Summary

William G. Buttlar, Armelle Chabot

5 CHAPTER 5 - SUMMARY

Prepared by William Buttlar (1), Armelle Chabot (2)

(1) University of Missouri, USA

(2) IFSTTAR/MAST, France

Abstract

This chapter presents a summary of the key findings of this state-of-the-art report on the mechanisms of cracking and debonding in asphalt and composite pavements. Some of these keys have ben presented during the 8th Rilem International Conference on Mechanisms of cracking and Debonding in Pavements in Nantes (MCD2016). It also contains the key recommendations developed by the TG2 group, which produced a RILEM recommendation document as a culminating activity in the final year of the RILEM Technical Committee TC241-MCD. Remaining challenges in the area of asphalt and composite pavement cracking and debonding and recommendations for further study are then summarized.

5.1 INTRODUCTION

This chapter presents a summary of the key findings of this state-of-the-art report on the mechanisms of cracking and debonding in asphalt and composite pavements. Some of these keys have ben presented during the 8th Rilem International Conference on Mechanisms of cracking and Debonding in Pavements in Nantes (MCD2016) [1] and in the three supplementary issues that have been published thereafter [2-4]. It also contains the key recommendations developed by the TG2 group [5], which produced a RILEM recommendation document as a culminating activity in the final year of the RILEM Technical Committee TC241-MCD. Remaining challenges in the area of asphalt and composite pavement cracking and debonding and recommendations for further study are then summarized.

With the exception of permanent deformation (rutting), which appears to be well under control in highly developed countries, the primary challenges in the design and preservation of modern asphalt pavements relate to the prevention and control of various cracking modes. This includes thermal cracking, reflective cracking, block cracking, and fatigue cracking, which can emanate from the bottom, top, or interior of the bound asphalt layers in a flexible pavement system. Interface (partial or total) debonding and interface sliding behaviour are also important topics that need to be analysed in pavement cracking studies, as this form of deterioration can lead to subsequent tearing (slippage cracking) and/or accelerated fatigue cracking of the asphalt pavement surface.

Rutting and cracking are often thought to represent opposite sides of the spectrum in asphalt mixture design. A simple rule-of-thumb in asphalt mix design suggests that lower asphalt content mixtures produce less rutting but more cracking in asphalt mixtures, and vice-versa. Some pavement engineers describe this dichotomy in terms of a swinging pendulum, where the pendulum has currently swung in the direction of less rutting and more cracking. This may be a result of the focus in modern mix design methods to prevent rutting through more aggressive asphalt compactive effort in design (Superpave gyratory compactor usage, along with relatively high design gyration targets). In addition, some pavement engineers point to higher recycling rates and changes in binder supplies. For instance, modern refining techniques are squeezing more light ends out of asphalt, rendering it less ductile and/or leading to the heterogenization of the binder system through the blending of soft and hard binder components, the use of acids, rejuvenators, recycled engine oil bottoms, and/or other modifiers. These changes may alter the binder's ability to resist cracking and fatigue, to heal microdamage, and to bond with aggregates in the mixture or with other pavement layers. Moreover, the aforementioned rule-of-thumb misses a number of important considerations necessary for a more comprehensive flexible and composite pavement engineering approach, including: consideration of the role of the entire pavement structure (all layers and interfaces) in the development of cracking and debonding in the asphalt layers, the possibility for the development of highly crack and rut resistant surface materials (such as stone-mastic asphalt), and the intentional use of preventive maintenance as a strategy to achieve economical rut and crack resistant pavement system designs. To this end, the development of advanced tests and comprehensive models and field studies continue to be a pressing need in the pavement engineering community. These contemporary pavement cracking issues were the basis for the activities conducted under RILEM TC-241MCD, and have been addressed, at least in part, in this state-of-the-art report.

5.2 TC-241 MCD STAR DOCUMENT SUMMARY

The organization of a large group of researchers into teams to work on modern pavement cracking challenges can take one of several logical forms. In the precursor to RILEM TC241-MCD, the RILEM Cracking in Pavements (CAP) technical committee divided researchers into three teams, focused on field studies (CAP TG-01), testing (CAP TG-02), and modelling (CAP TG-03). RILEM TC241-MCD sought to re-shuffle research teams to invoke new synergies, by reorganizing technical committees into the categories of cracking in bulk materials (TG-01), cracking at pavement interfaces (TG-02), and advanced measurement techniques for cracking studies (TG-03), whereby each TG could consider contemporary tests, models, and field studies to reach their stated objectives. Common sets of field and lab data, and generalized modelling schemes, and researchers working across the various committees, served to connect the three technical committees in an integrated fashion.

5.1.1. Summary of STAR Chapter 1

As developed in TC-CAP, and summarized in this STAR (Chapter 1, section X), scientific progress in complex 'mechanistic-empirical' fields such as pavement engineering necessarily involve a cyclic progression of 'QVCV,' or Qualification, Verification, Calibration, and Validation. Chapter 1 of this STAR document provided background information on field observations and accelerated pavement testing (APT) campaigns, which were used by researchers in the test and model qualification process. In other words, the observed cracking patterns and their hypothesized driving mechanisms on modern pavements and APT facilities across the world served to define the requisite physics to be included in tests and models, and to be studied using advanced measurement techniques by TC241-MCD researchers in the three aforementioned technical committees.

Among the information presented in Chapter 1, the following key field and APT observations provided motivation for the development of better tests and models to understand and describe cracking mechanisms in modern pavement structures:

- Examination of more than a dozen French motorways over the past decade has highlighted the importance of layer debonding in the development of fatigue and reflective cracking within asphalt paving layers. Layer debonding was evident in pavement cores taken on these facilities and could also be detected through in-situ deflection testing, as indicated by higher pavement deflections and wider deflection basins as compared to pavements with well-bonded layers. Techniques for detecting debonding using ground penetrating radar have also shown promise.
- In the US, recent studies have recognized the need to better understand and predict thermal, block, and reflective cracking mechanisms via discrete fracture testing and modelling approaches, leading to fracture-mechanics inspired tests and models in the asphalt pavement research and practice communities. For instance, in a recent Pooled Fund study sponsored by ten states residing in colder climates in the US and the Federal Highway Administration, the disk-shaped compact tension test (DC(T)), which is now specified in ASTM D7313, and a cohesive zone fracture model were implemented in a thermal cracking specification, involving fracture energy requirements and an optional finite element based thermal cracking simulation model, called ILLI-TC.
- Field studies involving ultra-thin bonded wearing courses and stress absorbing membrane interlayers also highlighted the need to better understand the mechanics-related phenomena associated with pavement layer bonding and bond degradation, as conflicting viewpoints regarding proper tack coat (adhesive) materials and application rates and the relative contribution of pavement grinding/milling seem to prevail in the current literature.
- In accelerated pavement testing (APT) studies conducted in France, fatigue prediction models appear to provide reasonable estimates for fatigue life of asphalt pavements, but greatly under-predict the fatigue life of thicker asphalt pavements. This highlighted the need to develop better models for damage and crack initiation and propagation and to introduce a very thin bitumen interface layer or to include discontinuities such as vertical discontinuities or partial debonding between layers into pavement models. The findings also suggested limitations which need to be addressed in developing and interpreting future APT studies, such as differences between APT and actual pavement performance in terms of asphalt aging, healing, and climate. The studies also highlighted the need for improvements in sensors and other methods to collect data related to pavement cracking mechanisms in the field and on APT experiments.

- In reflective cracking APT studies in France carried out using the FABAC device, clear evidence of the role of interface debonding between Portland cement concrete (PCC) and asphalt layers was observed and modelled. A flow-chart type schema describing numerous manifestations of reflective crack development and propagation was developed as part of the study.
- In another APT cracking study carried out at IFSTTAR, geotextile grids were shown to significantly retard the rate of cracking in asphalt paving surfaces, and differences between layer bonding and subsequent cracking rates in asphalt overlays were reported when comparing the various grids investigated.
- Similarly, in an APT reflective cracking study conducted in the US, the role of debonding in the specific type of reflective cracking observed, and its rate of development, was studied. In additional, the phenomena of 'crack jumping' over single-layered stress absorbing membrane interlayer (SAMI) systems was described, and dual-layer SAMI systems were shown to be more effective in mitigating reflective cracking in asphalt overlays placed over PCC.
- An overarching strategy for the continued evolution of cracking tests and models was presented, termed the QVCV approach. Building on the V&V technique used in the experimental mechanics community, a 'Qualification, Verification, Calibration, and Validation,' or QCVC approach was introduced for use in the pavement mechanics community. In addition to model verification (checking vs. closed-form solutions) and validation (checking model efficacy vs. real-world cracking phenomena and/or cracking data outside of the calibration data set), the importance of model qualification (motivating/informing/refining models with field observations) and proper distinction between model calibration and validation is highlighted in the QVCV approach.

Following the motivation and test/model qualification information presented in Chapter 1, Chapters 2-4 of this state-of-the-art report described the recent and ongoing work of the three RILEM TC241-MCD technical groups. The major findings presented in these chapters are now summarized.

5.1.2. Summary of STAR Chapter II: Cracking in Asphalt Material

Chapter II contains a number of contributions from RILEM TC241-MCD, TG-01 members pertaining to tests and models developed to better understanding and characterize cracking within the asphalt 'bulk' material. In light of these contributions, continued research needs were identified. These include:

- A unified laboratory test and model that can characterize and capture the response of asphalt mixtures under all the modes that affect its properties (temperatures, loading rates, aging effect etc.) has been identified as an important research need by a number of groups. Although the present report demonstrates that the current state-of-the-art in characterization and modelling of asphalt bulk fracture is capable of capturing material response under wide-range of conditions, the present approaches are still incapable of capturing a sufficient combination of variables that affect the fracture behaviour in asphalt paving layers.
- The major scientific shortcomings in the field of fracture in bulk asphalt materials identified through this review include:

- o Limited ability of current models to capture both static and cyclic crack growth in a seamless, universal manner
- o Current models and tests still lack a complete fundamental understanding of the healing processes present in asphalt
- o Most laboratory tests and analysis procedures focus on the use of global specimen responses; more research is needed on the incorporation of local material responses from laboratory tests in models, such as those being measured in new, advanced asphalt cracking characterization techniques (Chapter 4)
- o The development of universal criteria from model qualification, verification, calibration and validation are still needed

5.1.3. Summary of STAR Chapter III: Interface Debonding Behavior

Chapter III contains contributions from RILEM TC241-MCD, TG-02 members pertaining to tests and models developed to better understand and characterize interface debonding behaviour in layered flexible and composite pavement systems. In light of these contributions, continuing research needs were identified. Members of the TG-02 group also developed and submitted formal recommendations to RILEM [5]. The group reported that, for further development of interlayer bond tests and models, it is crucial to improve the phenomenological understanding of the mechanisms and influencing parameters associated with interlayer bonding and bond deterioration. The recommendations of the TG-02 group included:

- Moisture /water effect infiltration through cracks and other pavement defects have a significant influence on the quality of interlayer bond. Moisture was found to reduce bond strength drastically. Its effect should be investigated in more detail and moisture should be integrated in the standard methods and considered in pavement design tools.
- Improved phenomenological understanding of the mechanisms associated with interlayer debonding in terms of the geometrical surface conditions of the interface are needed. Advanced contact interface constitutive models, finite element modeling to directly consider local interface topology, as well as roughness measurements at the interface should be further developed. Improved, simplified models should then be developed and introduced into standard pavement design tools.
- The size of test specimens bears great influence on the outcome of interlayer bond tests. As demonstrated by an interlaboratory test program initiated by RILEM, specimens with larger diameters were found to achieve higher bond values compared to specimens with smaller diameters. Further, it was demonstrated that larger the nominal maximum aggregate size mixtures require larger test specimens, when testing pavements with reinforcing interlayers). In some larger test assemblies, the dead weight contribution of the specimen might have to be taken into account to properly interpret results.
- Temperature effects on bond behaviour should be studied in more detail. For instance, on one hand shear bond strength decreases with increasing temperature, while on the other hand, increased temperatures may positively affect self- and traffic-induced healing effects. It was further observed that interlayer bond defects or weaknesses seem to appear more obvious when testing is performed at very low temperatures, such as -20°C.

- There is a need to conduct cyclic and static round robin tests to compare the outcome of different devices and methods in more detail and to develop harmonized testing procedures and requirements.
- There is a need to focus more on comparing laboratory results with in situ measurements and observations, as significant differences exist between laboratory results and field performance have been identified. Such comparisons will likely lead to adjustments and improvements in laboratory bond tests and specification requirements. For instance, the technique of testing actual field specimens and comparison to full-scale accelerated loading experiments have been shown to be effective in improving the understanding of debonding mechanisms and in the improved interpretation of laboratory test data.
- There is a need to develop energy-based approaches for modelling interface damage, with the goal of quantifying damage evolution during bond tests. The introduction of rest periods during cyclic testing can be performed to assess the healing mechanism.
- The importance of testing a sufficient number of test specimens, which depends on the test method used and the applied testing conditions (i.e., static vs. cyclic), was identified.
- There is a need to implement advanced measurement systems in the study of pavement debonding, such as:
    - NDT (Non-destructive testing) in field experiments;
    - Advanced sensors for the measurement of in-situ interface behaviour under traffic loading, and'
    - DIC (Digital image correlation) techniques for advanced interpretation of laboratory interface debonding tests.

Building on this identified scientific lack, other future research topics were identified by TG-02, including:

- Advances in mechanical modelling, such as debonding energy and surface temperature gradient, should be developed.
- As observed in the construction process, less-than-ideal moisture and dust/debris conditions existing prior to asphalt layer placement and more exact pavement texture information should be included as parameters in advanced debonding models.
- Further investigation on different tack coat types, a wider range of application rates, and different HMA mixtures under different temperature and moisture conditions and different modes of failure including mode I, mode II and mixed mode is recommended.
- Data coming from interface bonding tests should also be utilized in numerically-based pavement simulation models, in order to gain additional insight towards the mechanisms of interface debonding and its prevention.
- Further research should consider predicting results for interlayer bond problems using Artificial Neural Network (ANN) modelling, utilizing combined data sets from laboratories and field installations worldwide.

5.1.4. Summary of STAR Chapter IV: Advanced Measurement Techniques

Chapter IV contains a number of contributions from RILEM TC241-MCD, TG-03 members pertaining to advanced measurements techniques for asphalt cracking studies. This included many emerging techniques that are new (or relatively new) to the pavement engineering community, such as: digital image correlation (DIC) [6], optical strain measurement systems, X-ray computed tomography + tension/compression testing systems, deflection devices and analysis of stress wave propagation, radar analysis, imaging of dieletric contrasts through electromagnetic waves, acoustic emissions (AE) based tests, and passive and active seismic NDT testing.

In light of these contributions, continued research needs were identified. These include:

- Continued development of advanced, in-situ tests, possibly combining two or more of the new advanced measurement techniques reviewed herein.
- Further development of acoustic emissions techniques, which provide considerable new insight towards the microcracking behaviour in modern, heterogeneous paving materials.
- Improvements in x-ray CT techniques, particularly in terms of scanning speed, so that more useful 3D cracking process zone development and crack propagation information can be obtained.
- Common to virtually all emerging, advanced measurement systems is the need for continued calibration, validation and standardization of the techniques.
- The reviewed techniques lend themselves nicely to implementation in intelligent infrastructure and smart city systems, but integration into these systems is an open research topic.

5.3 ASSESSMENT OF RESEARCH NEEDS

As summarized in the previous section, significant progress has been made over the past decade in understanding and characterizing the mechanisms of cracking and debonding in asphalt pavement systems. That notwithstanding, significant challenges still remain in the quest for a deeper understanding of these mechanisms, leading to better tests, better specifications, and better asphalt durability. Many of the remaining challenges, which are summarized below, are driven by the complexity of asphalt concrete and composite pavements, the stochastic nature of material, traffic and environment, the scarcity and expense associated with detailed field data, and the challenges associated with measuring and imaging cracking mechanisms in asphalt concrete. Some of the key remaining *research needs*, as outlined and/or informed by this compilation of recent works and as identified by RILEM TC-241 MCD members include:

- More resolute and less costly approaches for 3-D microstructural imaging of asphalt materials, particularly to capture crack various cracking stages and mechanisms (nucleation, initiation, propagation, fracture process zone behavior, etc.)
- More accurate and efficient micromechanical simulations of cracking in asphalt
- Advancing mixed-mode crack tests and models
- Advancing interface crack measurements and models
- Transfer of developed technologies into practical tests and specifications
- Better and more accessible field data, which is required for test and model development and validation

- Cracking evaluation of sustainable asphalt materials

At the time of this writing, the aforementioned research needs were being discussed and prioritized by RILEM TC 241-MCD members. These recommendations can be used to form a work plan for a new Technical Committee, which can serve to help advance the state-of-the-art in understanding, testing, and designing crack-resistant asphalt pavement materials and systems through collaboration across the international pavement engineering community.

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