Development of New Mechanistic Pavement Design Approach for Cement Stabilized Bases

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ABSTRACT: In-situ cementations stabilization is increasingly considered as an effective and environmentally friendly way to rehabilitate degraded unbound pavements. However, the testing and design methods for these stabilized pavement materials have not been sufficiently advanced scientifically. Currently, it is attempted to directly use laboratory derived fatigue relationships to pavements in service. However, the laboratory tests do not simulate the actual road pavement conditions such as three dimensional stress conditions, difference in pavement thickness, axle load types, and other material factors including initial state, strength gain with time, and material variability. In addition, the load damage exponent (m) used in the fatigue relationship, m = 12 is currently used to convert the damage of any axle load to an equivalent number of standard axle repetitions, which is an approximate and convenient approach. This paper includes the investigation of effect of axle configurations on the cement stabilized pavement response using the computer program CIRCLY. It also presents a proposed detail bottom-up research study to address the issues in the current design approach.

1 INTRODUCTION

In-situ cementations stabilization is increasingly considered as an effective way for the strengthening of existing degraded unbound pavements. The main deterioration mode of the stabilized pavements is fatigue cracking. The four-point bending flexural beam test is used to characterize the flexural fatigue performance of cement stabilized pavement materials in the laboratory. This test is considered to be a closer representation of the bending stress/strain gradients applied to cemented pavement layers in service (Austroads, 2012). Fig. 1 illustrates the flexural modulus variation with number of load cycles applied in a fatigue test. The three phases of fatigue cracking identified by Theyse et al. (1996) under traffic loading are clearly visible in laboratory flexural fatigue testing. In the "bedding-in" phase (pre-cracked phase), the flexural modulus of the beam specimen decreases rapidly, however; it decreases at a slow, constant rate in effective fatigue life phase. After this effective fatigue life phase, an accelerated rate in modulus reduction is observed and the specimen then fails after some additional load cycles. Based on the breaking load of stabilized materials tested in four point bending apparatus using the same beam geometry used in fatigue testing; the appropriate load magnitude (60-90% of the breaking load) is selected for the fatigue testing.

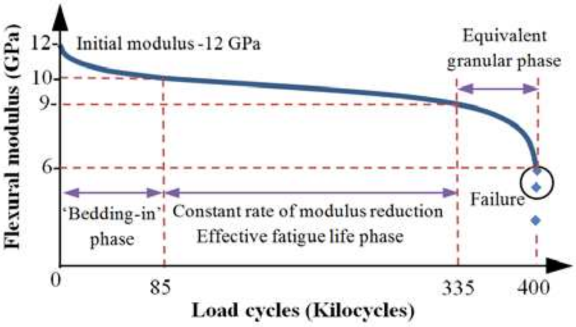

Fig. 1 Typical flexural modulus variation during fatigue tests (Austroads, 2010)

Based on the flexural modulus variation during fatigue tests, the fatigue life is defined as the number of load cycles (N) applied to the beam specimen to reduce the flexural modulus to half of the initial flexural modulus (Austroads, 2010).

2 CURRENT DESIGN PRACTICE

2.1 *Fatigue criteria of cement stabilized materials*

The following empirical relationship (Eq. 1) is used in Australia to determine the fatigue life of cement stabilized pavement bases in service (Austroads, 2012). However, this empirical relationship was developed on the basis of laboratory fatigue characteristics of cemented materials.

$$N = RF\left[\frac{\frac{113000}{E^{0.804}} + 191}{\mu\varepsilon}\right]^{m} \quad (1)$$

Where N is allowable number of repetitions of the load, $\mu\varepsilon$ is load-induced tensile strain at base of cement stabilized material (microstrain), E is cement stabilized material modulus (MPa), m is load damage exponent (12 for cement stabilized materials) and RF is the reliability factor for cement stabilized materials fatigue, which takes into account the uncertainty associated with material input data.

2.2 *Design traffic*

2.2.1 *Equivalence of axle loads*

Table 1 shows the equivalent axle loads for common axle configurations, which are considered to produce equivalent damage on the pavement as a standard axle. The standard axle is a single axle with dual tires (SADT), which transmit an axle load of 80kN to the pavement. These equivalent axle loads were empirically derived assuming equal maximum surface deflection under an axle configuration load causes equal damage (Austroads, 2008a).

Table 1. Equivalent axle loads (Austroads, 2012)

Axle configuration	Load (kN)
Single axle with single tires (SAST)	53
Single axle with dual tires (SADT)	80
Tandem axle with single tires (TAST)	90
Tandem axle with dual tires (TADT)	135
Tri-axle with dual tires (TRDT)	181
Quad-axle with dual tires (QADT)	221

2.2.2 *Standard Axle Repetitions (SAR)*

The pavement damage due to various axle loads is calculated using appropriate equivalent axle loads (Table 1). These equivalent axle loads are used to convert the damage of any axle load to an equivalent number of load repetitions of a standard axle. The following empirical relationship (Eq. 2) is used to convert the damage of any axle load to an equivalent number of standard axle repetitions (Austroads, 2012).

$$SAR_m = \left(\frac{L_{ij}}{SLi}\right)^m \quad (2)$$

Where SAR is number of Standard Axle Repetitions which causes the same amount of damage as a single passage of axle configuration i with axle load L_{ij} where the load damage exponent is m, SL_i is equivalent axle load for axle configuration i (Table 1), L_{ij} is the j^{th} axle load magnitude on the axle configuration i and m is the load damage exponent for the damage type.

Since fatigue is the damage in cement stabilized pavement bases under traffic loading, currently, it is attempted to use the load damage exponent (m) used in the fatigue relationship, m = 12 to determine the Standard Axle Repetitions (SAR).

2.3 *Mechanistic design procedure*

Cement stabilized materials are considered homogeneous, isotropic and elastic with a Poisson's ratio of around 0.2 in the design of pavements. The computer program CIRCLY (Mincad Systems, 2012) is commonly used in Australia for the mechanistic analysis and design of flexible pavements. Pavement responses to axle loading are calculated using the linear elastic computer program CIRCLY. The critical locations of the strains within a flexible pavement structure under standard axle loading are shown in Fig. 2.

The critical location within the pavement under standard axle loading could be either along vertical axis directly below the inner wheel of the dual wheel group or along the vertical axis located symmetrically between a pair of dual wheels (Austroads, 2012). Shape of the tire footprint is assumed to be circular, and also the tire contact stress is assumed to be uniform over the loaded area. Based on these assumptions, the standard axle loading (SADT) could be considered as four uniformly loaded circular areas of equal area and for the purpose of design, tire contact stress is taken as 750 kPa (Austroads, 2012). The structural capacity of the candidate pavement is assessed from the Cumulative Damage Factor (CDF) obtains in CIRCLY analysis. CDF is the ratio between number of standard axle load repetitions (design traffic) and allowable number of load repetitions.

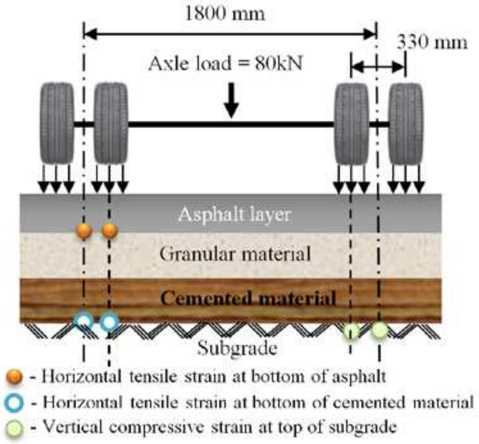

Fig. 2 Critical locations of the stains in a pavement structure under standard axle loading (SADT)

3 EFFECT OF AXLE CONFIGURATIONS ON THE PAVEMENT RESPONSE

Pavement structure consisting of asphalt layer (Elastic modulus = 2800 MPa and Poisson's ratio ν= 0.4), cement treated base (Elastic modulus = 2000 MPa Poisson's ratio ν = 0.2) and subgrade (CBR of 6) was modeled in CIRCLY. All layers are treated as elastic layers. Asphalt layer thicknesses of 30 mm and 175 mm and Cement Treated Base (CTB) thicknesses of 150, 250 and 350 mm were used in this analysis. The half-tandem axle with single tires (TAST), spaced at 1.3 m with a tire contact stress of 0.844 MPa (under equivalent axle load 90 kN) was modeled. The interaction between the two axles can be clearly seen in Fig. 3. The level of interaction increases with increasing CTB thickness and the lowest level of interaction can be considered as two distinct loads (Fig. 3).

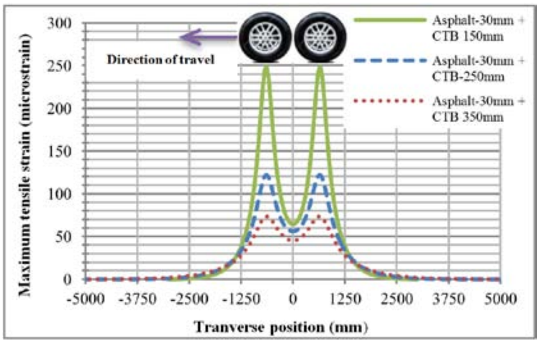

Fig. 3 Shapes of maximum tensile strains at bottom of Cement Treated Base (CTB) loaded with TAST

The level of interaction between the two axles in the lowest thickness CTB (150 mm) decreases with increasing asphalt layer thickness, while it remains same in the other two CTBs (Fig. 3 and Fig. 4).

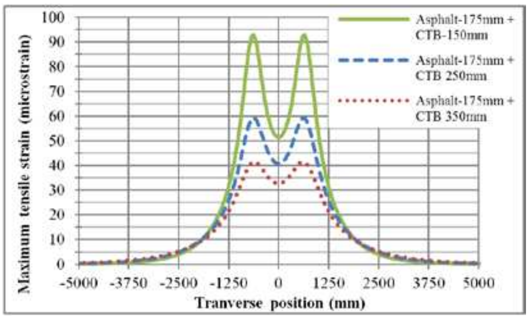

Fig. 4 Shapes of maximum tensile strains at bottom of Cement Treated Base (CTB) loaded with TAST

The half-tri axle with dual tires (TRDT), spaced at 1.3 m with a tire contact stress of 0.633 MPa (under equivalent axle load 181 kN) was also modeled. Fig. 5 and Fig. 6 show the interaction between three axles clearly.

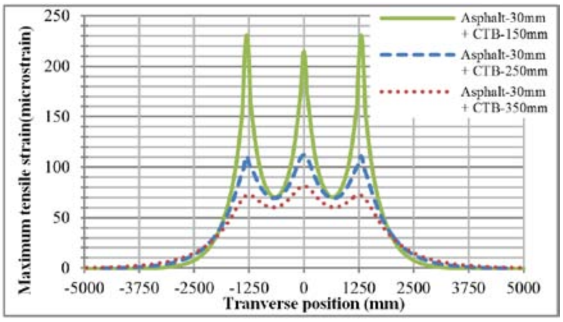

Fig. 5 Shapes of maximum tensile strains at bottom of Cement Treated Base (CTB) loaded with TRDT

The level of interaction increases with increasing CTB thickness and the lowest level of interaction can be considered as three distinct loads (Fig. 5).

The level of interaction in the lowest thickness CTB (150 mm) decreases with increasing asphalt layer thickness, while it remains same in the other two CTBs (Fig. 5 and Fig. 6). This is similar to the pavements loaded with TAST.

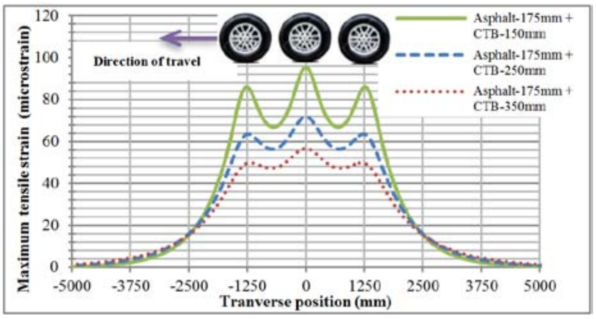

Fig. 6 Shapes of maximum tensile strains at bottom of Cement Treated Base (CTB) loaded with TRDT

In the current design approach, the amount of damage created by these axle configurations are assumed to be same and a single passage of these axle configurations is taken as one Standard Axle Repetition (SAR). This assumption is not appropriate in thinner pavements design.

4 ISSUES IN THE CURRENT DESIGN PRACTICE

Currently, it is attempted to directly use laboratory derived fatigue relationship to pavements in service. However, the laboratory flexural beam test does not simulate the actual road pavement conditions such as three dimensional stress conditions, difference in pavement thickness, axle load types, and other material factors including initial state, strength gain with time, and material variability (laboratory-field shift factors). Besides, a load damage exponent (m) of 12 is used in fatigue relationship, but values in the range 6 to 26 were reported for different cement stabilized pavement materials (Austroads, 2014). Since the load damage exponent is a power in fatigue relationship, its incorrect choice has major implications for the service life and cost of the designed pavement.

Australia being the only country to incorporate modulus into the fatigue relationship (Yeo, 2012), but the standard modulus test method used in Australia doesn't specify suitable loading conditions at which testing should be conducted. Austroads (2011) reported that the flexural modulus of the cement stabilized materials tested show lower modulus values with increasing load level. Incorrect choice of flexural modulus values in pavement structural design could have a major impact on the performance of cement stabilized pavement bases in service under heavy axle loading.

As far as the design traffic calculation procedure is concerned, the load damage exponent (m) used in the fatigue relationship, $m = 12$ is currently used to convert the damage of any axle load to an equivalent number of standard axle repetitions. This approach is approximate and convenient, but requires more rigorous theoretical and experimental investigation.

5 CONCLUSIONS

Since the laboratory four-point bending flexural beam test does not simulate the actual pavement conditions, the development of a suitable material constitutive model using laboratory tests which can capture the damage evaluation of stabilized pavements under three dimensional repetitive loadings could be useful in explaining the material behavior and understanding associated shift factors when stress and boundary conditions change from laboratory to field. Accordingly, a series of appropriate laboratory tests need to be carried out, to develop a suitable damage model by characterizing the microstructure of fatigue damage of cement stabilized materials under various test conditions including varying beam thicknesses under the same geometry, a range of loading conditions and different curing ages. The damage model can then be used in simulation of pavement behavior preferably after implementation into a finite element program such as general purpose software program ABAQUS.

With the application of the constitutive modelling and test data, new fatigue relationships could be developed catering to both laboratory tests and field conditions.

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