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

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HIGHLIGHTS

- Cold mix asphalt mixtures reinforced using natural fibres.
- Modelling rutting phenomena of new CMA mixtures.
- Model can properly predict rutting of reinforced and unreinforced CMA mixtures.
- CMA quality is an important factor to reduce rutting within layer depth.
- Results show that natural fibre has positive effects on rutting behaviour of CMA.

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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.

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.

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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:

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

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:

$$\sigma(t) = E\varepsilon \tag{2}$$

$$\varepsilon(t) = D\sigma \tag{3}$$

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 (Fig. 1a), while the Kelvin-Voigt model consists of one dashpot and one spring in parallel (Fig. 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

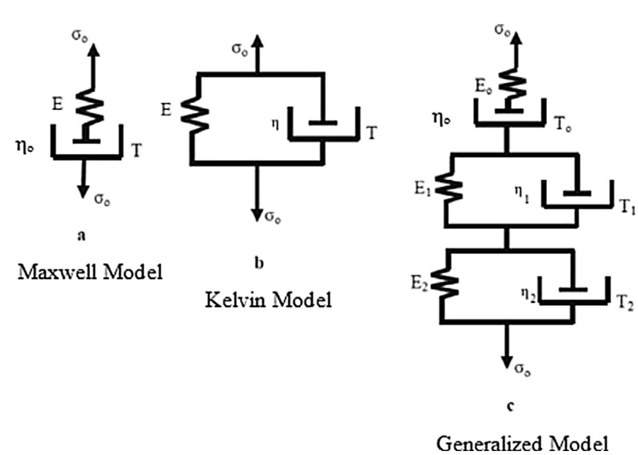

Fig. 1. Mechanical models for viscoelastic materials.