decreasing the element number for meshing a pavement structure. It will provide an adequately precise solution at a sufficient computational effort.

Through the mashing process, the element type and nodes number should be defined. Simple 8-node brick elements in three dimensional finite element model, which is selected to use in the analysis, or 4-node quadrilateral elements in two dimensions are allowing linear approximations of the movements between the corner nodes. Some elements have more nodes at the midpoint of each edge which will accommodate higher order approximating polynomials and the computational effort will increase significantly. Therefore, the most common way is utilizing simple finite elements and increase the density in areas of high preferred accuracy.

Figure 4 shows the plan view of the pavement surface. The tyre imprint area is modelled as a 29 x 20 mm rectangular area. The vertical and horizontal lines define the different meshing areas. The static load area is shown in the centre at which the most refined mesh is defined. All pavement layers are simulated with the same shape configuration. After completing zone configuration, a mesh study is carried out to find the optimal mesh density for each zone. Figure 5 shows the final mesh for the top surface layer. A denser mesh is employed in zones near to the load, whilst a relatively coarser mesh is used further away from the loading zones in both directions.

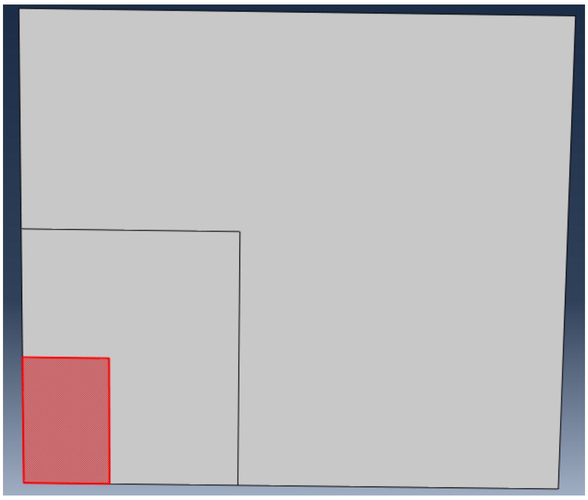

Figure 4. Pavement surface plan.

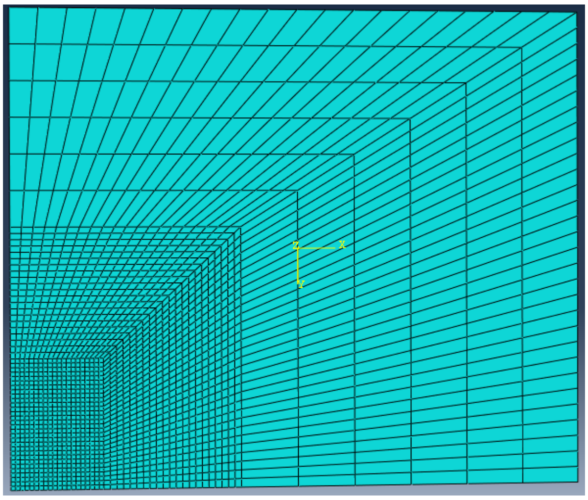

Figure 5. The final mesh of the top surface layer.

Each pavement structure layer is modelled individually as one part in the ABAQUS solid modeller. The same meshing processing by zones is used to the surface and under layers of pavement structure cross section shown in Figure 6. In order to determine a suitable element size to ensure a desired degree of accuracy and convergence for the developed model, several meshing iterations were used to reach the best and most accurate mesh size as shown in Figures 7 and 8.

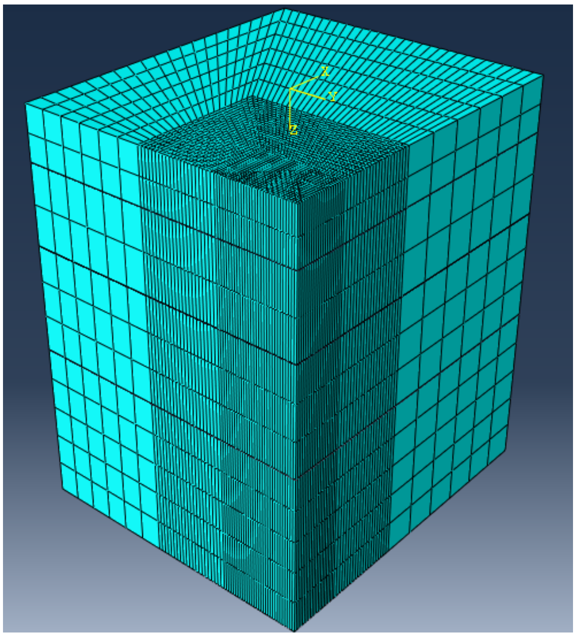

Figure 6. The final mesh of the pavement layers.

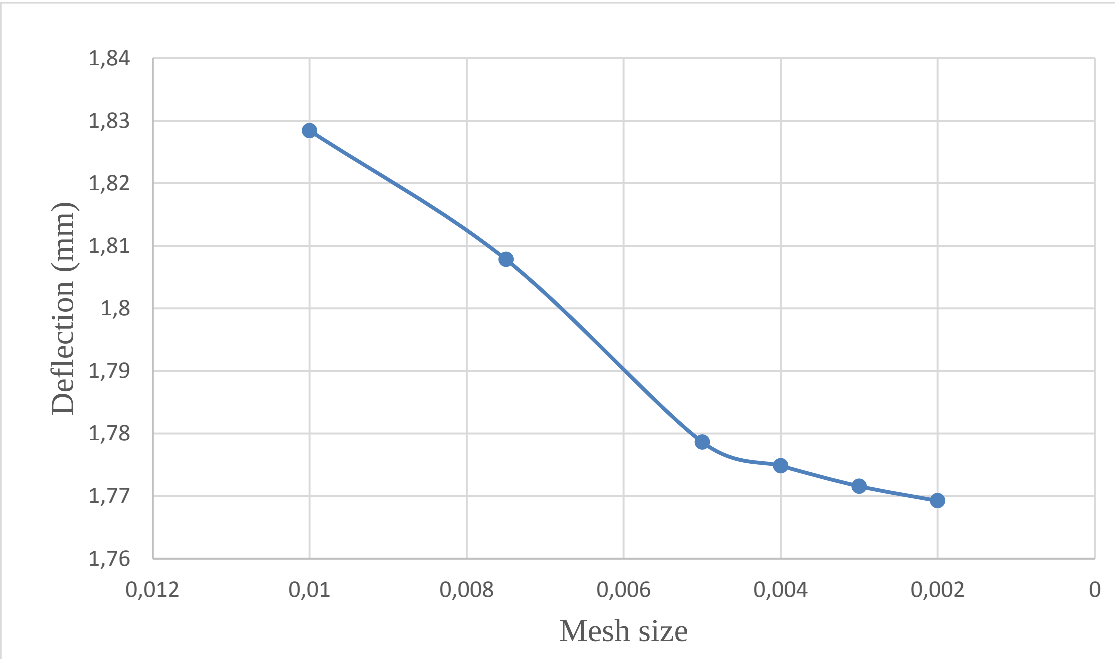

Figure 7. Mesh convergence of the finest area.

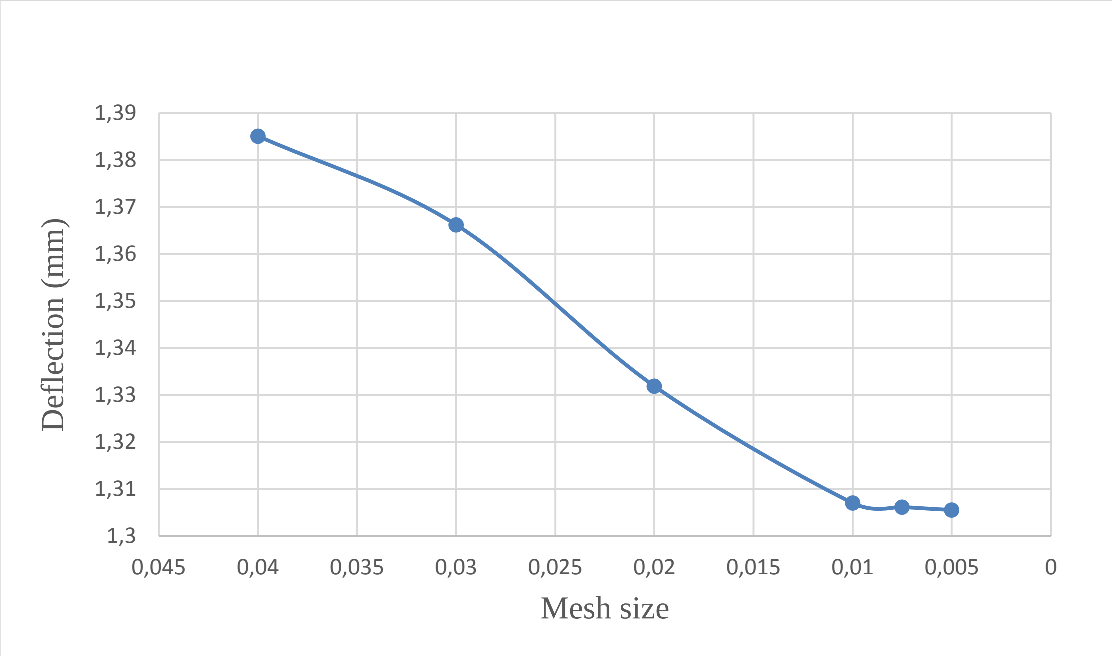

Figure 8. Mesh convergence of the middle area.

4.4. *Material properties*

In this stage of this report, all pavement material behaviours are modelled to be homogeneous isotropic linearly elastic responding to the applied load as static load. Experimental tests are carried out on CBEM after two days of curing as a conventional mix (without reinforcement) to obtain elastic properties of bituminous mixtures. The other layers are assumed granular base, granular subbase and subgrade and their properties were obtained from [8]. The elastic material properties are shown in Table 5.

Table 5. Elastic material properties.

Layer	Modulus of Elasticity (E) (MPa)	Poisson's ratio	Density (kg/m^3)
Surface	278	0.4	2200
Granular base	200	0.35	2000
Granular subbase	100	0.35	1800
Subgrade	50	0.3	1700

4.5. *Load application*

The prescribed applied load of the problem can be from forces, pressures or displacements for pavement structural analysis. In the loaded area, which is rectangular, pressure load is applied directly to the nodes and transformed into nodal forces as shown in Figure 3. In this report to simulate the static wheel load, a linear loading increment from zero to the maximum known value is performed.

Rahman, Mahmud [9] presents that tyre imprint area has to be a rectangular area which is more suitable than circular or ellipsoid tyre imprint areas. Also, this study shows that the tyre pressure is uniformly distributed over the contact area. The tyre imprint pressure load, which applied directly on the finite elements underneath the wheel path, is performed as 0.7 MPa (100 psi) which is to a single axial wheel load (40 KN) divided to the contact tyre footprint area (58000 mm^2).

5. Finite element simulation analysis

The parameters studied in this report are the vertical deflection of the pavement layers under the centre of the load and the vertical surface deflection (deformation) of the top of the surface layer (CBEM) in two dimensions. The top of the surface layer and the cross-sectional view of the pavement after applying the load are shown in

Figures 9 and 10 respectively. The pavement is symmetric with respect to x and y axes, therefore, one quarter of the pavement has been modelled to reduce analysis cost in terms of analysis running time, pre-processing effort and computer resources.

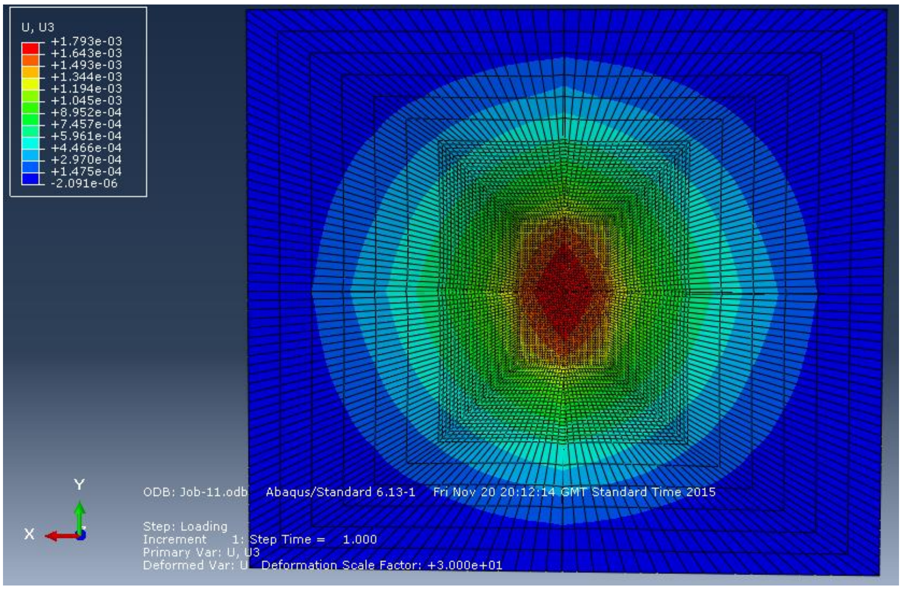

Figure 9. Top of the surface layer after applied load.

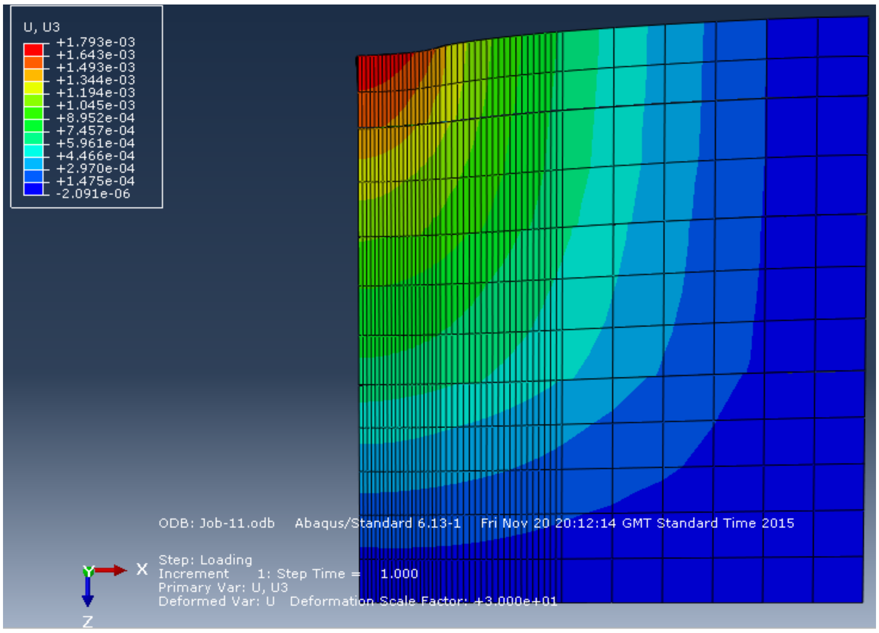

Figure 10. Cross-sectional view of pavement structure after applied load.

5.1. *Vertical deflection distribution*

The vertical deflection distribution along the pavement's cross-section for the unreinforced and reinforced pavement is extended along the bituminous layer, the granular base layer, the granular subbase layer and the subgrade layer. Two and seven days curing time were used in this report to obtain the strength of CBEM as a surface course. The vertical deflection distribution is changed when the surface layer strength increases as shown in Figures 11 to 14. The magnitude of maximum vertical deflection decreases when the magnitude of Modulus of elasticity increases. Figure 15 shows the vertical deflection variations between unreinforced and reinforced pavements with glass fibre during different curing times.

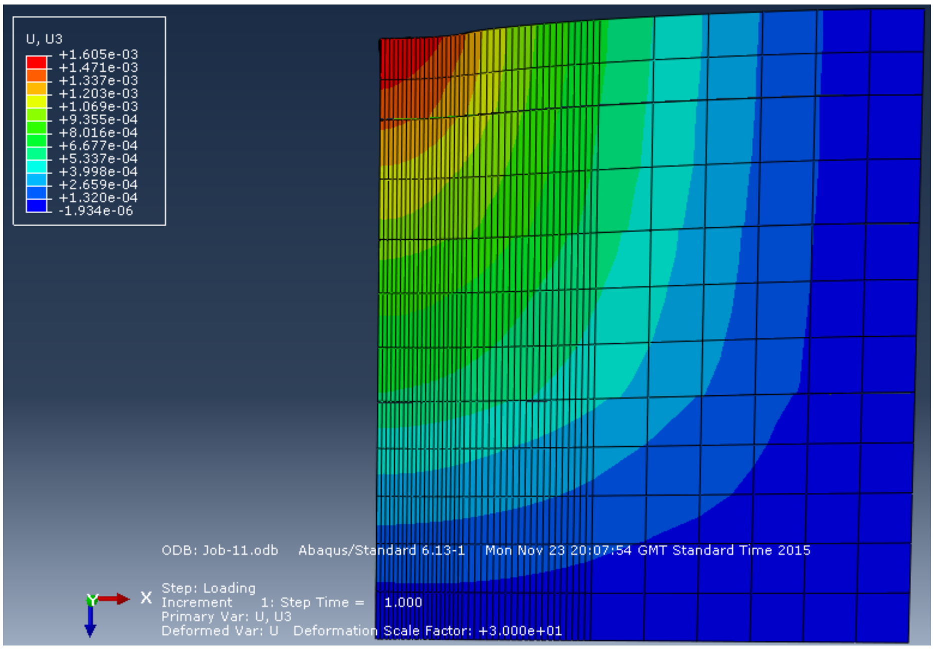

Figure 11. The vertical deflection distribution along the pavement's cross-section for the unreinforced pavement after 2 days curing.

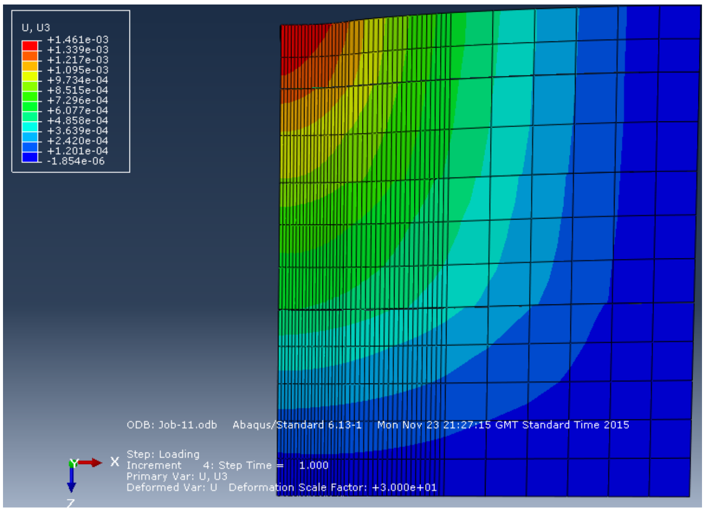

Figure 12. The vertical deflection distribution along the pavement's cross-section for the unreinforced pavement after 7 days curing.

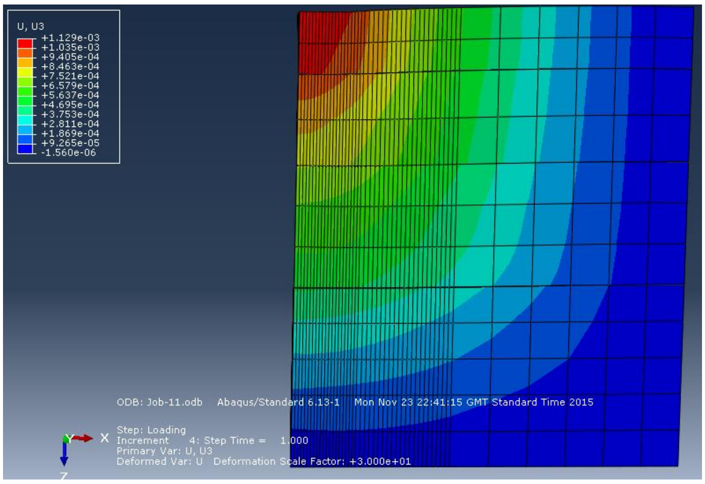

Figure 13. The vertical deflection distribution along the pavement's cross-section for the glass fibre reinforced pavement after 2 days curing.

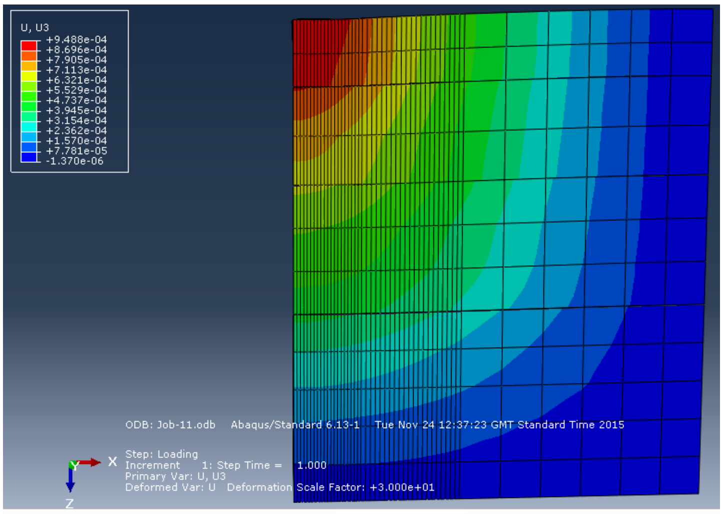

Figure 14. The vertical deflection distribution along the pavement's cross-section for the glass fibre reinforced pavement after 7 days curing.

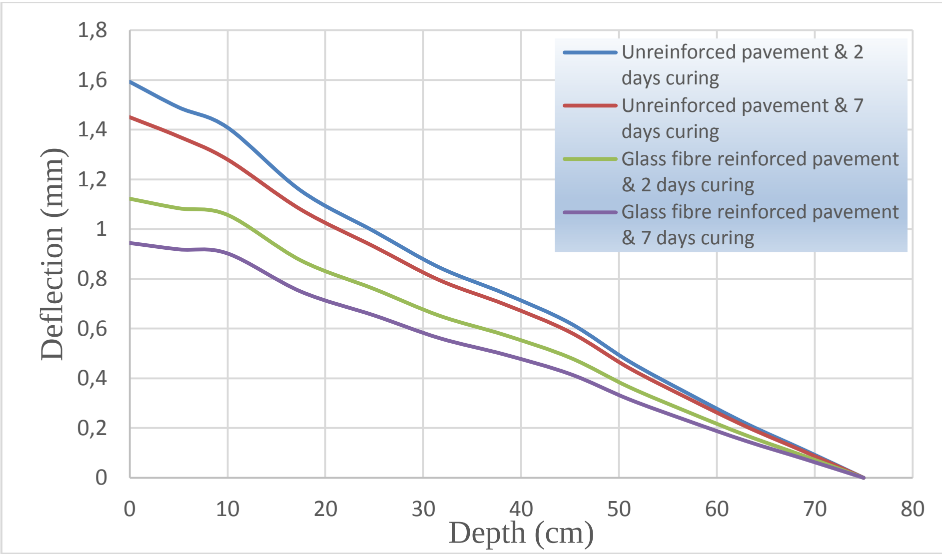

Figure 15. The vertical deflection variations between the unreinforced and reinforced pavement by glass fibre with different curing times.

6. Conclusion

It can be concluded that the highest reduction of the vertical deflection is achieved for pavement with 0.35% glass fibre after 7 days of curing time. This reduction, which reaches nearly 59%, is achieved when the stiffness modulus increased from 278 MPa for unreinforced pavement to 1060 MPa for pavement reinforced with glass fibre.

Acknowledgements

The first author wishes to express his sincere gratitude to the Itaqi Ministry of Higher Education and Scientific Research and Al-Muthanna University in Iraq for providing the financial support. The authors also thank David Jobling-Purser, Steve Joyce, Neil Turner and Richard Lavery who helped the authors a lot to complete this study.

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