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Correlation of Extensional Bitumen Properties with 4-Point Bending Beam Asphalt Mixture Fatigue Life

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***Abstract*— In South Africa, over the last two decades, there has been a need to improve on the ductility specification test and to better simulate ageing of the asphalt bitumen in the laboratory for the control of fatigue cracking distress. Focusing on the former, various extensional tests have been recommended to replace the ductility test. Initially, this brought the Force-Ductility (FD) test to South Africa followed by a wave of surrogate Dynamic Shear Rheometer (DSR) protocols. More recently, the Double-Edge-Notched Tension (DENT) test has been introduced. This paper aims to compare these extensional tests and their surrogates with Four-Point Bending Beam (4-PBB) asphalt mixture fatigue results of various bitumen, using similar mix designs in terms of binder content, voids, gradation and aggregate types. The DENT test provides a measure of strain tolerance in the ductile state under severe constraint, expressed as the approximate Critical Crack Tip Opening Displacement (CTOD). The CTOD property was identified to be the most accurate in relation to asphalt mixture fatigue life. This paper discusses the significance of CTOD as an improved parameter for predicting fatigue life in South African asphalt mixtures.**

Keywords—extensional properties, ductility, DENT test, fatigue behaviour, hot mix asphalt

I. INTRODUCTION

It is widely accepted that alligator-type cracking in asphalt pavements is due to either flexural load-induced fatigue failure and/or localised overloading. More recently, it has been proposed that restrained expansion and contraction of the asphalt surfacing layer, known as thermal ratchetting, can induce micro-cracks which can further propagate into this form of distress [1]. Based on the former views, it has been argued that asphalt layers experience higher cyclic strain at intermediate field temperatures due to weak/weakened subsurface layers and/or as a result of softening of the asphalt binder [2]. The repeated application of stresses from wheel loads will result in reduced stiffness and reduced strength of the asphalt layer at these temperatures. This will usually show up as fatigue cracking once the number of traffic loads exceeds the capability of the asphalt layer to resist damage accumulation. The cracks will allow water to enter the pavement, weakening the underlying layers and eventually leading to complete road failure.

Properties of bitumen slowly change during service and under repeated loading, becoming more prone to fatigue cracking. It is therefore important to develop laboratory tests that accurately predict fatigue behaviour. So, this paper explores the use of extensional tests for fatigue specification grading.

Extensional testing of bitumen began in 1903 when Dow developed the ductility test [3]. Due to its simplicity and accuracy, the ductility test became a part of many bitumen specifications around the world. The importance of the test has been debated for decades. It remains highly likely, as suggested by Halstead [4], that ductility is an indication of the internal structural equilibrium of the constituents of bitumen, which in turn has a bearing on the bitumen performance in service.

Kandhal [5] linked ductility results with performance in experimental pavement sections in Pennsylvania. He showed that a decrease in low temperature ductility occurs with asphalt ageing and was able to correlate limiting ductility values with the onset of various distresses (loss of fines, ravelling and cracking). His work has recently inspired a number of research studies linking such findings to fatigue cracking predictions in the laboratory and in service.

Given the challenges with the ductility test (e.g., difficulty of reaching failure, sample requirements, etc.), researchers have attempted to develop surrogate test methods using low strain rheological tests with the DSR [6, 7]. Unfortunately, these tests have achieved limited correlations with ductility for highly modified bitumen [6] and, as low strain rheological tests, their applicability for the prediction of high strain failure in asphalt mixtures remains uncertain.

Currently, there is still an appreciation for the need to improve on the ductility test as well as to better simulate ageing of bitumen in the laboratory to better control fatigue behaviour. Focussing on the former, various extensional tests have been recommended as improved surrogates to the ductility test. In South Africa, this brought about the use of the FD test and its DSR surrogate the Binder Yield Energy Test (BYET) and, more recently, the DENT test. To evaluate these extensional tests for fatigue characterisation, this paper provides a comparison between bitumen extensional properties and 4-PBB asphalt mix properties of the same bitumen in asphalt mixes of similar mix designs in terms of binder content, voids, grading and aggregates. The 4-PBB test is the recommended test for determining asphalt fatigue behaviour in local asphalt pavements [8, 9]. In addition, this paper discusses the importance of having an improved bitumen fatigue test as a tool for selecting bituminous binders in a continuously changing bitumen manufacturing environment.

It is finally noted that bitumen is a viscoelastic material, so in order to relate bitumen properties from different test configurations (applying different stress distributions to the bitumen), there is a need to optimize test temperature and loading time for the different tests in order for them to be comparable. Given the fact that this was not done for this study, this correlation exercise carries an inherent limitation and should therefore be viewed as a preliminary investigation that warrants further work.

II. EXPERIMENTAL

The binders were obtained from several commercial suppliers in South Africa. All binders conformed to SANS-4001 [10] (unmodified binders) and TG1 [11] (modified binders) requirements. A summary of grades, modifications and sources is shown in Table I below.

TABLE I. SELECTED BITUMENS FOR THIS STUDY

Binder grade	Chemistry/Modification	Source
50/70 Penetration grade binder	Unknown (Experimental)	Created at the Colas laboratory
50/70 Penetration grade bitumen	Unmodified	Refinery 1: Produced March 2010
50/70 Penetration grade bitumen	Unmodified	Refinery 1: Produced June 2012
A-P1	EVA-modified binder	Ex-National Asphalt
A-E1	Terpolymer-modified binder	DuPont South Africa (Elvaloy)
A-E2	SBS-modified binder	Ex-Colas

The selected binders were evaluated as supplied and incorporated in asphalt mix to evaluate their 4-PBB fatigue lives.

The binders were evaluated after RTFOT as opposed to PAV ageing in order for the binder results to be better correlated with their corresponding asphalt mix fatigue results, as the asphalt mix had only been short-term oven aged. In addition, questions remain over the accuracy of PAV ageing as a simulation of longer ageing of the asphalt bitumen in service, so it was decided as more appropriate not to introduce another variable in this correlation study that could contribute towards errors in the predictions.

The asphalt mixes manufactured with the selected binders were evaluated with the 4-PBB test for their fatigue resistance properties (Section A). For correlation with the 4-PBB test results, the individual binders were tested for their FD properties (Section B), BYET properties (Section C) and DENT properties (Section D).

III. RESULTS AND DISCUSSION

A. *Fatigue Testing of Asphalt Mixes in 4-PBB*

The selected bitumens were used to prepare medium continuously-graded hot mix asphalt specimens of similar sieve analysis (Table II, Fig. 1), binder contents between 4.6 and 5.0% by weight of the mix, and void contents between 6 and 8%. The mix specimens were short-term aged for four hours in an oven at their compaction temperature in order to simulate the ageing that a binder undergoes during hot mix asphalt manufacture, transport to site and laying. Having prepared HMA specimens with similar asphalt mix properties and subjected them to similar sample ageing conditions, the influence of the binder on the 4-PBB test results could then be determined.

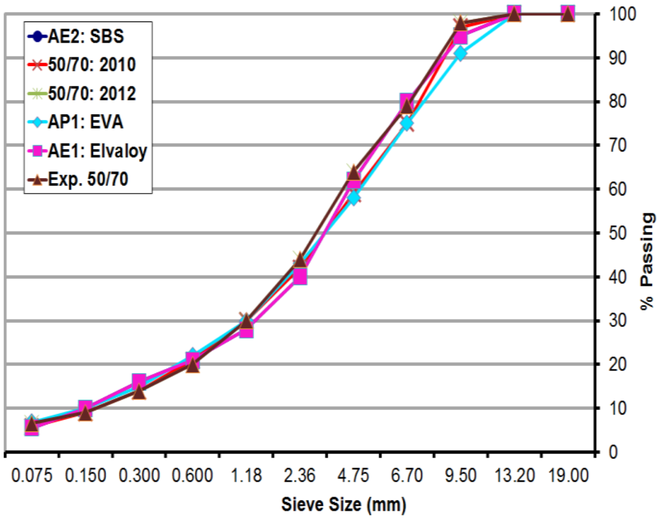

Fig. 1. Sieve analysis for aggregate used to produce asphalt mixtures.

TABLE II. GRADING AND BINDER CONTENTS OF ASPHALT MIXES

Sieve Size	AE2: SBS	50/70: 2010	50/70: 2012	AP1: EVA	AE1: Elvaloy	Exp. 50/70
	% Passing					
13.2	100	100	100	100	100	100
9.5	95	97	98	91	95	98
6.7	80	75	79	75	80	79
4.75	62	59	64	58	62	64
2.36	40	42	44	43	40	44
1.18	28	30	30	30	28	30
0.6	21	21	20	22	21	20
0.3	16	14	14	15	16	14
0.15	10	9	9	10	10	9
0.075	5.5	5.8	6.6	6.9	5.5	6.6
Binder Content (%)	4.7	5.0	4.7	4.8	4.7	4.7

The fatigue tests were performed using an IPC 4-PBB test setup according to the AASHTO T 321 [12] test method and a CSIR test protocol [13]. The fatigue failure criterion was defined as the number of load cycles to reach a 50% reduction in initial stiffness ($N_{50\%}$). The fatigue test was conducted at a temperature of 10°C, a frequency of 10 Hz (continuous sinusoidal), and strain amplitude levels of between 200 and 600 µm/m. Fatigue testing was done on prismatic beam specimens of 400 mm x 63 mm x 50 mm dimensions prepared from slabs. At 300 µm/m, the lowest strain amplitude that all the mixes had in common, the number of repetitions to failure were determined for all HMA specimens. The calculated values shown in Table III were used for the correlation with bitumen properties.

TABLE III. CYCLES TO FAILURE FOR ASPHALT MIXTURES AT THE 300 MICROSTRAIN LEVEL

Sample	**No. of repetitions to failure at 300 µm/m**
50/70 Penetration grade (Experimental)	103 177
50/70 Penetration grade (2010)	124 788
50/70 Penetration grade (2012)	144 813
A-P1: EVA-modified binder	375 620
A-E1:Terpolymer-modified binder	507 650
A-E2: SBS-modified binder	3 743 218

B. *Force-Ductility Testing of Bitumens*

The cohesive strength of a bitumen is one of a number of properties that could be considered a reasonable candidate indicator for fatigue cracking in asphalt pavements. It can be measured through the bitumen's ability to withstand tensile stresses. Given the viscoelastic nature of bitumen, its greatest susceptibility to cracking due to cohesive failure is expected at lower and intermediate service temperatures.

Upon the removal of the ductility test from the national specification in South Africa, a test measuring force during elongation, i.e. the FD test, was introduced as a measure of cohesive strength. It was included as part of Technical Guideline 1 [14] for polymer-modified binders used in road construction. It was conducted on bitumen that had undergone RTFOT-ageing. Although it could differentiate modified binders, its link to performance could not be established and it was eventually removed from the 2015 edition of TG1. Fig. 2 illustrates the binder test specimen being pulled apart in a temperature-controlled water bath.

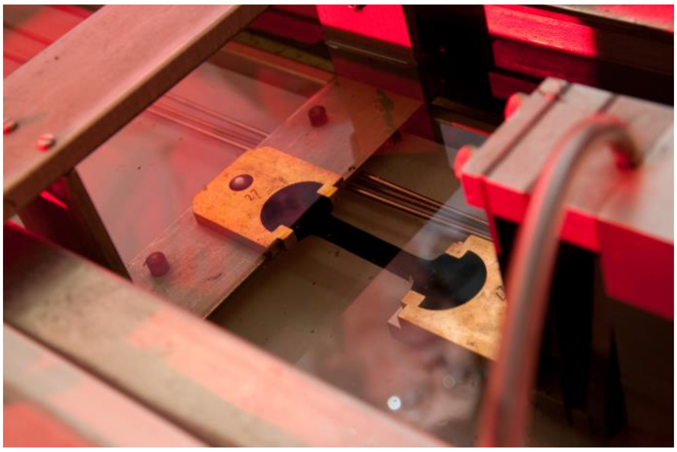

Fig. 2. Force-Ductility test specimen being pulled apart [15].

The FD test results represent the cumulated deformation energy beyond a clearly defined point after the initial peak between 200 mm and 400 mm, for RTFOT-aged binders, are shown in Fig. 3. They do not correlate with the 4-PBB mixture test results. However, they were able to rank polymer-modified binders above unmodified binders in terms of fatigue behaviour, as was observed with the 4-PBB results.

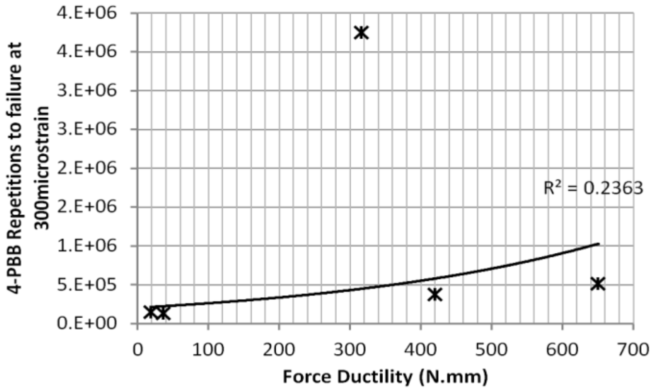

Fig. 3. Graph showing the FD at 15°C of the bituminous binders versus number of repetitions to failure of their corresponding asphalt mixes.

Even without the most extreme point of the A-E2 SBS-modified binder in Fig.3, the predicted fatigue ranking from the FD results do not correspond to that of the 4-PBB results. Technically, a correlation exercise is only meaningful when the ranking of the binder testing and the asphalt testing can be aligned.

A large reason for why there is a poor correlation between the ductility and FD results on the one hand and the mixture fatigue results on the other hand is likely due to the design of the brass inserts that transfer the load from the test machine to the bitumen. Different binders will show varying degrees of detachment and pull out from the brass inserts. Hence, the test measures properties that are influenced by the material and the specimen geometry. Fig. 4 shows two photographs to illustrate these difficulties.

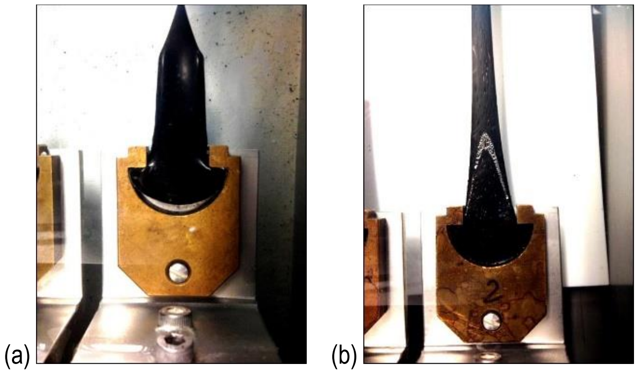

Fig. 4. Specimens after testing that show (a) detachment and (b) pulling out of bitumen during testing. Note: In (b) a straight line with silver marker had been drawn across the bitumen prior to testing to emphasize the degree by which the bitumen pulls out of the brass during testing.

C. *Binder Yield Energy Test*

The FD concept can be further evaluated through a surrogate test referred to as the Binder Yield Energy Test (BYET). It is conducted using a DSR at a set temperature and a fixed rate of strain. At four evaluated conditions, two temperatures and two strain rates, the BYET produced different sets of predicted fatigue rankings. The correlation results are presented in Fig. 5. The best ranking of the BYET test was at 10°C and 1% strain where the line of best fit had a correlation of $R^2 = 0.7189$. The only constant at all the BYET conditions is the ranking of polymer-modified binders above unmodified binders, as was also observed with the FD test and the 4-PBB results.

Interestingly, as the conditions of the BYET test approach those of the FD test, in terms of temperature and strain rate, the correlation improves between these two properties (see Fig. 6).

D. *Double-Edge-Notched Tension*

It has been argued that the limitation of the FD test has been the high non-essential or plastic work (w_p) dissipated during testing [17]. Notched tests enable the calculation of the essential work of failure (w_e), which is an inherent material property, that can be used to calculate the CTOD, a measure of strain tolerance in the ductile regime under high constraint, that better relates to fatigue cracking resistance behaviour of bitumen in service [17].

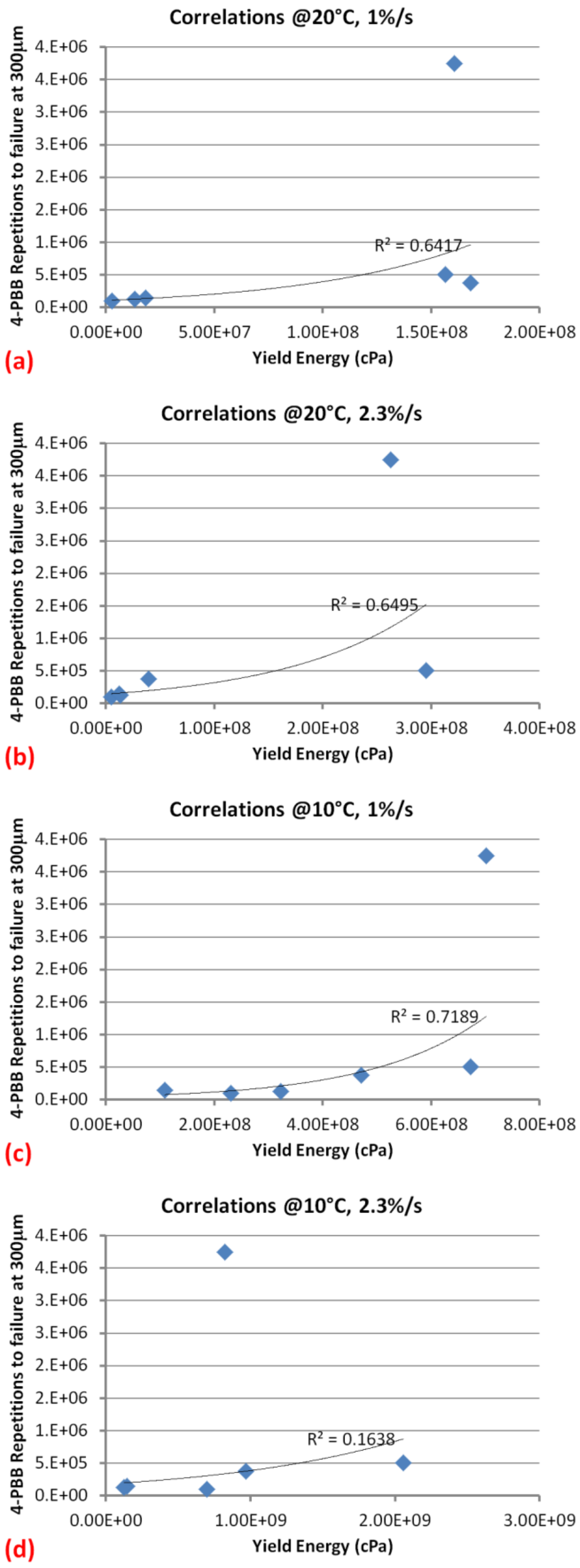

Fig. 5. (a-d) Correlation between 4-PBB repetitions to failure at 300µm and the BYET yield energy up to maximum stress parameter [16].

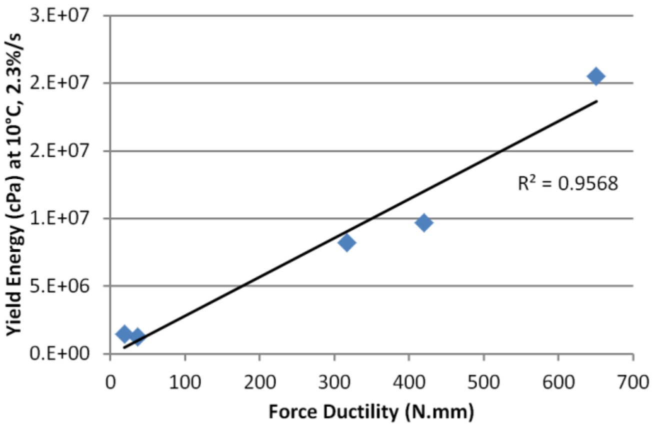

Fig. 6. Correlation between FD at 15°C and BYET yield energy up to maximum stress parameter at 10°C (strain = 2.3%/s).

The CTOD (δ_t) is calculated using the equation:

$$\delta_t = w_e/\sigma_n \qquad ...(1)$$

where w_e is the specific essential work of fracture (i.e. w_t for $\ell = 0.0$) obtained from the line of best fit for samples tested at different ligaments (w_e versus ℓ); σ_n is the net section stress as calculated by dividing the average peak load obtained for the sample tested with the smallest ligament length (P_{peak}) over the product of the geometric constant describing the shape of the plastic zone (β) and ligament length (ℓ).

The RTFOT-aged binders were prepared at ligament lengths of 5 mm, 10 mm and 15 mm, according to method AASHTO TP 113 [18], and they were tested at 15°C and 50 mm/min. Fig. 7 illustrates the DENT test specimens just prior to being pulled apart in a temperature-controlled water bath.

Fig. 8 shows an impressive correlation obtained when CTOD values are plotted against the 4-PBB results. In addition, there is an alignment in ranking observed between the binder test results and the asphalt test results.

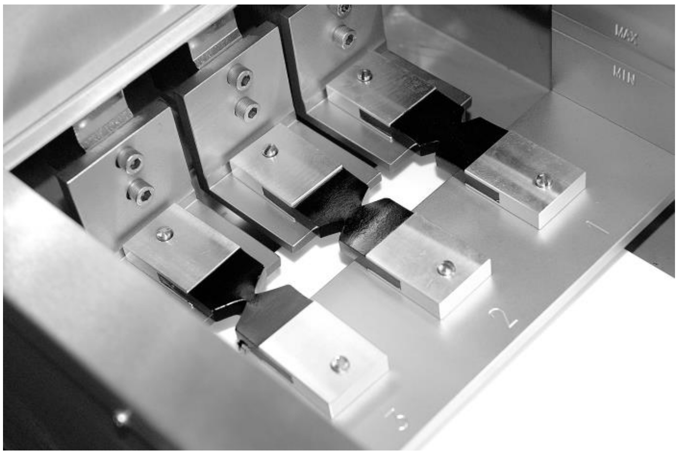

Fig. 7. Double-Edge-Notched Tension (DENT) test specimens just prior to testing (water was removed for picture clarity).

Gibson et al. [19] showed that the CTOD property outperformed others when it comes to predicting fatigue in a recent United States' Federal Highway Administration Accelerated Loading Facility (ALF) experiment as well as laboratory mixture tests (see Table IV). Previous to this study, the Ontario Ministry of Transport using Provincial Highway 655 materials, evaluated the CTOD parameter against the Binder Yield Energy and SHRP G*sinδ. The CTOD parameter outperformed the other two parameters by far, but with a reduced composite score of 0.59 to 0.73 [20]. This lower accuracy can likely be attributed to confounding effects of variations in chemical ageing and low temperature properties.

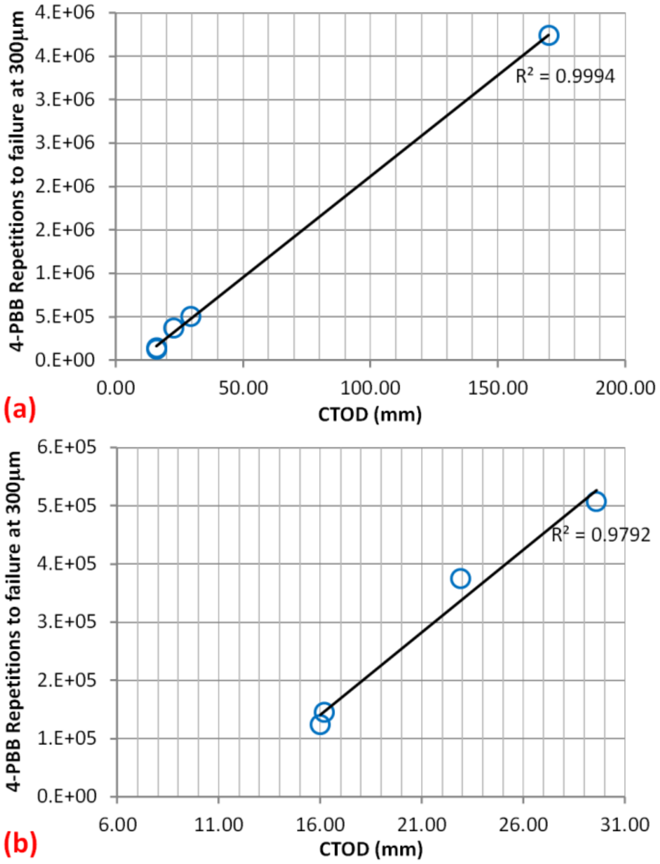

Fig. 8. Graph (a) showing CTOD at 15°C and 50 mm/min of the bituminous binders versus the number of repetitions to failure of their corresponding asphalt mixes, and (b) without the most extreme point at CTOD = 170 mm.

TABLE IV. FHWA CORRELATION OF FATIGUE GRADING TESTS TO ALF FIELD PERFORMANCE [19]

Binder Test for Fatigue Cracking	Correlation Composite Score
Approximate CTOD	0.99
BYET Energy	0.88
Time Sweep in DSR	0.88
Failure Strain in DTT	0.81
Superpave® |G*|.sinδ	0.75
Large Strain Time Sweep	0.67
Essential Work of Failure (w_e)	0.55
BBR m-value	0.54
Stress Sweep	0.69*

*Incorrect trend direction

E. *CTOD versus Superpave LVE Properties*

Having established good correlations between 4-PBB result and the CTOD property, the current limitations of low strain Superpave tests can be appreciated for the South African binders in Table V. Fig. 9 below shows a poor correlation between the CTOD property and the SHRP G*sinδ parameter for these binders. Based on correlations of G*sinδ and asphalt mix fatigue performance [21, 22], this Superpave fatigue parameter has been found unreliable due to its determination within the linear viscoelastic (LVE) range of non-damaged specimens [23]. It has been argued that the majority of testing during SHRP was done on unmodified bitumen [24]. The introduction of modified binders resulted in complex systems that did not exhibit simple rheological behaviour, rendering the performance graded (PG) binder specification parameters such as G*sinδ less relevant to actual field performance.

TABLE V. SOUTH AFRICAN BINDERS INVESTIGATED BY HESP AND PALIUKAITE [25].

Sample	**Pertinent Compositional Information**		
	Base Bitumen	***Modifier***	***Other Additives***
SA-1	50/70 pen Sapref, Durban	5% EVA	None
SA-2	50/70 pen Shell, Durban	4% FT Wax[a]	None
SA-3	50/70 pen Sapref, Durban	FT Wax + SBS	Wax Link[b]
SA-4	50/70 pen Sapref, Durban	4.3% SBS	Proprietary
SA-5	50/70 pen Sapref, Durban	4.0% SBS	Reatalink[b]
SA-6	50/70 pen Sapref, Durban	4.6% EVA	None
SA-7	70/100 pen Chevron, CT	4.3% SBS	None

[a]FT = Fischer-Tropsch process.

[b]Crosslinking agent produced by Sasol.

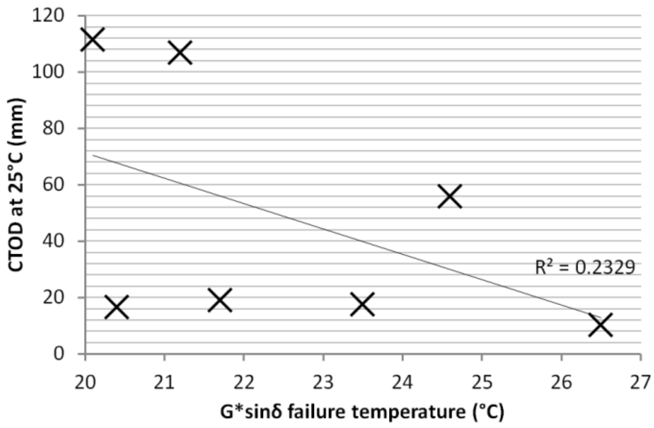

Fig. 9. CTOD at 25°C and 50 mm/min versus Superpave DSR fatigue parameter. Both parameters determined on PAV residues [25].

F. *CTOD versus Jnr Properties*

More recently, the DENT test has been used to distinguish between East African bitumens conforming to PG 70-22 criteria [26], as per AASHTO M320 contractual requirements. Using tests that better predict asphalt properties, the performance variability of binders classified into the same PG grade as per the SHRP parameters of AASHTO M320 can be explored. The following trends were observed based on the CTOD and J_{nr} results displayed in Fig. 10:

- Not every bitumen that meets the PG 70 HT G*/sinδ criterion falls in the same J_{nr} class;
- Bitumens that meet the PG LT BBR criteria will not necessarily have similar CTOD values; and
- The lack of a relationship between CTOD and J_{nr} means that manufacturers use various methods to produce bitumens for the required PG HT criteria (i.e. various crudes, formulations and processing conditions) that can affect low temperature behaviour to a significant degree. Hence, the need for specifications that include parameters that better predict actual field performance remains urgent.

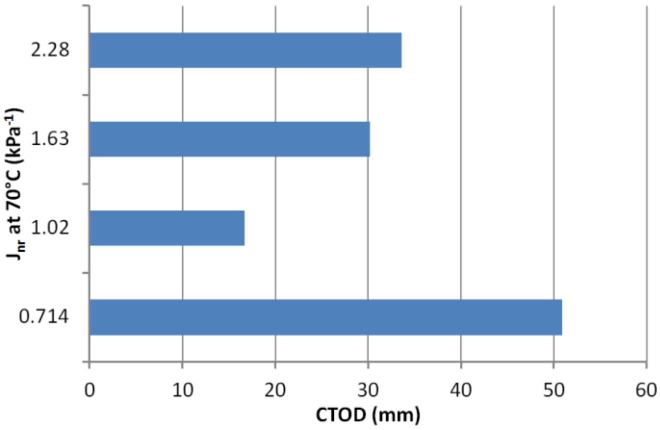

Fig. 10. J_{nr} at 70°C (after RTFOT) versus CTOD at 25°C and 50 mm/min of PAV residues.

G. *CTOD as a Quality Control Test for Bitumen Rubber*

South African bitumen rubber semi-open graded mixes (BRASO) are designed at a higher binder content than the HMA medium continuously graded mixes investigated in this paper. As a result, they could not be added to this correlation exercise. However, given the main reason for using BRASO mixes is to improve the fatigue behaviour of asphalt mixes, the CTOD parameter can be used as a performance criterion to quantify the fatigue effect of crumb rubber in the bitumen as well as distinguish poorly modified blends [27]. Fig. 11 shows the improved CTOD property for a bitumen modified with crumb rubber compared to a standard 50/70 pen grade binder (unmodified).

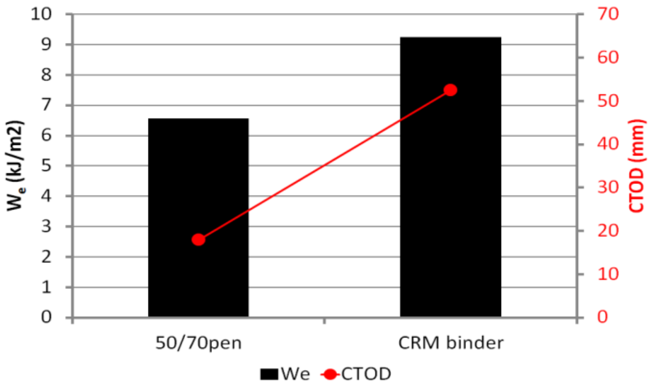

Fig. 11. CTOD at 15°C and 50 mm/min of an unaged 50/70 pen bitumen and a CRM bitumen sample.

IV. CONCLUSIONS

Results presented show that essential and non-essential failure properties should be separated when testing bituminous binders in order to provide improved correlation with asphalt mixture test findings.

High strain failure tests are more accurate than low strain rheological tests in predicting bituminous binder fatigue performance.

The 4-PBB asphalt test results showed a high correlation with the CTOD of the respective bituminous binders.

This study provides a limited validation for the use of the approximate CTOD parameter in controlling fatigue cracking behaviour in service.

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