PRACTICAL APPROACHES TO CONTINUUM DAMAGE FATIGUE ANALYSIS

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INTRODUCTION

The Federal Highway Administration (FHWA) has been funding the development of several classes of models that help us understand and characterize asphalt materials: binder, mastic, fine aggregate matrix phase, and full mixture. One category of models being developed is the continuum damage model (CDM). Presently, at least three approaches have been developed by researchers who are now part of the Asphalt Research Consortium (ARC). These approaches share a common general approach to continuum damage analysis and are based on simple, efficient tests. These methodologies are referenced in the refereed literature. They are now ready for a side by side evaluation to demonstrate their relative attributes. With this in mind, this White Paper presents a short description of simplified continuum damage fatigue analysis. In addition this White Paper proposes a workshop to further acquaint practitioners with these fatigue testing and analysis approaches.

BACKGROUND

Continuum damage theory (CDT) was first developed by Janus Murzewski in 1957. Murzewski originally developed the theory as a way to describe the probabilistic degradation of cohesion in a mechanical body. The theory was further developed and improved upon during 1960's by many well-known researchers, but really began to be a popular analysis method in the 1970's due to numerous and parallel international efforts. One area of research that utilized the emerging technique was that of Dr. Richard Schapery. He developed work potential theory based on continuum damage mechanics to explain the way solid rocket fuels behaved under tensile loading. Solid rocket fuels share some important characteristics with hot-mix asphalt (HMA)—they are both semisolid, visco-elastic materials that are sensitive to both loading time and temperature. Because of this similarity, work potential theory became the foundation for modern HMA continuum damage models. The application of work potential theory to modeling of HMA behavior was first attempted by the research team at NC State University and Texas A&M University, led by Richard Kim, Dallas Little, and Bob Lytton These researchers have shown with their research over the past 15 years that CDT does an excellent job of explaining how HMA materials and pavements behave during fatigue loading.

While the terminology used in CDT can in some cases be very different from what pavement engineers normally use and the mathematics used to explain CDT theory can also be challenging, it is not necessary to memorize the jargon and master advanced calculus in order to understand the basic concepts involved in CDT and to appreciate how it can be practically applied to pavement design and analysis. The purpose of this White Paper is to explain the basics of CDT in simple terms, and also to explain recent developments in the practical application of CDT that are likely to impact practicing engineers over the next 5 to 10 years. In addition, this document includes a summary of a proposed workshop which will describe basic CDT principles and demonstrate two approaches to CDT-based materials characterization and discuss their application to a common set of materials.

The first concept that needs to be understood when discussing CDT is damage. “Damage”, as it is used in CDT is an abstract term denoting changes that occur in the microstructure of a body. These changes ultimately result in a loss of the material’s ability to withstand deformation (that is, loss in material integrity). An easy way to consider the concept of damage is to imagine an HMA sample that has an initial modulus of 500,000 lb/in^2 and is loaded for 15,000 cycles after which it has a modulus of only 400,000 lb/in^2. In CDT, one would say that this HMA sample has undergone significant damage and that the effect of this damage is a loss of 20 % of its initial, undamaged modulus. The rate at which HMA accumulates damage depends on the temperature, the modulus of the HMA, the applied stress and strain, and a number of other factors. It’s important to understand that CDT cannot be applied to the growth of large cracks—it only applies to the initiation and growth of very small cracks and other forms of micro-damage. This isn’t as big a problem as it first might seem, since the goal in designing a pavement should be to avoid large cracks altogether. By applying CDT to materials testing and pavement design and analysis, we can potentially prevent the formation of visible cracks in a pavement for many years.

The general way of performing a continuum damage test is to load a cylindrical specimen and measure how its behavior changes compared to some ideal undamaged response. This can either be done using loading at a constant rate of strain or by cyclical loading. Constant rate of strain loading has the advantages of being relatively quick, maintaining a uniform state of stress and strain, generating a relatively small amount of data and simple data interpretation. Unfortunately, the load levels required to fail samples at fast-enough rates exceeds the limits of currently available Asphalt Mixture Performance Test (AMPT) devices. On the other hand, cyclical testing is relatively easy to perform on the AMPT (or similar equipment). Cyclical loading is usually done in full reversal (“push-pull”) just as in a fatigue test. Also as in a fatigue test, cyclical loading makes it possible to directly monitor the modulus of the specimen as it is damaged. There are a number of different approaches to characterizing damage behavior using cyclical loading, which vary in the number of tests used and conditions under which they are performed Whatever the formal test protocol is, the data is analyzed with the goal of generating a single function that uniquely and completely describes how that material responds to damage, that is, what the net effect is of some accumulated damage on the material modulus. When combined with the known undamaged modulus (|E*|), this damage function can be used to define the effect of any loading history on the material response—essential information when predicting the response of an actual pavement structure to real-world traffic loading.

Two other important concepts that must be understood when using CDT to explain the way pavements behave under fatigue loading are healing and damage tolerance. In the previous example, if we were to stop loading the specimen and allow it to rest for several hours, the damaged modulus would begin to slowly increase, approaching its original undamaged value. This is called healing. It occurs because asphalt cement—even at low temperatures—can slowly flow, so that microcracks and other forms of micro-damage can at least partially heal over time. The rate of healing will depend on the asphalt binder used in a mixture, and also on time and temperature. Since the damage in work potential theory is defined as any microstructural changes in a material, healing can be considered as the damage that is beneficial to the material's cracking performance. Richard Kim and associates at NCSU have successfully used work potential theory to model the healing behavior of HMA. Recently, researchers in the ARC project at Texas A&M and the University of Texas at Austin have developed another healing model. These models explain that healing is the cumulative impact of very small healing events that occurs between each load cycle. The ARC healing model establishes that healing depends on the viscoelastic properties of the binder that impact the rate of crack closure during the rest periods, the surface and bond energy properties of the binder that impact the rate of nano and micro crack closure during rest periods and the morphology of asphalt binder functional groups that actually diffuse across nano and microcrack boundaries and re-establish crack integrity. This can have a huge impact on the net loss of modulus during fatigue loading, the actual fatigue life of an HMA mixture, and that mixture's "endurance limit".

When an HMA specimen is loaded for a long enough period of time, eventually large cracks will occur and begin to propagate. This is sometimes called "localization." The ability of an HMA mix to withstand damage without the formation of large cracks has been called damage tolerance. This is an important practical property of HMA, since the appearance of large cracks in an HMA pavement clearly represent one form of failure. The point at which large cracks begin to occur under cyclic loading varies from mix to mix, and like most other aspects of HMA behavior depends on temperature, frequency of loading and several other factors. In general, as temperature decreases and an HMA mixture stiffens its damage tolerance will decrease.

It is enlightening to consider how damage accumulation, healing and damage tolerance must all be considered when predicting the fatigue behavior of HMA pavements. It has been known for years that in laboratory fatigue tests the rate of accumulation of damage in HMA mixes increases with increasing temperature. However, in real pavements fatigue damage appears to be most severe at intermediate temperatures. Healing and damage tolerance explain this discrepancy. Although pavements will accumulate damage more quickly at higher temperatures, healing also occurs more quickly at higher temperatures, and so the overall rate of damage might actually decrease with increasing temperature in a real pavement subjected to intermittent traffic loading. Furthermore, because the damage tolerance of HMA is higher at higher temperatures, a pavement will be less likely to form large cracks at higher temperatures. Therefore, the net accumulation of damage in a pavement, and the likelihood that large cracks will form and propagate increase with decreasing temperature. However, at very low temperatures the pavement is so stiff that the strains under loading become very small, and the rate of damage accumulation becomes very small. Therefore, the critical temperatures for fatigue damage are typically intermediate temperatures, 10° to 20°C.

Our understanding of CDT and how to apply it in practical ways to HMA pavement design and analysis has improved dramatically over the past 10 years. The technology can now be applied by engineers in HMA testing with substantially less effort than traditional flexural fatigue. In fact, CDT testing can provide much more information than flexural fatigue testing in a much shorter period of time. Along with simpler and more efficient CDT testing methods, several researchers have been working to develop practical pavement design and analysis software that incorporates CDT in predicting fatigue behavior. The sections below discuss three important recent developments in CDT: the concept of reduced cycles, the simplified viscoelastic continuum damage (S-VECD) approach, and the DMA analysis. Also recent improvements in CDT-based pavement design and analysis are discussed.

REDUCED CYCLES AND ENDURANCE LIMIT METHOD OF ANALYSIS

Traditionally, CDT damage functions—damage "master curves"—have been given by showing relative modulus as a function of the damage parameter "*S*." Recently, it has been found that fatigue damage can much more simply be expressed as a function of reduced loading cycles rather than *S*. Once fatigue data is collected at several strain levels and temperatures, a simple trial-and-error procedure is used to determine the value of the parameter α, which is the primary material constant characteristic of the rate of damage accumulation. This results in a fatigue master curve which shows damage as a function of reduced loading cycles. Using this master curve, the damage can be calculated for any set of conditions, given loading frequency, number of loading cycles, initial modulus, applied strain and temperature. The simplicity of this approach makes it relatively easy to implement CDT damage functions in existing software for pavement analysis and design. This technique also makes CDT testing and analysis easy to perform using standardized equipment and methods. The procedure is described in detail in the paper "Analysis of HMA Fatigue Data Using the Concepts of Reduced Loading Cycles and Endurance Limit," by Christensen and Bonaquist, to be published in the *Journal of the Association of Asphalt Paving Technologists*, Vol. 78, 2009.

SIMPLIFIED VECD MODEL AND ENDURANCE LIMIT

An alternative CDT method that also offers simplifying features is the Simplified Viscoelastic Continuum Damage (S-VECD) model. This model uses data from cyclic testing to develop the damage characteristic relationship. This approach retains the reliance on *S*, but greatly simplifies the characterization procedure using results from fatigue data generated at a single strain level and temperature. Details on this method can be found in the recently published report *Development of a Multiaxial Viscoelastoplastic Continuum Damage Model for Asphalt Mixtures*, FHWA-HRT-08-073, by Kim, Guddati, Underwood, Yun, Subramanian and Savadatti. Analysis and characterization can be performed very quickly using an Excel spreadsheet. Although an exact physical interpretation of *S* is not yet available, the theoretical generality afforded by this approach is significant. By including the more theoretically founded CDT as a basis, the S-VECD model is mechanistically rigorous and the damage function characterized within its framework can be used for determining the material effects of frequency, temperature, strain amplitude, modulus, mode-of-loading, endurance limit, etc. as well as directly included for general pavement analysis applications, as discussed in the paper "Response and Fatigue Performance Modeling of ALF Pavements Using 3-D Finite Element Analysis and a Simplified Viscoelastic Continuum Damage Model," by Underwood, Kim, Guddati, Thirunavukkarasu, Savadatti, to be published in the *Journal of the Association of Asphalt Paving Technologists*, Vol. 78, 2009.

SIMPLE TESTING IN TORSIONAL MODE – DYNAMIC MECHANICAL ANALYSIS (DMA)

In addition to CDT for full scale asphalt mixtures, Yong-Rak Kim et al. (2006) identified a simple method for applying continuum damage analysis to torsional testing of small cylindrical samples using dynamic mechanical analysis (DMA). The DMA samples are comprised of the binder, the fine aggregate component smaller than about 1.2 mm, and the mineral filler. The DMA samples are first subjected to low strain level testing to provide base-line linear viscoelastic properties and then subjected to higher strain or stress level to damage the samples, and the progression of damage is then charted with loading cycles to monitor the decay of shear modulus, G*, versus number of loading cycles.

While the DMA testing is limited to specimens comprised of the fine aggregate matrix (FAM), advantages include:
(1) a single Superpave Gyratory Compactor (SGC) sample can provide the basis for obtaining through coring at least 25, 50 mm-length by 12 mm-diameter cylindrical samples for testing;
(2) The ends of the SGC sample is cut to produce DMA samples of uniform void content;
(3) The uniform void content throughout the sample translates to lower variability among samples and the ability to make strong statistical inferences;
(5) DMA testing can be performed following and effective and efficient moisture saturation of the sample to investigate the impact of moisture on the fatigue life.

Table 1 summarizes the similarities and differences among the three methods presented above.

PRACTICAL USE OF CD IN PAVEMENT DESIGN

CDT can be used in two approaches in the analysis of fatigue resistance of asphalt pavements. The first approach is intended to use the laboratory results to directly rank the performance of asphalt mixtures in a given pavement structure. It is emphasized that the factors used to conduct a laboratory fatigue experiment should be selected based on knowledge of the pavement structure in which they will be used. It is well known the fatigue resistance of asphalt mixtures depends on the pavement structural design. For example, a mixture that can have good fatigue resistance in a thick pavement (5 inches thick or greater) may have poor resistance in a thin pavement (3 inches thick or less). This happens because the pavement structure and the stiffness of the asphalt layer affect the magnitudes of stresses and strains that the asphalt layer experience in the pavement. Therefore, the laboratory evaluation method should consider the pavement structure in which an asphalt mixture will be used. There are two questions that have to be answered first in order to conduct a laboratory test for evaluation of fatigue resistance: (1) should the test be conducted in a controlled-stress or a controlled-strain mode, and (2) what are the stress or strain magnitudes at which the test should be conducted?

Table 1. Comparison of Three CDT Based Methods

Feature	Description of Feature for Each of Three Methods		
	Reduced Cycles	S-VECD	DMA
CDT Characterization Test	4 strain-controlled cyclic tests at 2 temperatures x 2 strain levels	1 frequency-temperature sweep dynamic modulus test and 1 controlled crosshead cyclic test at 1 temperature and 1 strain level	Strain-controlled or Stress-controlled
Material Tested	HMA	HMA	Sand asphalt
Total No. of Samples	4 tests total: 2 temperatures x 2 strain levels	6 specimens	4 tests total: 2 temperatures x 2 strain levels
Sample Geometry	Cylindrical, 150 mm high by 100 mm dia.	Cylindrical, 150 mm high by 100 mm dia.	Cylindrical, 50 mm high by 12 mm dia.
Testing Machine	AMPT or similar servo-hydraulic system	AMPT or similar servo-hydraulic system	Dynamic mechanical analyzer or similar rheometers
Analysis Software	Spreadsheet	Spreadsheet	Spreadsheet
Material Coefficients	α, T_g; k_1, k_2, describing damage function	Prony coefficients and a, b describing damage function	Coefficients for reduced cycles or S-VECD method
Outcomes	Complete characterization of damage in HMA under fatigue loading over wide range of temperature, strain and loading frequencies; endurance limit values	Complete characterization of damage in HMA under fatigue loading over wide range of temperature, strain and loading frequencies, including prediction of N_f vs. tensile strain relationship and endurance limit	Simple, economical and complete characterization of damage in sand asphalt under fatigue loading over wide range of temperature, strain and loading frequencies.
Agency/Contractor Application	Evaluation of HMA fatigue resistance, pavement analysis and design, forensics, research	N_f vs. tensile strain relationship; Endurance limit as a function of temperature and frequency; Cracking performance prediction of asphalt pavement using VECD-FEP++; Material selection; Performance-based mixture design; New materials development; Performance-Related Specification; Mechanistic pavement design	Evaluation of local materials (binders and aggregates) for fatigue damage, healing, aging, and moisture damage; Screening of materials; A simple specification test for resistance to fatigue damage.

Comment [YRK1]: We need to agree on the contents of this table and then it needs to be filled by AAT, TAMU, and NCSU.

Comment [YRK2]: I changed the row heading to make it clearer. Can you fill up the number of samples you need for your test?

Comment [YRK3]: I just put here the same amount of testing as the case with reduced cycles, because I believe DMA needs less amount of testing anyway. However, this depends on the purpose and scope of the work. We will get at least 20-25 specimens from one SGC puck, so a lot of things can be done.

As for the first question, it has been shown by many researchers that the stress-controlled test is more suitable when an asphalt mixture is used in a thick pavement, while strain controlled test is more suitable when the asphalt mixture will be used in a thin pavement. The mechanistic nature of the CDT approaches allows the prediction of HMA fatigue performance under both modes of loading from a single mode of loading and therefore reduces the testing requirements significantly. As for the second question—the magnitude of stresses or strains to be used in testing—the mechanistic nature of CDT allows the fatigue performance prediction of HMAs under a wide range of strains and stresses from a much simpler test protocol (e.g., a cyclic fatigue test at one strain level). These two characteristics of CDT make the required test protocol for the calibration of the CDT-based model simpler than those for traditional, empirical approaches.

The second approach for the use of CDT is mechanistic pavement analysis. The mechanistic basis of the CDT approaches makes it easier to implement the damage functions in pavement structural analysis programs for pavement analysis and design in a rigorous way. For example, the NCSU and TAMU have successfully integrated the CDT model into a finite element program. These programs allow the accurate evaluation of effects of boundary condition (e.g., layer thicknesses), mixture properties, and temperature changes on the pavement performance. It is not necessary to assume *a priori* the location of distress initiation, nor the path of distress evolution. Not having to make such assumptions is a feature of these CDT-based pavement analysis programs that is essential in evaluating complex pavement structures, such as perpetual pavements. The flexible nature of the CDT-based pavement analysis programs allows cracks to initiate and propagate wherever the fundamental material law suggests. As a result, much more realistic and accurate cracking simulation can be accomplished using these programs. Ongoing research at NCSU and TAMU focuses on improving these programs to include the prediction of permanent deformation, moisture damage, healing, aging, nonlinear base and subgrade, and layer interface condition.

THE FUTURE OF HMA FATIGUE TESTING AND ANALYSIS

CDT provides an opportunity for efficient and accurate approach to testing, analyzing and predicting the fatigue behavior of HMA mixtures and pavements. Practical, standardized test methods that can be performed on reasonably priced commercially available test equipment have already been developed and are being used by a limited number of testing laboratories. It is now feasible to input CDT based damage functions into existing linear viscoelastic (LVE) pavement design methods. More advanced pavement design software is being developed that includes not only CDT damage functions, but models for healing and damage tolerance. Pavement engineers interested in both materials testing and pavement design and analysis should learn more about CDT—it is likely to become the most common method of fatigue testing and pavement modeling in the next five to ten years. The material characterization program for the CDT-based models is greatly simplified and reduced from conventional fatigue test protocols due to their mechanistic nature. The reduced testing program with more accurate characterization of the material behavior will benefit taxpayers by providing longer lasting pavements at a lower cost. For the same reason, CDT-based testing and pavement design and analysis will benefit contractors involved in building warranteed pavements. CDT might eventually lead to effective performance-based specifications for fatigue resistance in both asphalt binders and HMA mixtures, by providing a better basic understanding of the fundamental mechanisms involved in fatigue and crack initiation in these materials.

CONTINUUM DAMAGE APPROACH EVALUATION

To highlight the differences and capabilities of the Reduced Cycle, S-VECD and DMA continuum damage modeling approaches, a series of experiments is planned. A total of three different mixtures, each exhibiting different fatigue behaviors will be tested and analyzed by several laboratories using different CDT-based approaches. These materials will be selected based in part from pavement sections with sufficient material, and either known or soon to be known performance. The experiments performed on each material are shown in table 2. A total of 450 kg (1,000 lb) of each material will be needed to complete the testing as currently planned.

Based on experience at NCSU, 100 mm diameter by 150 mm height samples will produce negligible end effects so it is proposed that all testing be conducted on 100 mm diameter by 150 mm tall samples cored and cut from standard gyratory specimens. However, the gauge length for these specimens should be the standard AMPT length of 70 mm. This plan allows the use of some tests for the dual purpose of characterization using both the Reduced Cycle and S-VECD approaches. One issue that will need to be addressed before embarking on this study is whether the S-VECD approach can effectively use the AMPT $|E^*|$ protocol. It is likely that the AMPT $|E^*|$ protocol will yield enough information for the purposes of this comparison, but some analytical study is warranted. This proposed experimental program is based on the assumption that the AMPT protocol can indeed be used.

Table 2. CDT Experimental Program

Test	Temperature (°C)	Level	Replicates	Purpose
Linear viscoelastic (LVE) modulus, |E*|	3 to 4, typically ranging from 5 to 35°C	In linear strain range, typically 75 to 150 × 10^{-6}	3	LVE Characterization
Controlled Strain (actuator) Fatigue	10	L[1]	3	Reduced Cycle and DMA Characterization
	10	H[2]	3	Reduced Cycle and DMA Characterization
	20	L[1]	3	Reduced Cycle, S-VECD and DMA Characterization
	20	H[2]	3	Reduced Cycle, S-VECD and DMA Characterization
Controlled Stress Fatigue	15	M[3]	3	Reduced Cycle and S-VECD Verification

[1] Low strain level chosen to yield N_f of approximately 1000 cycles

[2] High strain level chosen to yield N_f of approximately 10000 cycles

[3] Moderate stress level chosen to yield N_f of approximately 5000 cycles

Tests will consist of |*E**| at temperatures commensurate with the AMPT protocol, controlled strain (actuator) fatigue tests and controlled stress tests. The controlled actuator tests will be conducted at two different temperatures, 10° and 20°C, at two different strain levels, and with three replicates (total of six specimens). The results from all of the fatigue tests will be combined with the |*E**| data to characterize the Reduced Cycle. The results from only the 20°C tests will be used or characterizing the S-VECD. When characterized, the CDT approaches will be used to rank and predict the response of the materials as if they were subjected to pure controlled strain input conditions. As a verification study the models will also be used to predict and rank the behavior of the controlled stress tests, which will be conducted in push-pull mode at 15°C. Finally, to investigate the ability of both CDT approaches to capture the effects of material aging one of the mixtures will be chosen and characterization tests only will be performed on oven aged samples. The aging conditions will be consistent with AASHTO R30.

CONTINUUM DAMAGE WORKSHOP

The purpose of the proposed continuum damage workshop is to present in-depth practical information on the use of continuum damage methods to characterize the fatigue behavior of HMA mixes, and how this information is then used in pavement design and analysis. A second purpose is to present and compare several different approaches to CDT-based fatigue testing and analysis and how the results can be used in solving practical problems in pavement engineering. The intended audience is practicing pavement engineers who are interested in CDT and want to learn more about it without dealing in calculus and other advanced mathematics. The workshop will include an introductory presentation on the history of CDT and its application to HMA mixtures and pavements. Another segment of the workshop will include a detailed discussion of practical CD fatigue testing using the AMPT (or similar devices) and analysis of the resulting data using the concepts of reduced cycles and endurance limit. This presentation will include detailed, step-by-step procedures for testing and data analysis, using data from actual HMA specimens.

NCSU has offered to host the workshop. This is particularly appropriate as Richard Kim has been one of the leaders in CDT for many years. He will present information on how CDT is incorporated into pavement design and analysis, and the benefits of using this approach compared to traditional methods of predicting fatigue behavior of flexible pavements. During the workshop a tour of their laboratory facility that will include demonstrations of continuum damage tests.

FEEDBACK REQUEST FROM FHWA ASPHALT EXPERT TASK GROUPS

Do you see the advantages of using the continuum damage approaches to obtain mixture fatigue results over beam testing?

- Do you feel that the proposed testing plan is appropriate?
    - If not, why not?
- Are there any material sources that you would recommend as appropriate for the experimental program?
- Is a workshop the best way to bring these techniques to practitioners?
    - If so, then whom should attend and at what venue?
    - Should it be just a comparison of results, or hands on analysis of experimental data?
    - Should all 3 approaches be addressed in the workshop?