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Nonlinear elasto–plastic performance prediction of materials stabilized with bitumen emulsion in rural road pavements

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ABSTRACT

This article presents numerical modelling of rural road pavement sections recycled in situ with two materials stabilized with bitumen emulsion. The two materials stabilized with bitumen emulsion are base course materials comprising 25% reclaimed asphalt pavement and 75% natural aggregates with and without 1% cement. A 3D-finite difference model was used to determine the response of these pavement sections when subjected to two types of loads with four types of soil subgrades of varying resistances. A nonlinear elasto–plastic Mohr-Coulomb model was used in the two materials stabilized with bitumen emulsion, and a nonlinear model was adopted in the four soil subgrades. Both the resilient and permanent behaviours of these materials were modelled. An analysis was conducted on rutting and fatigue resistances of the base course materials. The base course material containing 1% cement is more resistant and is apt for use in lightly trafficked rural roads. Both base course materials stabilized with bitumen emulsion will first fail from rutting before fatigue.

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1. Introduction

One of the primary goals of highway administrations is to maintain the road network in an optimal state of repair and operation. A large part of these networks is composed of lightly trafficked rural roads that use flexible pavements constructed with thin wearing courses comprising asphalt materials and base courses fabricated with unbound granular materials resting upon soil subgrades of relatively low resistance. One of the most effective actions for the maintenance of these pavements was found to be in situ treatment of recycled pavement with bitumen emulsion. In keeping with this convention, the process known as Full Depth Reclamation (**FDR**) is a rehabilitation technique in which the full thickness of an asphalt wearing course and a predetermined portion of an underlying unbound granular base course are uniformly milled, pulverized and blended to provide a new base course material stabilized with bitumen emulsion (**BSM**) [1].

In recent years, research on **BSM** has focussed mainly on characterisation, formulation and implementation. Significant progress has been made in these fields. However, relatively little ground has been gained in the study of the mechanical behaviour of **BSM** for improving the structural design of the rehabilitation solutions. Most of the methods used to analyse structural designs do not consider the specific mechanical characteristics of **BSM**. A number of different researchers have reported that these materials play a structural role that varies between the application range of unbound granular materials and the asphalt mixes [2–4]. In this sense, **BSM** exhibits a nonlinear behaviour similar to that of unbound granular materials, which depends on the pavement stress states, with the most critical mechanical property being shear stress resistance [3–5]. In other words, the failure of these materials is mainly due to significant permanent deformation (rutting) that has an irreversible and negative effect on the structural and functional state of the pavement [2].

The objective of this article is to determine the pavement responses at critical positions in two rural roads pavement sections with **BSM** base courses. For this purpose, a 3D-finite difference model will be used considering the **BSM**-specific mechanical characteristics. The permanent deformation (rutting) produced in the **BSM** will be attained. In addition, fatigue resistance will be analysed.

2. Pavement analysis model

2.1. 3D finite difference model

Two three-layer system sections are modelled (Fig. 1). The first section was studied earlier in South Africa [3]. It consists of a Hot Mix Asphalt **(HMA)** wearing course 40 mm thick overlying a **BSM** base course 200 mm thick placed directly over the subgrade. South Africa typically rehabilitates roads with 40 mm **HMA** wearing courses and

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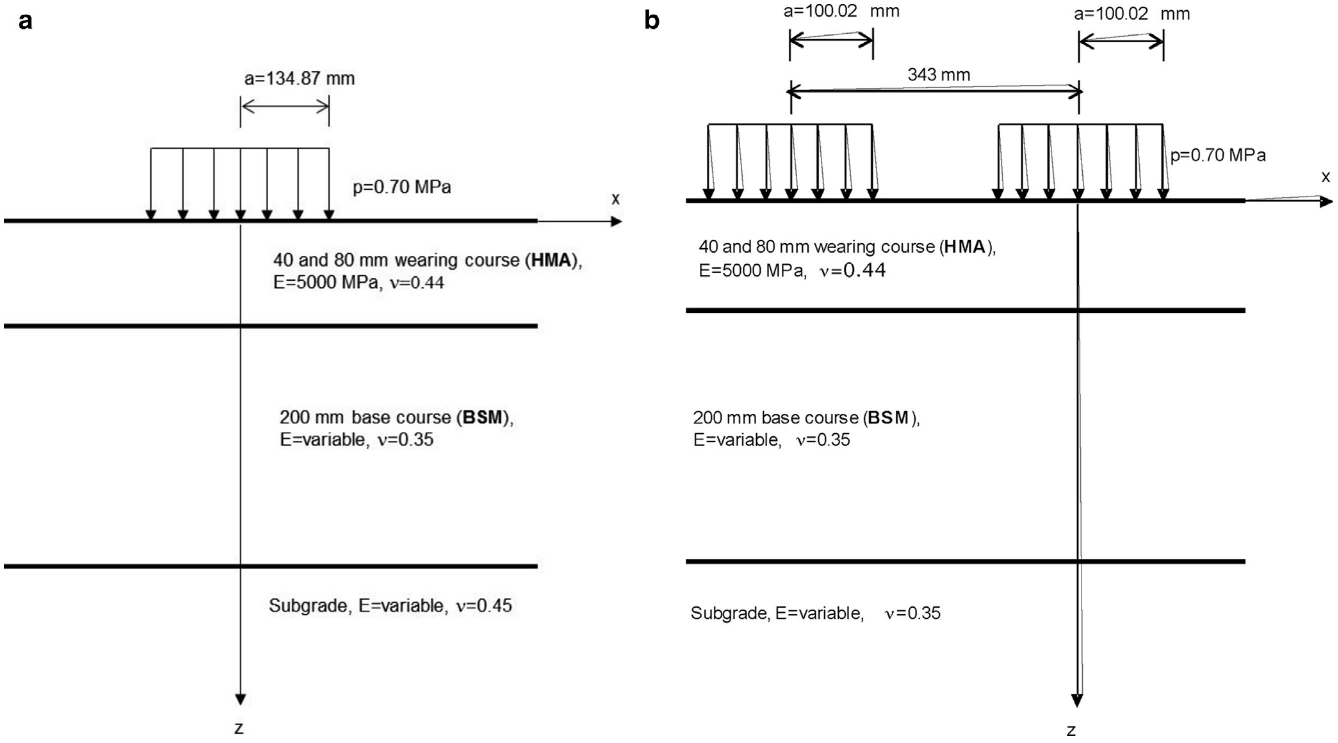

Fig. 1. Pavement structure used for modelling: (a) single tire (**ST**), (b) dual tyres (**DT**).

200 mm **BSM** base courses. This type of rehabilitation specifically belongs to category **C**: rural roads that are lightly trafficked or strategic roads. These roads have an 80% design reliability and 0.3 to 1 million equivalent standard axle loads (0.3 to 1 **MESA**) [6]. The second section is similar but with an **HMA** wearing course 80 mm thick. This second section is not used in the South Africa roads and is analysed for comparison with the first section.

On the other hand, the permissible axle load in South Africa of a single axle with dual wheels is 88 kN, whereas the permissible axle load of a single axle with single wheels used as steering axle is 77 kN, and that of a single axle with single wheels that is not a steering axle is 80 kN [7]. Therefore, two load configurations are used: an 80 kN single axle with two single tyres (**ST**) (Fig. 1a) and an 88 kN single axle with two dual tyres (**DT**) (Fig. 1b). A homogeneous circular load **p** = 0.70 MPa with a radius **a** = 134.87 mm is applied to the single tyre. For dual tyres, **p** is also 0.70 MPa but with **a** = 100.02 mm, and the distance between radial centres is equal to 343.00 mm.

The numerical modelling of the stress state produced in the pavement, created by the application of a static load on its surface, was carried out with the commercial code FLAC3D- 3.10 (Fast Lagrangian Analysis of Continua in 3-Dimensions) [8]. This is a three-dimensional code that uses a specific scheme of finite differences that allows the elastic–plastic behaviour of the materials used in pavement layers to be simulated. The materials are represented by polyhedric elements forming a three-dimensional grid that fits the shape of the modelled object. Each element behaves according to an established law of stress–strain (linear or nonlinear) in response to the loads applied and the boundary conditions. Fig. 2 shows the finite difference grid and the coordinate system used for dual tyres. The model comprises 2,500 elements and 2,900 nodes.

Given the conditions of symmetry entailed in the problem (in terms of geometry and loads), only one-fourth of the real problem is studied. The following boundary conditions were applied (Fig. 2):

- Movements prevented in direction ‘x’ on plane x = 0 (symmetry plane).
- Movements prevented in direction ‘y’ on plane y = 0 (symmetry plane).
- Movements prevented in directions ‘x’ and ‘y’ on the lateral (circular) edge of the grid. The lateral (circular) edge of the grid was located far from the load (1.4 m away from the tyre centre) so that it would have a minimal effect on the results.
- All movements prevented on the lower plane $z = -1.24$ m.

Continuity conditions are satisfied at the layer interfaces. The process reproduced with the numerical model consists of two phases: the first provides the in situ state of stresses existing in the pavement before applying the load. Once the state of mechanical equilibrium has been reached for the specific weights and boundary conditions applied, all movements of the model start out at zero. The load is applied in the second phase.

2.2. Material characterization

2.2.1. HMA wearing course

In this research, emphasis should be given to nonlinear elastic-plastic Mohr–Coulomb modelling of the **BSM** base course. In the **HMA** wearing course, a linear elastic behaviour is considered. This layer is characterised by the values of the following parameters: specific weight $\gamma = 24$ kN/m^3, coefficient of earth pressure at rest $K_0 = 0.6$, elastic modulus $E = 5{,}000$ MPa and Poisson’s coefficient $\nu = 0.44$ [3].

2.2.2. BSM base course

It is assumed that **FDR**-type treatments are carried out on a pavement that originally consisted of a thin bituminous wearing course and a thick unbound granular base course. Hence, the resulting **BSM** comprises only 25% Reclaimed Asphalt Pavement (**RAP**). Moreover, two different cases are considered: (a) 25% **RAP**+75% natural aggregates (**R0**) and (b) 25% **RAP**+75% natural aggregates+1% cement (**R1**). These two **BSM** base courses are characterised by the values of the following parameters: $\gamma = 22$ kN/m^3; $K_0 = 0.6$ and $\nu = 0.35$ [3].

A nonlinear elastic behaviour is assumed [9]. In keeping with this, the well-known M_r-Θ model, initially developed for unbound

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