Estimation of Crack-Opening and Crack-Spacing in Cement Treated Base Layers

M.Woldekidan, M. Huurman

BAM Wegen bv, The Netherlands

Abstract

This paper present the development of a practical tool for estimating crack formation phenomenon in Cement Treated Base (CTB) layers. The tool is developed in a numerical environment. The various factors that influence crack formation in CTB layers are first identified. For determining crack initiation moment, all influencing factors are combined to dictate a single governing term, i.e. the ultimate stress state. This implies the combination of factors that vary from temperature fluctuations, shrinkage(hydration), traffic loading and pavement boundary conditions, are all combined to dictate the ultimate stress state in the CTB layer. When the ultimate stress state in the layer exceeds the available material strength, cracking is initiated. Depending on the crack characteristic, i.e. spacing and opening, and the top layer property, cracks from the CTB layer may grow up to the surface resulting in reflective cracking. In the presented tool the whole phenomenon of stress built up within the material, time evolution of material response and strength property, are all integrated into a numerical model that ultimately predicts the crack initiation moment, crack opening and crack spacing as a function of time. The tool can be utilized as a decision-supporting tool in optimizing the combined effects of material property, mechanical loads, environmental loads, as well as effects of pre-cracking on the ultimate crack spacing and crack opening in a CTB layer. The paper discusses the details of the approach and present illustrative results.

1. Introduction

Reflective cracking is a commonly encountered problem in asphalt pavements with Cement Treated Base (CTB) layer. The phenomenon of crack formation in a CTB layer is inevitable. The challenge facing road engineers is to control the crack formation and growth within a CTB layer so that the occurrence of reflective cracking on top layers remain limited. Many factors contribute to the initiation of crack in a CTB layer. The main factors include but are not limited to traffic, temperature fluctuation, hydration shrinkage etc. From engineering mechanics point of view, all these factors dictate a single governing term for crack initiation, i.e. the ultimate stress state within the material. In other words, the effects of the various factors can be superposed to dictate the ultimate stress state within the CTB material. When the ultimate stress state in the material exceeds the available material strength, cracking is initiated. Depending on the crack characteristic, such as crack spacing and opening, of the CTB layer, cracks from the CTB layer may ultimately grow up to the top layer resulting in cracking of the asphalt top layer. This is commonly known as reflective cracking.

To minimize the occurrence of reflective cracking in practice, several measures are taken. The measures include methods such as micro-cracking, which is the process of introducing several micro cracks in a CTB layer, and the use of stress absorbing membrane interlayer (SAMI) in between the CTB and the top asphalt layer. Predicting the crack formation behaviour of a given pavement layer is challenging because the crack formation depends on various factors such as development of material strength, rate of shrinkage (curing), intensity of traffic and environmental loading, etc. These factors are also intricately linked to each other. In view of this complexity, availability of tools for evaluating the cracking potential of a CTB layers will be of high value in achieving optimum design for pavement structures.

The work presented in this paper involves the development of such supporting tool for estimating crack formation in cemented base layers. The developed tool is based on numerical analysis. As such, the whole phenomenon of stress built up within the CTB layer in relation to the evolution of the material-strength development are all integrated into a numerical model that ultimately predicts the crack initiation moment, the resulting crack opening and the crack spacing as a function of time. The tool can be utilized as a decision-supporting tool in optimizing the combined effects of material property, mechanical loads, environmental loads, as well as effects of pre-cracking on the ultimate crack spacing and crack opening for cemented treated base layer. After crack initiation there exist a secondary phase where crack grows slowly as a function of time resulting in a full crack formation. This secondary crack growth phenomenon involves fracture mechanics and it is not addressed in the scope of this article. The estimation of the crack spacing and opening in this article is therefore based on the crack initiation moment. The paper discusses the details of the approach and present results demonstrating the model output.

2. Methodology

2.1 Finite Element Model

CTB layers shrink as a result of change in temperature or drying-curing process. When the layer shrinks, the length tends to shorten. Since the layer is restrained at the bottom against sliding, tensile stresses develop at the bottom layer. When the pavement is in service, traffic induced tensile tresses also adds up. Cracking is initiated when the tensile stress in the CTB layer, σ_{xx}, exceeds the available tensile strength of the material. σ_{xx} is thus influenced by the combined effects of shrinkage due to hardening, shrinkage due to temperature fluctuations, the restraining effects of underlying layer (resistance against sliding hereafter referred as bedding constant) and traffic loads. To understand the whole phenomenon, the approach used in this work is first to understand the relation between the development of stress under the CTB base for various levels of shrinkage(temperature induced) in relation to the bedding constant and the CTB layer geometry, i.e. thickness and length. For this a Finite Element (FE) model was utilized. Fig.1 illustrates the finite element model for the CTB layer with length L and CTB layer thickness H.

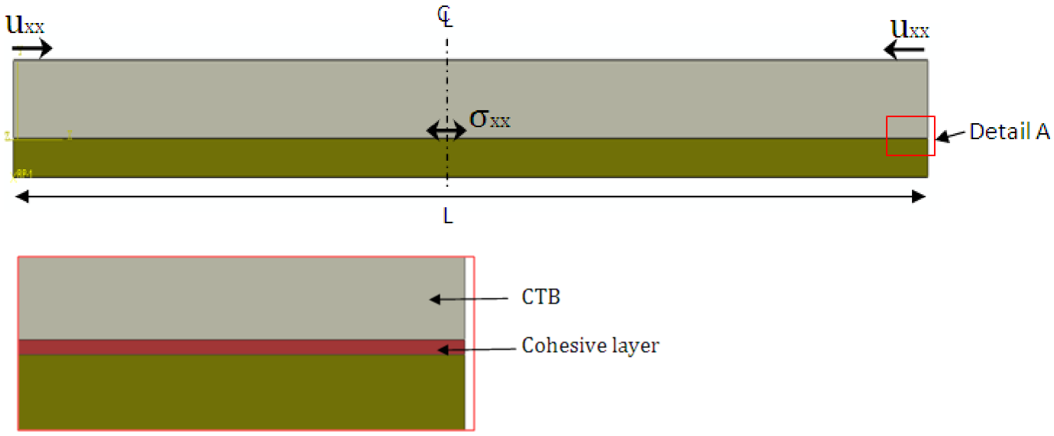

Fig.1 Two dimensional FE Model.

The restraint at the bottom of the CTB layer is modeled with a cohesive layer. The CTB layer was assigned a material property consisting of an elastic modulus, coefficient of thermal expansion and a poisons ratio. The sub base layer is modeled as an elastic material resting on an elastic foundation with foundation stiffness per area of 1000N/mm2. By simulating a temperature difference in the CTB layer, the development of σ_{xx} and Uxx for different combinations of CTB layer thickness (H), Length (L), and Bedding constant (Ch) were studied. Uxx is the displacement at the end of the CTB layer. This term will be used in determining the crack opening. Table.1 summarizes the matrix of the variables used in the simulations.

Table.1 Matrix of variables used in the Simulation

Input parameters	Values used in the simulations	Simulation outputs
E-modulus	5000 to 10,000 MPa	
Length of CTB layer	10 m to 30 m	
Thickness of CTB layer	250 mm to 750 mm	σ_{xx} at the CTB bottom Uxx at the end of CTB layer
Cohesive layer property (Ch)	1E-6 to 0.5	
Cohesive layer property (Cv)	0.2	
Coefficient of Lin.exp. (α_T)	7E-6	
Temperature Change (ΔT)	1°C to 10°C	

The results obtained from the simulation were analyzed. The effect of each variables on the stress at the bottom and horizontal displacement at the ends were analyzed. For brevity, all the obtained results are not presented. To illustrate the results the data obtained for a CTB thickness of 250 mm and simulated temperature fluctuation of 5°C is presented in Fig.2. In Fig.2(left) illustration is given on the relationship between σ_{xx} and bedding constant Ch. Fig.2(right) illustrates similar results but for varying lengths.

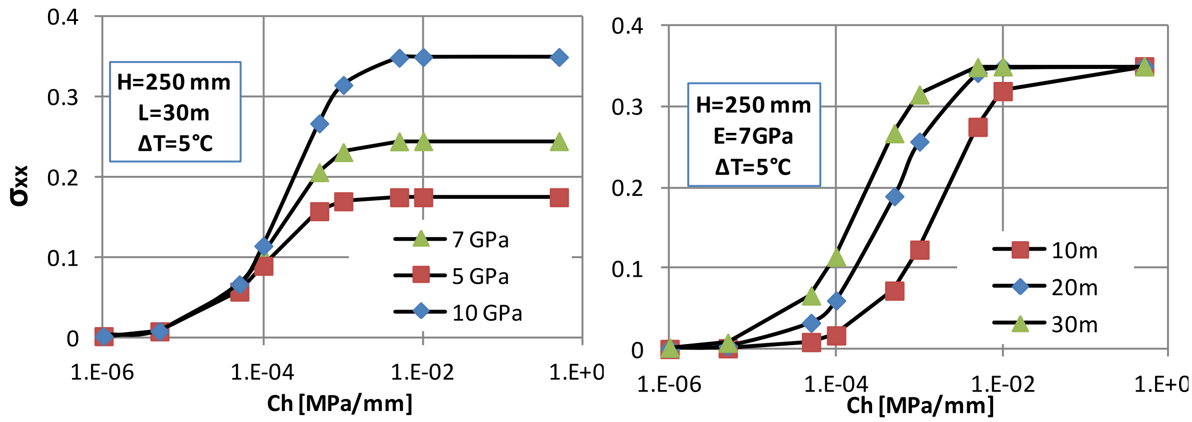

Fig. 2 σxx vs Ch (left: effect of E modulus, right: Effect of Length)

The corresponding relations obtained for the horizontal displacement at the end of the CTB layer is presented in Fig.3

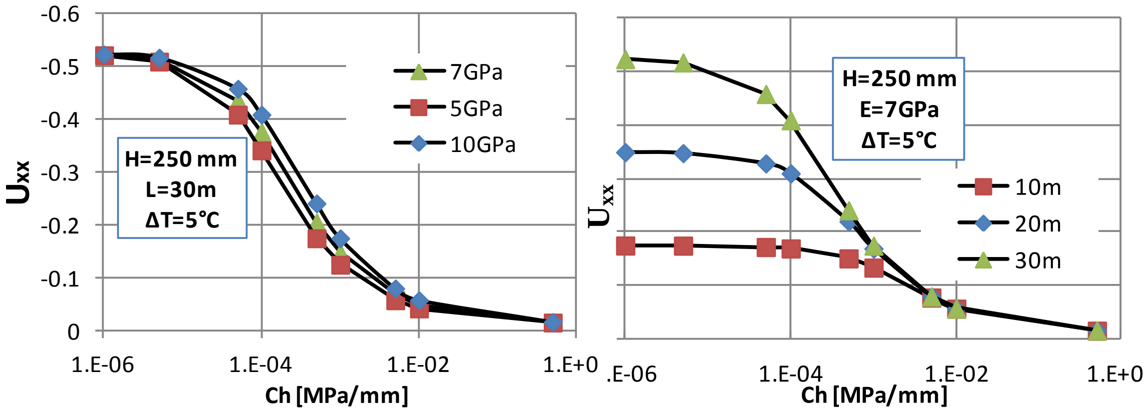

Fig.3 Uxx vs Ch (left: effect of E modulus, right: Effect of Length)

2.2 Analysis: Stress and Displacement

As illustrated in Fig.2 and Fig.3, the relation between σ_{xx} and the horizontal bedding constant follows the form of S-function. To make the analysis global, so as to include all relevant parameters together, a parameter β is defined such that β =Ch/EH. Here E and H denote the E-modulus and the thickness of the CTB layer respectively. With this parameter, the function used to describe the development σ_{xx} is chosen. The form given in Eq.(1) is used to describe the stress at the bottom of the CTB layer:

$$\sigma_{xx} = \sigma_{\max} .S \text{, where } S = [1 - \exp(-(\beta / r)^m)] \qquad (1)$$

where σ_{xx} is the stress at the bottom of the CTB layer, $\sigma_{\max}$ is the maximum possible stress, r is a rotation point and m is a model parameter. For cases where only temperature stress is considered, such as in Fig.2(left), the maximum possible stress can be defined as $\sigma_{\max} = E\alpha_T \Delta T$. If strains due to hardening(ε_c) need to be included, the maximum possible stress can be rewritten as $\sigma_{\max} = E(\alpha_T \Delta T + \varepsilon_c)$. As can be seen from Fig.2(right), the rotation point, r, is a function of the slab length. It is described with the following relation:

$$\log(r) = -(a.\log(L) + b) \qquad (2)$$

In Eq(2), a and b are model parameters and L is the length in m.

Referring to Fig.3, the displacement Uxx at the end of the CTB slab length, which will be later used to determine the crack opening, can also be described with functions of similar nature. The following relations were derived to describe the displacement.

$$U_{xx} = U_{\max}[C_1 - \exp(-((1-S)/R)^m)].[a_1 + b_1 S] \qquad (3)$$

In Eq.(3), U_{xx} denotes the horizontal displacement, $U_{\max}$ denotes the maximum displacement, S is the shape function as defined in Eq.(1), R, m, a_1 and b_1 are model parameters. Using the relations given above, the FE data was used to perform regression analysis. The analysis leads to the model parameters given in Table.2.

Table.2 Model parameters

Eq.(1) and Eq.(2)			Eq.(3)	
C_1	1.01		a	2.02
a_1	10.87		b	6.91
b_1	-7.00		m	0.81
R	1.56E10			
n	0.104			

The model parameters in Table 2 were found to describe the simulated data quite accurate. To illustrate the quality of the obtained fit, results are presented in Fig.5. In this figure, the model description and the FE data for a case of E=5000MPa and H 500mm is presented for illustration. Similar accuracy was obtained in describing data for other E and H combinations.

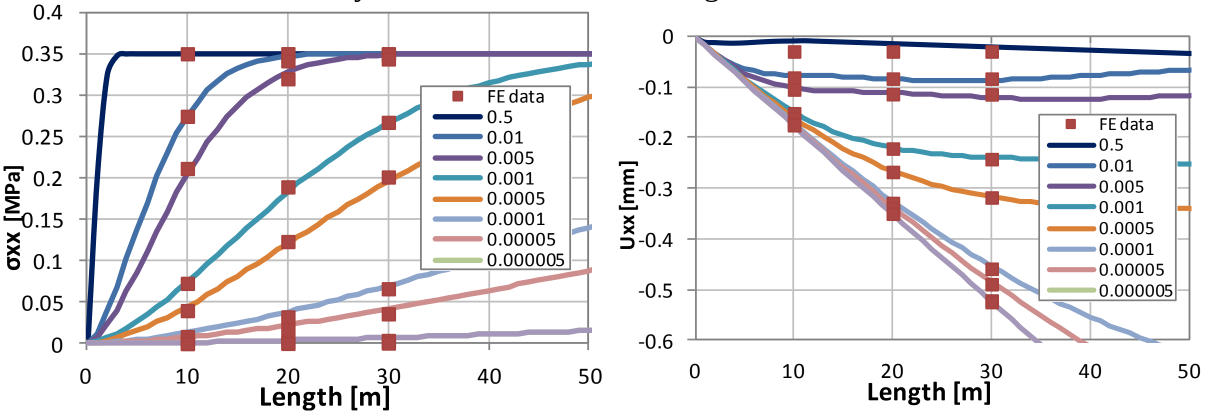

Fig.5 Model and FE simulated data for σ_{xx} and U_{xx} as a function of slab length and Ch

The above developed models can therefore be used to relate the expected tensile stress and the displacement for a given length, thickness, material properties and temperature loads. However, in reality the length is not known in priori. Rather it is determined after crack formation. The crack formation is related with the occurring tensile stress within the material and available tensile strength, both of which evolve with time. This implies the time varying material properties need to be coupled with the relations derived in the above sections.

2.3 Time varying factors

The strength and E-modulus properties of a cement treated layer evolve with time. Due to cement hydration, hardening strain develops with time. In addition to the temperature stresses, the hardening strain thus introduces additional loads in the CTB layer. The E-modulus, the tensile strength and compressive strength properties also changes with time as a result of curing. In order to incorporate these parameters in the model, further relations were sought that explain the time evolution of these properties. For the work presented in this paper, available relations from previous projects were adopted [1,2]. Depending on the type of the material, the relationships given hereafter can vary for other materials. In utilizing the tool for a given material, first the validity of these relations for the selected material need therefore to be checked and relevant relations need to be amended.

Strength and Material Properties

The time evolution of the E modulus is modeled as:

$$E = (E_0 - 4 f_c).(10 f_c)^{0.5} \quad (4)$$

Where E is the E-modulus, E_0=900 MPa is a model parameter (~1800 for concrete), f_c is the compressive strength in MPa. The compressive and tensile strength develop with time. For these properties the following relations are utilized:

$$f_c = a_2.t^{b_2} \quad , \quad f_t = 0.25 f_c^{\,2/3} \quad (5)$$

In Eq.(5), f_c denote the compressive strength, f_t is the tensile strength, t is time in days, a_2 and b_2 are model parameters.

The last important material property is the development of hardening strain. This property is assumed to follow a power function of the form:

$$\varepsilon_c = (1 - 0.5^t)\varepsilon_\infty \quad (6)$$

where ε_c is the strain as a result of hardening, t is time in years and ε_∞ is maximum hardening strain. This strain term can be superimposed together with the temperature strain to determine the maximum possible stress in the material.

Traffic stress

An estimate of the traffic stress is made using the relation given in Eq.(7).

$$\sigma_{traff} = a_3 E^{b_3} \quad (7)$$

where a_3 and b_3 are model parameters; b_3 in the range of 0.5. a_3 is estimated with an assumption that the traffic stress at 28days is in the order of $0.5 f_c(@28days)$. Another alternative approach for estimating the traffic induced stress is to perform multilayer computations for varying pavement thickness and material properties.

To incorporate the traffic stress in the model, the available tensile strength is adjusted . In other words, at any time t, the available tensile strength of the material is obtained by deducting the traffic stress from the tensile strength of the material at that moment. When the stress in the material due to temperature and curing exceeds the available tensile strength, cracking is initiated.

The above relations were all incorporated in a spread sheet program. To obtain reasonable temperature loads, daily temperature fluctuation data for years between 1985 to 2012 was downloaded from the Dutch Weather website (KNMI). The spreadsheet program was developed to perform series of tasks based on user inputs. The program requires the following inputs:

- model parameters for Eq(1) to Eq(8).
- the day the pavement is opened for traffic.

Then the program performs the following tasks:

- computes ΔT for each days in relative to the daily temperature reported on the opening day.
- the hardening strain (Eq(6)), tensile and compressive strength(Eq(5)), E-modulus development (Eq(4)) , traffic stress (Eq(7)) will also be automatically computed for each days.
- maximum possible stress is computed using $\sigma_{\max} = E(\alpha_T \Delta T + \varepsilon_c)$ for each days.
- available tensile strength is computed as $\sigma_{xx} = f_c - \sigma_{traff}$
- β and r are computed
- crack spacing, L, is estimated using Eq.(2).
- S is computed using Eq(1)
- U_{max} is computed as L($\alpha_T \Delta T + \varepsilon_c$)
- Crack opening, $2.U_{xx}$, is computed using Eq(3)

3. *Model outputs:*

The tool can be used to investigate the effects of various variables; such as development of E modulus, the curing behavior, layer thickness, strength development rate, pre-cracking measures etc on the ultimate crack spacing and crack opening of the cemented layer. For cases where description of the time evolution of the materials require the use of other relations, those relations can easily be adopted in the spreadsheet program. To demonstrate the output of the program, the model parameters determined in the above sections were used. for the temperature data, the month of May 1985 is arbitrarily taken. This corresponds to the temperature data given in Fig.6.

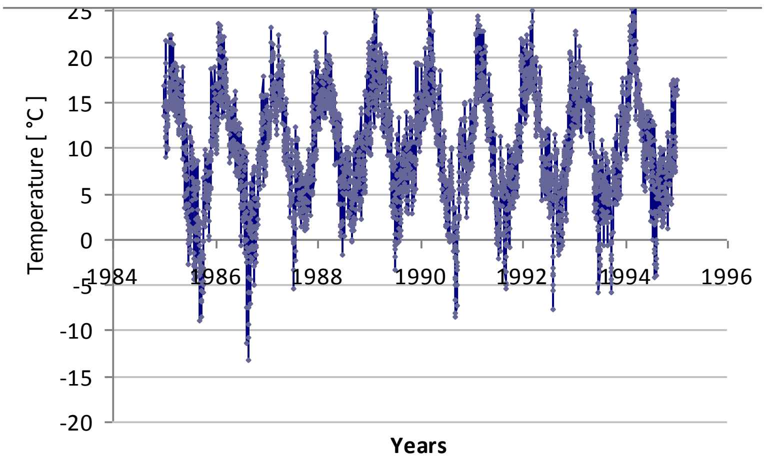

Fig.6 Daily temperature data for a period of 10 years

For the temperature data corresponding to Fig.6, the tool prediction for crack spacing and opening is illustrated in Fig.7.

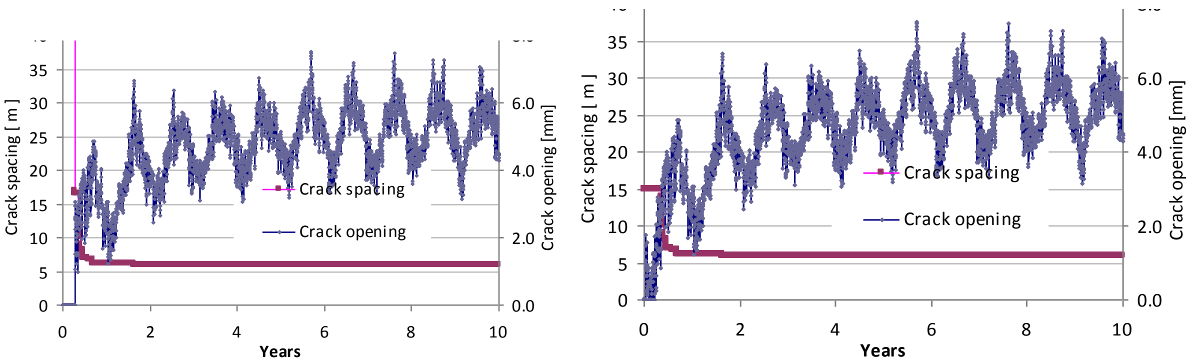

Fig.7 Illustration of model output: crack spacing and opening (left: no pre-cracking, right: pre-cracking at 15m)

Fig.7 illustrates the program output for estimating crack opening and spacing for a period of 10 years. The crack movement is a result of temperature fluctuations. The figure on the right shows effect of pre-cracking, which resulted in a limited crack opening within the first year as compared to the case without pre-cracking. In reference to Fig.7 (right), the ultimate crack opening, which is in the range of 3 to 7 mm, is not effected by pre-cracking. This is because the initially introduced crack spacing of 15m via pre-cracking is larger than the ultimate crack spacing, which the model predicts it to be about 6m.
To provide additional illustration, if one keeps all parameters the same but changes the traffic stress parameter a_3 which was estimated using an assumption that $\sigma_{traff}(@28days) = 0.5 f_c(@28days)$, to a different assumption with $\sigma_{traff}(@28days) = 0.01 f_c(@28days)$ thereby decreasing the traffic stress, the result in Fig.(8) is obtained.

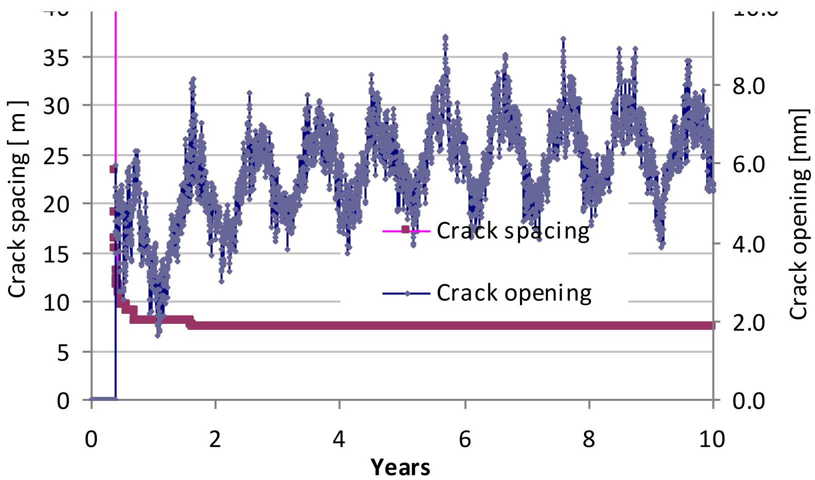

Fig.8 Effects of decreasing the traffic stress on crack spacing and opening

In fig.8 larger crack spacing (about 7.5m) is obtained in comparison to the 6m spacing obtained from Fig.7. This is a result of a decrease in traffic stress, which leads to an increase in the available material strength, and hence larger crack spacing. Associated with the larger crack spacing, the crack opening has also increased.

4. Conclusions and Recommendations

The development of a simplified practical tool for predicting the crack spacing and opening of cement bound layers is discussed in this paper. For crack initiation, the governing factor is taken as the ultimate stress state within the material. Crack initiation moment is defined as the moment at which the ultimate stress exceeds the available tensile strength of the material.

In developing the model, first numerical relations were derived that relate the state of stress at the bottom of the CTB layer with the layer geometry. Relations were also obtained relating the state of stress with the crack opening. The restraining interfacial friction force between the bottom of the CTB layer and the bottom layer is modeled as a cohesive layer. To simulate practical temperature loads, yearly temperature data was obtained from the Dutch KNMI website. For the material properties, available relations were adopted from literatures. The parameters for the material properties can be modified to suit relevant material cases. The numerically derived relations were then used together with the material properties and temperature loads for estimating the moment of crack formation, spacing and crack opening.

The tool requires the user to input material parameters, layer thickness, pre-cracking width if applicable, and planned traffic opening date. The program then uses the daily temperature database to automatically compute the temperature fluctuations and ultimately predicts the crack spacing and opening. This simplified tool can be used to asses cracking behavior of a cement bound road base. it can also be useful in assessing the effects pavement geometry and material parameters on the cracking behavior of the CTB layers.

While the tool is convenient in making practical assessments, it is developed based on available data for a certain material. For obtaining better results, it is recommended to adopt relevant material property relationships developed based on laboratory-field testing results. Such adjustments can be conveniently incorporated in the tool.

References

1. H. Pieterse, (2012). AGRAC, Praktijkervaring A4 (Practical experience), Report, The Netherlands
2. M. Oosterveld (2012). Design Report Material Research for Sand cement, RWG-R-0.1.8-002, Utrecht, The Netherlands.