IMPLEMENTATION AND EVALUATION OF AN HMA FRACTURE MECHANICS BASED DESIGN MODULE

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PREFACE

The work presented in this licentiate thesis has been carried out between August 2008 and Mars 2010 at the division of Highway and railway engineering, school of architecture and the built environment, Royal institute of technology (KTH).

I would like express my sincere gratitude to my supervisors Prof. Björn Birgisson and Dr. Denis Jelagin for their guidance and support throughout the whole process of this work.

Messrs Måns Collin, Klas Hermelin and Tomas Winnerholt are acknowledged for bringing their insight, experience and ideas to the table.

I would also like to express my gratitude to SBUF, Skanska Sweden and Trafikverket for their financial support of this work. My colleagues at the department have my gratitude for providing a creative and friendly atmosphere.

Finally, I would like to thank my family for their love and support that made this work possible.

Stockholm in April 2011

David Gullberg

LIST OF APPENDED PAPERS

This dissertation contains an introduction to the subject, a Swedish summary of the present work and two appended papers:

Paper A *"Evaluation of a novel calibrated-mechanistic model to design against fracture under Swedish conditions"*

Submitted for publication

Paper B *"Evaluation of the predictive models used in the new Swedish mechanistic-empirical design module"*

Submitted for publication

ABSTRACT

A thickness design module for flexible pavements, based on the HMA fracture mechanics framework, has been developed in order to design against premature failure caused by cracking. The HMA fracture mechanics based design module has been evaluated by designing typical Swedish pavements under typical Swedish climate and loading conditions and comparing the results with a reference design framework. The integrated set of material models predicting the necessary material strength- and creep compliance parameters for crack resistance evaluation within this framework has been evaluated against a number of field cores tested.

Results show that the design module developed is able to accurately predict cracking in Swedish flexible pavements, indicating that the principles behind the design procedure are fundamental and that the material models used are able to make qualitative predictions of the individual material properties used to estimates a mixtures' resistance to cracking.

SAMMANFATTNING

Denna avhandling beskriver implementering och verifiering av en dimensioneringsmodell baserad på ”HMA fracture mechanics” som först utvecklats vid University of Florida av bland annat Birgisson, m.fl. (2006), Roque, m.fl. (2004) och Zhang, m.fl. (2001). Ramverket bygger på att icke läkningsbara sprickor initieras om den upplösta kryptöjningsenergin i en asfaltbeläggning överstiger ett gränsvärde som är unikt för varje asfaltblandning. Dimensioneringsprocessen syftar till att kvantifiera detta gränsvärde och sedan jämföra detta med ett lägstavärde för detta gränsvärde som identifierats av Roque m.fl. (2004) genom prövning av provkroppar tagna i fält.

Som en del i utvärderingsarbetet av detta dimensioneringsverktyg har också de materialmodeller som ingår utvärderats mot fältprovkroppar med avseende på de egenskaper (draghållsfasthet och krypppotenslagsparametrar) som används för att uppskatta energigränsvärdet.

Resultaten visar att den implementerade dimensioneringsprocessen är kapabel att göra korrekta beräkningar av den beläggningstjocklek som krävs för att undvika sprickbildning, vilket har verifierats jämte dimensioneringsverktyget PMS Objekt (Djärf, m.fl., 1996; Vägverket, 2008) för 24 olika klimat- och trafikscenarion. Utvärderingen av materialmodellerna visar också att de uppskattningar av energigränsvärdet som görs utifrån materialets dynamiska styvhetsmoduls masterkurva ger en god överensstämmelse med faktiska uppmätta värden som presenterats av Roque, m.fl. (2004) och Roque & Zou (2010).

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CONTENT

INTRODUCTION

Load related top-down cracking, has recently been recognized as a major mode of premature pavement failure by a number of researchers such as Matsuno & Nishizawa (1992), Jacobs (1995), Myers (2000), Uhlmeyer, et al. (2000), Myers et, al. (2001) and Wang et al. (2003). As this mode of failure is not captured by traditional empirical or mechanistic-empirical design procedures, the HMA fracture mechanics framework – with an energy-based top-down cracking criteria – was developed in order to make design against this type of failure possible (Roque, et al., 2004).

The scope of this work is to implement and verify a pavement design module based on the HMA fracture mechanics framework. The accuracy of this model has been verified against the Swedish mechanistic empirical design software PMS Objekt (Djärf, et al., 1996; Vägverket, 2008) and the modelling of the material properties used in the design framework has been evaluated against 14 field sections previously tested by Roque, et al. (2004) and Roque & Zou (2010).

In the verification of the energy-based thickness design one additional assumption from the original work has been made: The energy-based design procedure is able to predict the general cracking-resistance of a pavement, not only the resistance to top-down cracking. Thus has the verification of the implemented design framework been evaluated against a design procedure (PMS Object) calibrated to all types of cracking (Djärf, et al., 1996).

Results from the verification show that the design module, once it has been calibrated with respect to local construction variability and traffic conditions, is able to accurately perform thickness design also for Swedish climate- and loading conditions using typical Swedish construction materials. This indicates that the material properties that are used to predict a mixtures' resistance to cracking are fundamental and thus independent of the local conditions.

HMA FRACTURE MECHANICS

They key features of HMA fracture mechanics are:

- Damage in asphalt mixture is equal to the dissipated creep strain energy (DCSE)
- There exists a damage threshold (called DCSE threshold or DCSE limit) in asphalt mixture that is independent of loading model or loading history
- Damage under the cracking threshold is fully healable
- Once the damage (DCSE) exceeds the damage threshold (DCSE limit), a macro-crack will initiate, or propagate if a crack is already present
- A macro-crack is not healable.

This means that the initiation and propagation of cracks in asphalt mixtures can be determined for any loading condition by calculating the amount of dissipated creep strain energy (DCSE) and comparing this with the DCSE-threshold of a mixture.

THE ENERGY RATIO CONCEPT

Roque, et al. (2004) defined the energy ratio (ER) as the ratio between the minimum DCSE for a pavement to perform well in the field according to test-results (DCSE or $DCSE_{min}$) and the DCSE-limit (equation 1-3). For a mixture to perform well, and not experience premature cracking, this ratio has to be greater than the Optimum ER which is a target energy ratio based on traffic and reliability to account for field conditions. This concept is outlined in figure 1, while figure 2 illustrates how DCSE and $DCSE_L$ are estimated based on strength- and creep power law parameters:

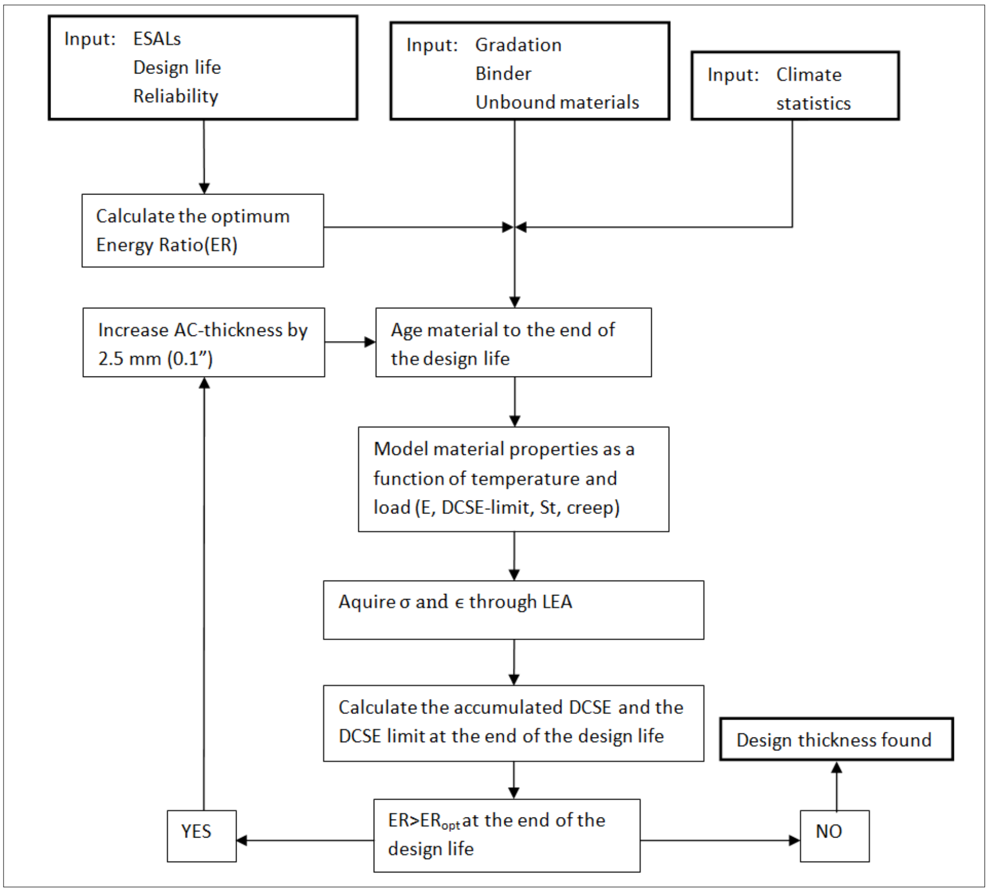

Figure 1. *Design framework based on energy ratio*

$$DCSE = \frac{m^{2.98} \times D_1}{f\left(S_t, \sigma_{\max}\right)}$$

$$f(S_t, \sigma_{\max}) = \frac{6.36 - S_t}{33.44 \times \sigma_{\max}^{3.1}} + 2.46 \times 10^{-8} \tag{1}$$

$$DCSE_L = 6.9 \times 10^7 \times \frac{S_t m D_1}{10^{3(m-1)}} \tag{2}$$

$$ER = \frac{DCSE_L}{DCSE} \tag{3}$$

Where *m and* D_1 are creep power law parameters, S_t is the tensile strength of the mixture and σ_{max} is the maximum tensile stress.

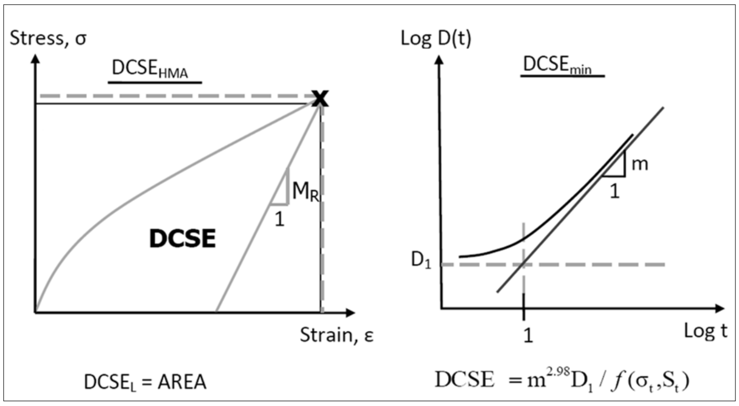

Figure 2. *DCSE and DCSE-limit* (Birgisson, et al., 2006)

SUMMARY OF APPENDED PAPERS

PAPER A

The scope of the work presented in this paper is to evaluate a new calibrated mechanistic (CM) pavement design module for its ability to predict pavement performance under Swedish load- and climate conditions. The analysis and design framework presented is an extension of the work made at the University of Florida by Zhang et al. (2001), Roque et al. (2004) and Birgisson, et al. (2006), where a pavement design framework was developed based on the principles of viscoelastic fracture mechanics. This approach allows for the prediction of crack initiation and crack growth in asphalt mixture subjected to any specified loading history.

To evaluate the module's ability to accurately perform pavement-design under different conditions two different mixtures, in three types of climates and subjected to four different traffic levels where designed. The results were compared to results produced by PMS Objekt - the current analytical model being used in Sweden. In order to make this comparison viable the conditions and mixes were selected to be well in range of the empirical data that's been used to calibrate PMS Objekt.

Results show that the designs thicknesses suggested by the HMA fracture mechanics based design module were almost identical to those suggested by the mechanistic-empirical model (PMS Objekt) for relevant Swedish conditions. This indicate that the design framework originally developed for mixtures used in Florida is indeed based on fundamental material properties and can be used in a large span of conditions once calibrated.

PAPER B

The necessary properties for HMA fracture mechanics based design (Roque, et al., 2004) can be quantified following five steps:

1. Determine mix-specific parameters and establish the dynamic modulus master curve
2. Calculate binder viscosity, η, at the temperature and age of interest in order to establish the shift factor
3. Using the relationship between dynamic modulus and creep compliance; calculate the power-law parameters D_0, D_1 and m
4. By utilizing the relationship between dynamic modulus in tension and tensile strength, determine the later
5. Using creep power law parameters and the tensile strength of the mixture, the $DCSE_L$ can be calculated. This is the mixture specific energy density threshold, under which micro damage is healable.

The goal of this paper is to evaluate the material models available to estimate the parameters needed in the HMA fracture mechanics based design framework shown in figure 1. This is done by comparing predicted material properties with actual, measured properties from fourteen pavement sections presented by Roque, et al. (2004) and Roque & Zou (2010).

Results from the evaluation show that the material models are able to predict the DCSE-threshold (limit) of the mixes which makes it possible to predict the crack-resistance of a pavement based on its composition (binder PG and gradation) and the mean annual air temperature at the location where it is intended to serve.

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