Streamlining the Double-Edge-Notched Tension Test for Asphalt

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Introduction

The DENT (Double-Edged-Notch Tension) test is a fracture test method used to simulate ductile failure and compare the strain tolerance of different asphalt binders. The currently accepted standard involves fabricating two beams from binder specimens with a 5-, 10-, or 15-mm ligament between two notches imitating cracks in the beam, then the load in the binder is measured as the sample is subjected to a constant displacement rate.

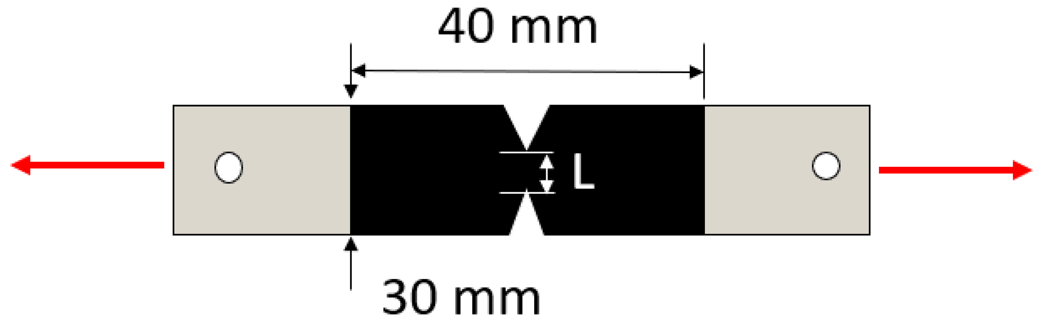

Fig. 1: DENT test specimen, where L is the ligament length

The raw data of Load and displacement was used to calculate various Parameters indicative of the binder's ability to resist such as the Crack Tip Opening Displacement (CTOD). Although this approach has shown to be a direct indicator of binder's strain tolerance, six tests are required to obtain CTOD following the current standard, which is time-consuming and expensive. Ideally, we could rank binder strain tolerance based on a few replicates using a single ligament length.

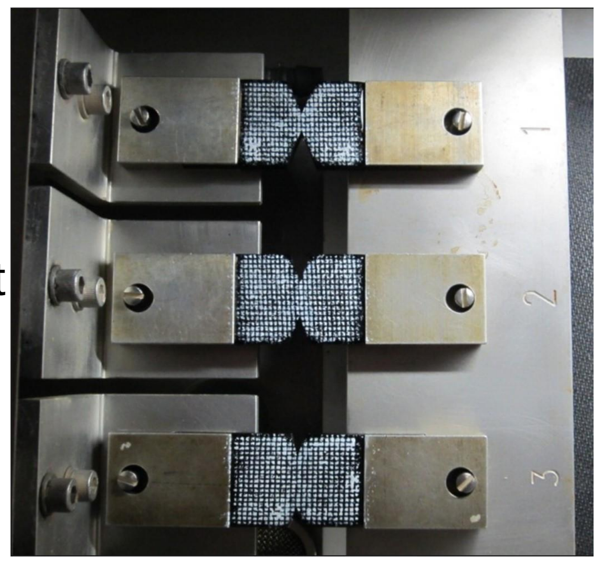

Fig. 2: DENT test with three ligament lengths

Motivation

The research team is investigating whether it is possible to reliably evaluate binder strain tolerance using fewer datasets, testing time, lower cost, and a smaller sample size. Effectively, we asked the question, "If less than three ligament lengths of an asphalt binder are tested using DENT, will the results be consistently accurate when compared with conclusions gathered from three lengths?".

Data Structure & Source

All calculations were performed using previously gathered DENT data from the Federal Highway Administration (FHWA) stored in 30 Excel spreadsheets. Each spreadsheet corresponded to one of thirty binders.

Data Analysis

My role was to write a program using R which would read each file to quickly perform relevant calculations for all iterations and store the results in plots and spreadsheets. Ultimately, it compared the various proposed testing and analysis approaches to evaluate binder strain tolerance (i.e., using one or two ligament lengths for calculation instead of three). Plots of individual parameters were generated using the "ggplot2" package, while plots of raw DENT data were done with base R. Individual parameters included the W_t (total work), the peak load, and the maximum displacement. W_e (essential work) and W_t are used to calculate CTOD. W_t was found as the area under the curve of the load-displacement Data for a particular ligament length, divided by its cross-sectional area.

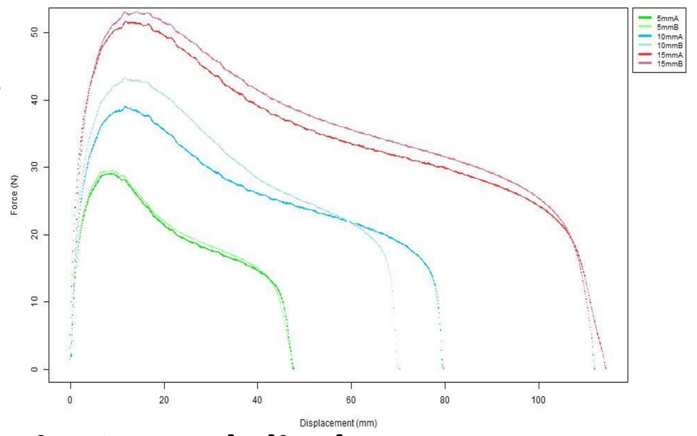

Fig. 3: Load-displacement curves.

To find W_e, the program calculated a best-fit line with L values on the horizontal axis and respective W_t values on the vertical axis for a particular binder, then generated a plot (fig. 4) With the corresponding equation. The Intercept constant from this equation is the essential work of fracture (W_e), see Eq. 1.

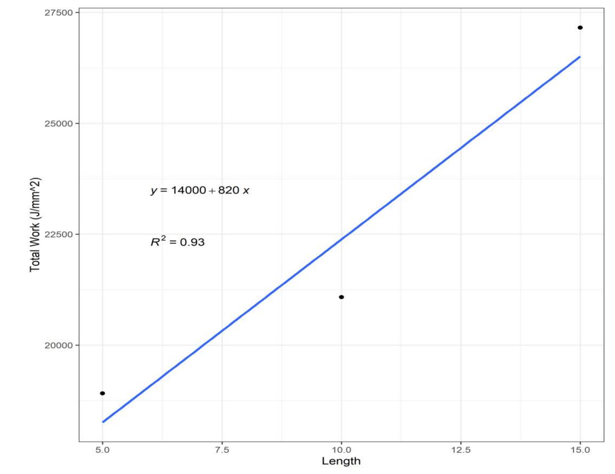

Fig. 4: Total work vs. ligament lengths regression.

$$W_t = W_e + \beta L W_p \quad \text{(Eq. 1)}$$

Where, $\beta L W_p$ is the Plastic work of fracture.

CTOD is determined from all three ligament lengths as in Eq. 2, then into a modified version for two lengths named "CTOD2P", or CTOD from 2 points (Eq. 3). Finally, a modified version of CTOD calculation from only a single length, "STI", or strain tolerance index (Eq. 4) is calculated. CTOD2P and STI averages between each replicate ("A" and "B") for all binders were analyzed using linear regression of the modified CTOD against their respective conventionally obtained CTOD following the standard method.

$$CTOD = \frac{W_e}{Peak\ Stress_{@L=5mm}} \quad \text{(Eq. 2)}$$

$$CTOD2P = \frac{W_e\ (From\ L=5{,}15mm\ only)}{Peak\ Stress_{@L=5mm}} \quad \text{(Eq. 3)}$$

$$STI = \frac{W_T(at\ L=10mm)}{Peak\ Stres_{@L=10mm}} \quad \text{(Eq. 4)}$$

Results

Upon obtaining conventional values of CTOD following the standard method, the CTOD2P, and STI averages for all binders, the binders were separated before plotting, with 5 binders randomly selected for the validation stage. The CTOD and modified values shown plotted against length in these results were generated as an average of each binder's two iterations.

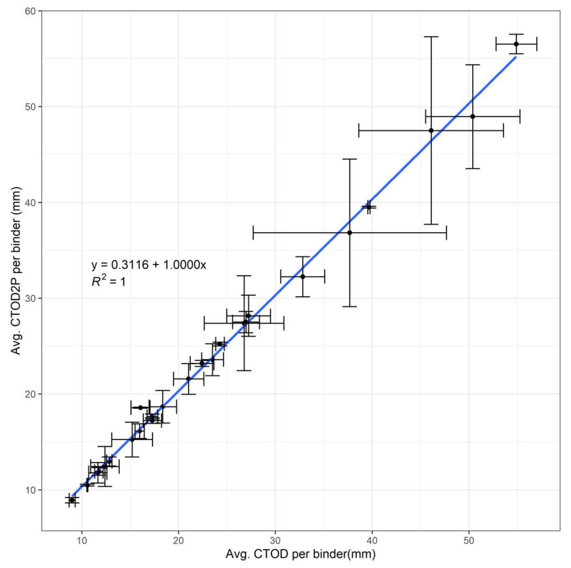

Fig. 5: Observed Avg. CTOD vs. Avg. CTOD2P with regression, R^2 value, and standard deviation.

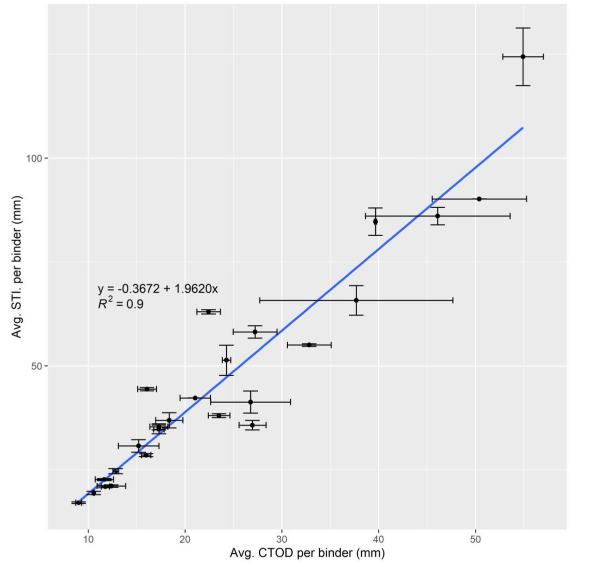

Fig. 6: Observed Avg. CTOD vs. Avg. STI with regression, R^2 value, and standard deviation.

As shown above, the training model's CTOD2P values produced an almost linear correlation with rigorously calculated CTOD values (0.99 R^2 value). The STI plot shows a similarly strong correlation (0.90 R^2), only differing by a skewed slope likely from the use of single-length peak load and total work values.

The standard deviation between the two iterations was used to generate error bars for each binder. As seen above, more binders had significantly large deviations where CTOD was above ~0.35. STI, generated from a single ligament length displayed smaller standard deviations, standard error, and coefficient of variance.

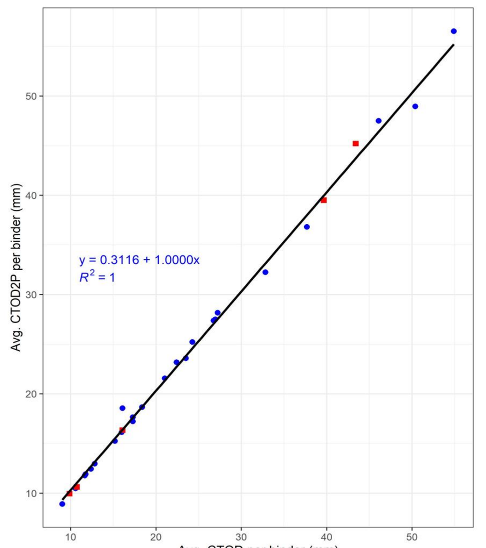

Fig. 7: Validation dataset overlaid on the training dataset for CTOD and CTOD2P.

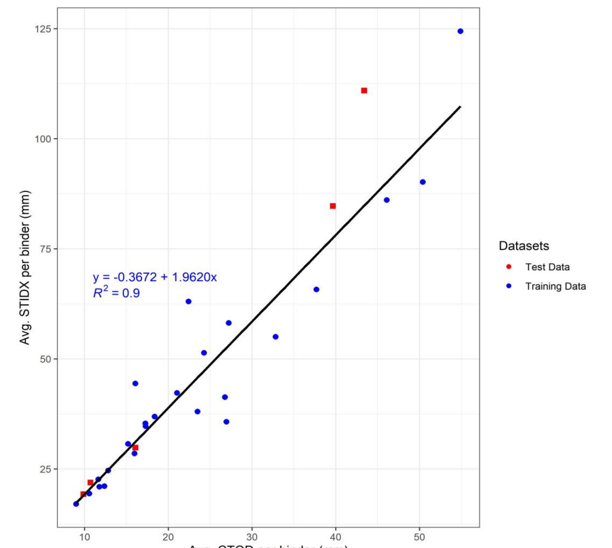

Fig. 8: Validation dataset overlaid on the training dataset for CTOD vs. STI.

When observed qualitatively, the validation dataset overlaid with the training model showed agreement between the two datasets, displaying the applicability of the studied approach on a wide range of binder types and formulations.

Conclusion

Given the strength of the correlation between CTOD2P and STI when plotted against CTOD, there is very supportive evidence that we can test two lengths without losing the reliability of the test. Additionally, shown by the consistency of the training model when compared to the independent test values, the results of the methodology are likely to be easily transferrable across sets of data, which is very supportive of the original hypothesis and promising for future research.

However, given the relatively small sample size, as well as the sparse inconsistencies seen in certain binders, more work is likely needed with more data before any sufficiently solid conclusions can be made. The code also shows much room for improvement and optimization, with a current running time of roughly 10 minutes to generate all calculations with respective plots. In the future, the code would run faster and work across different types of data sets where different sources might handle formatting or unit measurements differently.

Future Work

Along with the potential for analyses of larger, more diverse data sets, the research team has also proposed the future use of machine learning as a possible venue to explore other parameters to produce equally reliable comparisons and conclusions about the endurance of asphalt binders.

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