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Double-edge-notched tension testing of asphalt mastics

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HIGHLIGHTS

- DENT testing of mastics is highly correlated with results for straight asphalt cement.
- CTOD is highly correlated with the displacement at failure in double-edge-notched tension.
- Essential work of failure is correlated with the specific work of failure for the 5 mm ligament.
- Ductile failure properties depend on filler type.
- Shift factors for failure master curves differ from those determined at low strain.

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ABSTRACT

Asphalt cements were tested in double-edge-notched tension geometries, straight and modified with different fillers at a range of rates and temperatures. Master curves for the essential works (w_e), plastic works (βw_p), and approximate critical crack tip opening displacements were compared. Results for mastics obtained with a single small ligament length were found to be highly correlated with those obtained through the essential work of failure analysis suggesting that under certain circumstances it may be possible to simplify the analysis. Significant rate and temperature effects were found with slower rates and higher temperatures being more discriminating.

1. Introduction

The double-edge-notched tension (DENT) test for asphalt was developed by our group nearly 15 years ago as a replacement for the Superpave® loss modulus, $G^*\sin\delta$ [1–3]. The loss modulus had shown to be lacking for the performance grading of asphalt binders in fatigue. As a rheological test, it disregards high strain properties that may play determining roles in pavement cracking.

The DENT test was designed in the ductile state, deliberately close to the ductile-to-brittle transition, so that discriminating yet reproducible results can be obtained. DENT tests can also be done on asphalt binders and mixtures under restraint while being cooled to failure [4,5], or in direct tension in either the ductile-to-brittle transition zone or in the brittle state [6]. If suppliers decide to use binders that are too stiff then they risk a descent into the ductile-to-brittle regime with less reproducibility and thus a higher risk of failing the acceptance criteria. In the ductile-to-brittle failure zone, ductile and brittle micro mechanisms occur simultaneously and test reproducibility is inherently lower (e.g., [7,8]).

The DENT test determines an essential work of failure (w_e), a plastic or non-essential work of failure term (βw_p), and an approximate critical crack tip opening displacement (CTOD), the latter of which provides a measure of strain tolerance. Higher values allow the pavement to flex more before failing and thus should increase fatigue life. So far only the CTOD has been used for specification

Abbreviations: CTOD, critical crack tip opening displacement; DENT, double-edge-notched tension; DTT, direct tension test; BBR, bending beam rheometer; FHWA ALF, Federal Highway Administration accelerated loading facility; MTO, Ministry of Transportation of Ontario; PAV, pressure aging vessel; REOB, recycled engine oil bottoms; RET, reactive elastomeric terpolymer; SB, styrene-butadiene type copolymer; PPA or P^{31}, polyphosphoric acid; PG, performance grade; WLF, Williams-Landel-Ferry equation.

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grading although it is recognized that w_e and βw_p could also have merit in future specifications.

The CTOD has been validated on many occasions. Table 1 provides the correlation results from the Federal Highway Administration accelerated loading facility (FHWA ALF) [9]. The study was designed for the validation of test methods for fatigue cracking. The findings show that the CTOD scored highest in terms of its ability to correlate with fatigue.

Additional validation of the DENT test has been conducted on numerous other occasions (e.g., see: [10–12]). A consistent finding has been that poor performing binders hold low CTODs while superior performers retain high strain tolerance. However, pavements under-designed for thermal stress can also show cracking irrespective of CTOD. Since 2012, minimum CTOD criteria have been included on Ontario contracts that specify modified asphalt binder for provincial highway construction.

The short-term objective of this research is to develop a more accurate DENT protocol and associated specification for asphalt mastics. Mastics can be pulled apart at various rates and temperatures in water which should provide an improved understanding of various types of cracking (fatigue, low temperature, adhesive, wet, etc.). A long-term goal is to see such tests widely implemented for specification testing on paving contracts.

2. Background

2.1. Ductility testing

Our efforts to develop the DENT test were inspired by the earliest work on ductility testing. Dow [13] originally conducted the testing by hand. He pulled binder specimens apart and found that those that flow well would be of satisfactory performance in service. Those that failed abruptly were associated with lesser performance.

Over the years a number of studies investigating refinements of the ductility test have been published. Doyle [14], Kandhal [15] and Van Gooswilligen [16] all proposed to do the test at lower temperatures in order to improve the reproducibility and allegedly the ability of the test to discriminate performance differences. Kandhal [15] studied ten experimental pavements and concluded that recovered binders with a ductility at 15.6 °C (60°F) of 5–8 cm started to ravel, 3–5 cm would start to crack, and less than 3 cm would be cracked severely. He concluded that tests at reduced temperatures produced more reproducible results.

2.2. Superpave direct tension test (DTT)

The researchers that developed the Superpave binder specification dismissed the ductility test because, in their opinion it was not conducted in the proper temperature range to control cracking, ductility was not a rational test and did not give engineering properties [17]. Instead, they focused their attention on the development of the direct tension test (DTT) to measure failure in the ductile-to-brittle transition regime [17,18]. In the ductile-to-brittle state testing is highly variable due to the inherent presence of both ductile and brittle domains. Numerous researchers have investigated ways of improving the reproducibility of the DTT without much success. What they may not have realized is that the variability is inherent to the material and has little to do with the way in which specimens are made or tested (e.g., [7,8]).

Table 1
FHWA ALF validation of fatigue grading tests.

Binder Test for Fatigue Cracking	Composite Score
Approximate CTOD	0.99
Binder Yield Energy	0.88
Time Sweep in DSR	0.88
Failure Strain in DTT	0.81
Superpave $G^*\sin\delta$	0.75
Large Strain Time Sweep	0.67
w_e	0.55
BBR m-value	0.54

Note: For details see Gibson et al. 2012 [9].

2.3. Essential work of failure testing

The original work on the development of the DENT test set out to provide a mechanistic framework for the asphalt ductility test according to ideas proposed by Broberg [19], and further developed for ductile failure in thin sheets by Cotterell and Reddel [20]. A detailed review of the essential work of failure analysis has been provided on prior occasions so here only the most pertinent information follows. When a DENT specimen is pulled apart the force does work that is dissipated inside the specimen as either heat or is used to create new surfaces. The area under the force-displacement curve provides a measure of toughness and this can be seen as comprised of two contributions:

$$W_t = W_{essential} + W_{plastic} \quad (1)$$

The total essential work of failure, W_e (J), is needed to produce new surface area whereas the total plastic or non-essential work, W_p (J), is dissipated as heat away from the failure zone [1–3,19,20]. The above relationship can be rewritten assuming that the essential work scales with the cross-sectional area of the ligament (specimen thickness time ligament length, BL) between the two notches and the plastic work scales with a volume surrounding the ligament:

$$W_t = w_e \times BL + \beta w_p \times BL^2 \quad (2)$$

where the w_e ($J.m^{-2}$) is the specific essential work of failure, βw_p is the specific plastic work ($J.m^{-3}$) and β is a constant that describes the shape of the plastic zone ($\pi/4$ for a cylinder). Rearranged this becomes:

$$w_t = W_t/BL = w_e + \beta w_p \times L \quad (3)$$

where the specific total work of failure as measured through the area under the force-displacement curve plotted versus the ligament length, L (m), provides a straight line with an intercept equal to the essential work of failure, w_e, and the slope equal to the plastic work term, βw_p.

The essential work of failure can be divided by the net section stress in the smallest ligament length (L = 5 mm) to provide an approximate measure of the CTOD:

$$CTOD \sim w_e/\sigma_{net,section} \quad (4)$$

where the net section stress is obtained from the average peak loads in the smallest ligament tests. The CTOD is sensitive to asphalt cement quality and rapidly degrades when undesirable additives are added (e.g., recycled engine oil bottoms (REOB), waxes, air blown residues, reclaimed asphalt). While the CTOD is much reduced from regular ductility, it remains high compared to the failure strains of thin fibers of asphalt binder as they would fail in between aggregate particles [21]. This is likely due to the fact that failure in service occurs at lower temperatures than the 15 °C that was settled on [21].