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A viscoplastic model for permanent deformation prediction of reinforced cold mix asphalt

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HIGHLIGHTS

- The effects of natural and synthetic fibres on rutting resistance were investigated.
- FEM can effectively predict permanent deformation in CMA and HMA mixtures.
- Reinforced CMA mixtures show a lower rutting than conventional CMA and HMA mixtures.

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ABSTRACT

A reliable viscoplastic model of natural and synthetic fibres reinforced cold bitumen emulsion mixture is developed and applied to characterize the rutting behaviour of asphalt pavement by using finite element analysis. It is indicated that the traffic load parameters such as temperature, static loading condition and vehicular speed not only affects the rutting depth, it accelerates the rutting rate, causing the pavement earlier enter into rutting failure with shortened service life. Several finite element models (FEM) have been developed to simulate the behaviour of hot mix asphalts (HMAs), but none exists for cold mix asphalt (CMA) reinforced by natural and synthetic fibres. This research presents the first three dimension (3-D), finite element model (FEM) to assess the viscoplastic behaviour of reinforced CMA mixtures. The model is also able to predict rutting (permanent deformation) of asphalt mixtures under different traffic and environmental loadings, traditional HMA used as a comparison. The enhancement of the performance of CMA mixtures against permanent deformation using finite element software (ABAQUS) was validated by comparing the models' predictions with measurements from wheel-tracking tests at different temperatures (45 °C and 60 °C). A very good level of agreement was found between the rutting predicted by the model and the experimental test. The results show that the finite element model can successfully predict rutting of flexible pavements under different temperatures and wheel loading conditions. Finally, the natural and synthetic fibres reinforced CMA mixtures are much more effective at resisting permanent deformation damage than conventional cold and hot asphalt mixtures.

1. Introduction

Asphalt or bitumen are widely used in flexible pavements as aggregate binders because of their high adhesion properties. Flexible pavements are subject to cyclic and sometimes excessive loads during their service life [1,2]. Their surface is also temperature sensitive in terms of high temperature permanent deformation and low temperature cracking [3,4]. Permanent deformation (rutting) development is one of the major distresses that frequently occurs in flexible pavements due to the non-linear, viscous and plastic behaviours of asphalt mixes [5]. Permanent deformation can be defined as the unrecoverable vertical deformation of pavements under a vehicle wheel path caused by high temperatures and load repetition. Such deformation can be limited to the asphalt surface layers comprising the viscoelastic and viscoplastic properties of asphalt and the plastic characteristics of aggregates [6].

Hot mix asphalt (HMA) is the main source of flexible pavements used in 95% of the world's paved roads [7]. However, this mixture is considered environmentally unfriendly because it needs

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substantial amounts of energy to heat the aggregate and asphalt producing CO_2 emissions during both production and laying [8,9]. Nowadays, several flexible pavement design technologies have been invented to eliminate, or reduce, emissions and save energy regarding asphalt paving production [10]. Cold mix asphalt (CMA) is one of these technologies. CMA is defined as a bituminous mixture of aggregates and asphalt emulsion, mixed at ambient temperature which does not require the same amount of energy to produce the same CO_2 emissions as HMA [11]. However, it has been considered an inferior mix compared to HMA, mainly in terms of its mechanical properties, the extended curing period required to achieve an optimal performance and its weak early life strength [12]. Poor asphalt mix quality and inadequate design may result in an inefficiently designed layer.

Some strengthening techniques have been trialed in flexible pavements. The reinforcement of asphalt pavements is one method to improve the performance when pavements do not meet traffic, climate and pavement structural requirements. Fibre reinforcement improves the life of a pavement by increasing resistance to permanent deformation and cracking [13]. The addition of fibres to hot and cold mixes as a reinforcing material, enhances the strength, bonding and durability of such mixes [14]. The modification of asphalt mixtures with additives such as polyethylene and styrene-butadienestyrene has also been found to decrease permanent deformation and increase durability and resistances to moisture damage and low temperature cracking [15–19]. Modification of asphalt has gained the attention because of its better performance and considered a more economical option compared with neat asphalt binder based on life cycle cost [20].

Flexible pavement responses to traffic loadings are mainly affected by the properties of the materials [21]. A variety of three-dimensional (3-D), finite element simulations have been developed to analyse the responses of flexible pavements [22–27]. The strain experienced by asphalt mixtures under wheel loads has recoverable components (elastic and viscoelastic) and irrecoverable components (plastic and viscoplastic) [28]. Elastic and viscoelastic responses are seen at low traffic volume and low temperatures, while plastic and viscoplastic responses at high traffic volume and high temperatures. Selecting an appropriate constitutive law that takes into account asphalt mixtures' creep behaviour and calibration its parameters using creep testing is important to simulate permanent deformation of flexible pavements by finite element modelling [6]. Picoux, et al. [29] simulated the distribution of vertical deformation to a flexible pavement, subjected to different wheel loadings based on viscoelastic deformation theory. Dave, et al. [30] developed viscoelastic models to analyse the response of asphalt overlay using thermomechanical impact under different combinations of loading time and temperature. Kai and Fang [31] conducted a 3-D, finite element model of asphalt pavements based on the elastic half-space theory, again examining the effect of load and temperature. Xue, et al. [32] developed a dynamic model to describe the settlement of the surface of asphalt pavements under different temperatures. Pérez, et al. [33] simulated a nonlinear, elasto-plastic Mohr-Coulomb numerical model for recycled flexible pavements, to determine the response of these pavements under two different loads and four types of soil subgrade. Gu, et al. [34] evaluated the effect of geogrid-reinforced flexible pavements by developing two pairs of geogrid-reinforced and unreinforced pavement models. Finite element modeling revealed that rutting resistance is better in the geogrid-reinforced pavement in comparison to the unreinforced pavement.

This research focuses on the evaluation of the response of natural and synthetic fibre reinforced CMA to permanent deformation, using 3-D finite element modelling and experimental tests. The main objectives are to identify the most accurate and effective approach to describe fibre reinforced CMA mixtures using finite element modelling. A 3-D, finite element model is developed and included attention to viscoplastic material behaviours to precisely predict the behaviour of natural and synthetic fibres reinforcement on the development of permanent deformation resistance. Finally, the predicted results from the model are compared with those measured in the lab to identify and verify the applicability of the developed model.

2. Methodology

Firstly, all produced specimens in this research were designed and prepared according to the method that adopted by the Asphalt Institute (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design (MS-14)) [35]. After optimizing the emulsion, the length of the fibres and fibre content were determined. Different laboratory tests were used on the reinforced and unreinforced CMA mixtures to calibrate the parameters of creep power law and to determine the elastic modulus. These tests included the indirect tensile stiffness modulus test and the creep test. A wheel tracking test was also performed to measure the permanent deformation of the mixtures.

A 3-D, finite element model was then developed in ABAQUS with the required test properties. A comparison between measured and predicted results was then carried out to validate the efficiency of the developed model.

3. Viscoplastic behaviour of flexible pavements

Contemporary flexible pavement designs assume that the pavements' response to traffic and environmental stressors is elastic. However, the validity of this assumption is limited to low temperature climate conditions and under rapidly applied vehicle loadings where the deformation to asphalt surfaces is not permanent, returning back to its original shape when the load is removed. At high temperatures, or under slow moving loads, flexible pavements are subject to the type of plastic deformation, which is associated with viscous behaviour. This is the main reason for the development of a new model; to simulate the mechanical response of the new, reinforced, cold mix asphalt and hot mix asphalt. This model is characterized by the elasticity required to simulate the immediate response of the pavement, viscosity to simulate the pavements mechanical response dependent on the strain rate in terms of loading time, and plasticity to simulate plastic flow in terms of permanent deformation.

The viscoplastic deformation of flexible pavements generally depends on the stress level, loading time, number of cycles and temperature. The constitutive law for flexible pavements can be stated as [36]:

$$\varepsilon_{ij} = (\sigma_{ij}, t, N, T) \tag{1}$$

where:

ε_{ij} and σ_{ij} are the strain and stress components, respectively
t: time
N: loading cycles number
T: temperature

The creep test is used in this research to characterize the viscoplastic behaviour of both the cold and hot asphalt mixes. Four different types of strain develop in flexible pavements when a vehicle moves on the top of them: elastic recoverable strain (ε_e) which is time independent; plastic irrecoverable strain (ε_p) which is time independent; viscoelastic recoverable strain (ε_{ve}) which is time dependent, and viscoplastic irrecoverable strain (ε_{vp}) which