

FORCE DUCTILITY – A 5 YEAR FEEDBACK OF PERFORMANCE RESULTS

G.A.J. MTURI and M. NKGAPELE

CSIR Built Environment, Transport Infrastructure Engineering, Pretoria 0001, South Africa,
Email: gmturi@csir.co.za; tnkgapele@csir.co.za

ABSTRACT

The development of improved test protocols and procedures for modified bituminous binder materials is currently being pursued by the Council for Scientific and Industrial Research (CSIR). The determination of the cohesive strength of modified binders using the force ductility test is currently a requirement in the existing South African Technical Guideline 1 for Modified Bituminous Binders in Road Construction. A major drawback of this prerequisite when distinguishing between modified binders is the lack of collated force ductility data nationally. This paper tries to address this information gap through presenting a summary of test results for the force ductility test since 2007 as tested at the CSIR Bituminous Binders Laboratory. The paper also tries to propose specification routes in future revisions of this guideline document.

1. INTRODUCTION

The cohesive strength of bituminous road binders can be measured through their ability to resist or withstand tensile stresses. The cohesion of bitumen gives an indication of their resistance to cracking. The visco-elastic nature of bitumen makes their ability to crack (due to cohesive failure) greatest at low temperatures. As a result, the cohesion of bitumen is characterised by their ductility at low temperature and quantified by measuring the force during elongation in a test referred to as force ductility.

The force ductility test was introduced in 1976 (Anderson and Wiley, 1976) as a modified ductility method that gives a better indication of the low temperature performance of bituminous road binders. Button *et al.* (1987) showed in Figure 1 that a relationship exists between the maximum stress measured in the force ductility test for bituminous binders and the tensile strength of the corresponding asphalt mixes.

In the current force ductility test as specified in EN 13589 and EN 13703 test methods (TG1, 2007), samples of bitumen are prepared in ductility moulds and immersed in a water bath set at 5-15°C. A load cell measures the force required to pull the test specimens at a deformation rate of 50mm/min. Figure 2 illustrates the binder test specimen being pulled apart.

The result of the force-ductility test is a plot of force (stress) vs. distance (strain). The total area under the resulting force-distance curve is used to represent the cohesive energy (Read and Whiteoak, 2003). This area can differentiate between bitumens, see Figure 3. Performance can be measured through interpreting the results of the deformation energy ratio, maximum stress/force, modulus, the elastic phase (or the area under the curve before the initial primary peak), the total area under the stress-strain curve and/or the total ductility until specimen rupture.

The force ductility test is currently used in conjunction with AASHTO M-320 to characterize polymer-modified binders by some agencies in the US. In South Africa, the force ductility test was introduced in 2001 as part of Technical Guideline 1 (TG1, 2001) for polymer modified binders used in road construction. The test results were meant for 'report only' purposes without any pass or fail criteria. In the 2007 edition of this guideline document, the test was carried through but remained as 'report only'.

This paper presents a summary of test results for the force ductility test since 2007 as tested at the CSIR Bituminous Binders Laboratory. The paper also illustrates possible guideline limits and specification routes in future revisions of this guideline document.

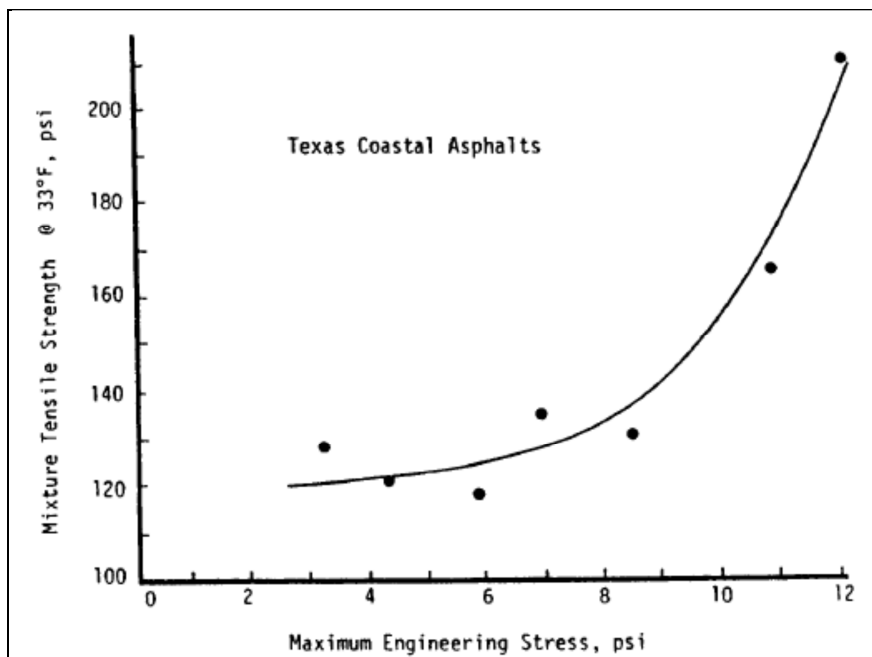


Figure 1: Mixture tensile strength as a function of maximum engineering stress. Mixture tensile strength was measured at 33°F (0.6°C) and 2 in./min. Force ductility data were measured at 4°C and after RTFOT ageing. (Button *et al.*, 1987)

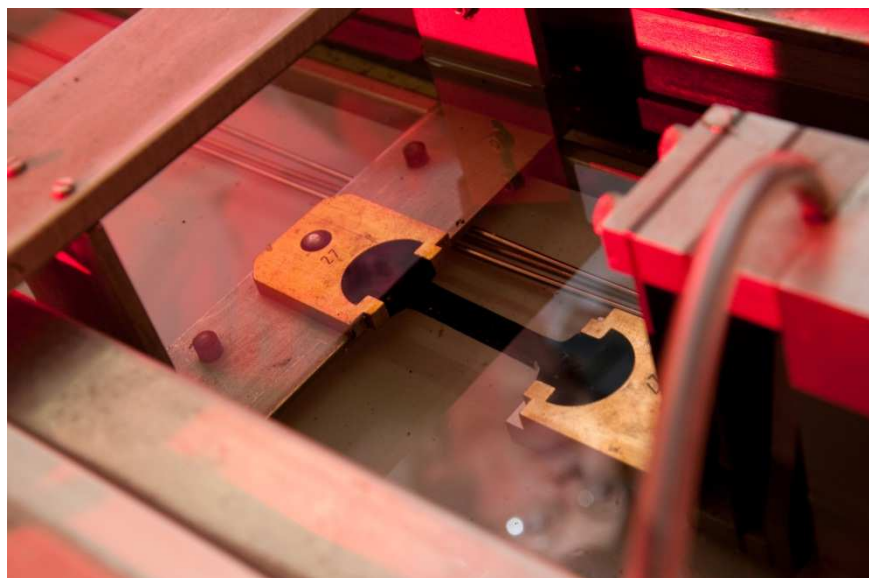


Figure 2: Force-ductility test specimens being pulled

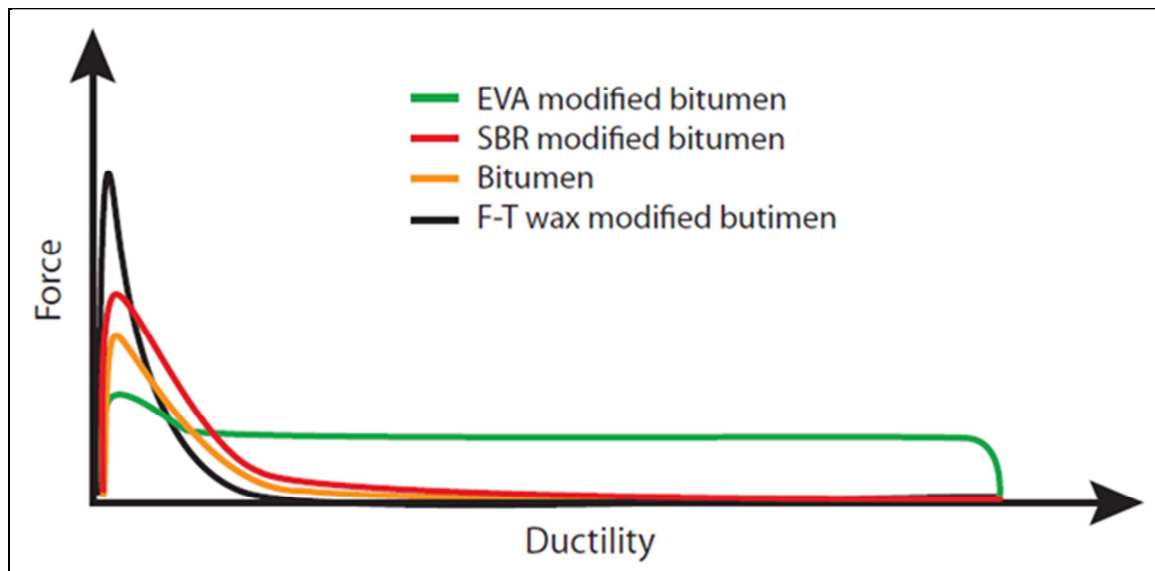


Figure 3: Force-ductility curves of typical South African bitumens (TG1, 2007)

2. EXPERIMENTAL

The binders analysed in this investigation were:

- Unmodified binders: 40/50pen grade bitumen, 60/70pen grade bitumen, 80/100pen grade bitumen and 20/30pen grade bitumen.
- Modified binders: styrene-butadiene-styrene (SBS) modified binder, crumb rubber modified (CRM) bitumen.

Ageing of the binders was done according to the following methods:

- The standard Rolling Thin-Film Oven test (RTFOT) according to ASTM D 2872: Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test).
- The Pressure Ageing Vessel (PAV) test in accordance with AASHTO R28-02: Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel.

Force ductility was determined as per DIN EN 13589 and evaluated in accordance with DIN EN 13703.

3. RESULTS AND DISCUSSIONS

3.1 Force ductility curve characterisation

Figure 4 shows force versus elongation for weakly and strongly cohesive binders. The magnitude of the modulus of elasticity is proportional to the slope of each curve, as shown by the green arrows.

A force versus ductility relationship shown in Figure 5 illustrates the following properties:

- Maximum force,
- Elastic phase, or the area under the curve before the initial primary peak,
- Total area under the curve, or the area indicating the toughness of the binder,
- Cumulated deformation energy up to 200mm (derived from the force and distance),
- Cumulated deformation energy between 200mm and 400mm (derived from the force and distance),
- Ductility.

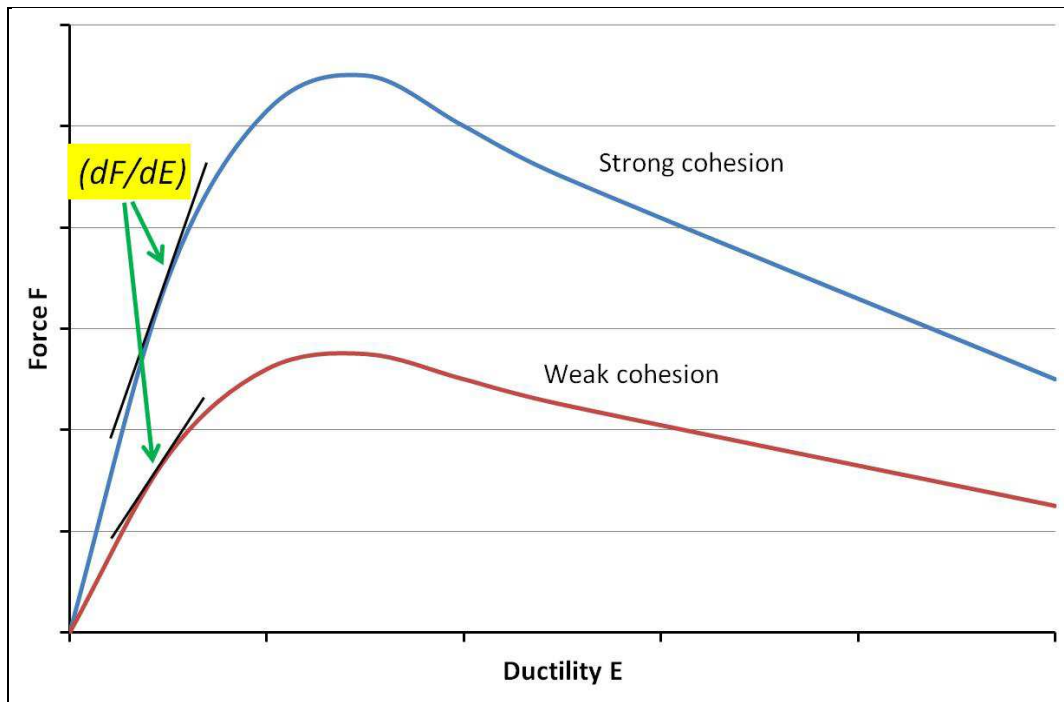


Figure 4: Properties of the force-ductility curve

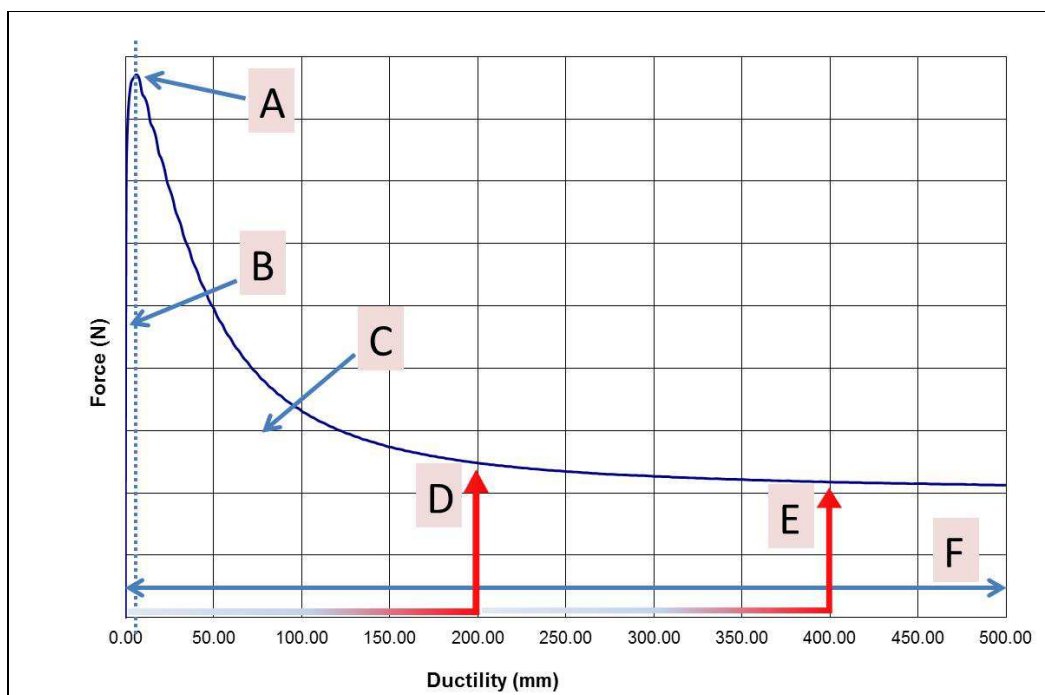


Figure 5: Properties of the force-ductility curve

3.2 Unmodified binders

Force ductility testing is not a requirement for unmodified binders nationally. But, the test can be used to give valuable information with regards to the binder quality and the presence of additives.

Figure 6 shows the ductility results of four unmodified binders, namely a 20/30pen, a 40/50pen, a 60/70pen and an 80/100pen grade bitumen, all conforming to SANS 307 requirements (SANS 307, 2005). The force ductility curves show an increase in the

maximum force, elastic phase and the total area under the curve with an increase in stiffness of the binder. Therefore the measured force is a direct function of binder stiffness at a particular test temperature and loading rate.

The 20/30pen grade binder (most stiff) and 80/100pen grade binder (least stiff) tend to snap prematurely (break apart during elongation) at this temperature, and there is a need for these binders to be tested at a different temperature. Ideally, binders should be tested at the equiviscous temperature but this approach would be impractical to adopt for routine testing. Previous experience has shown that the test temperatures for determining the deformation energy of unmodified bitumens should ideally be higher (15-25°C) for harder (stiffer) binders, and lower (5-15°C) for softer binders.

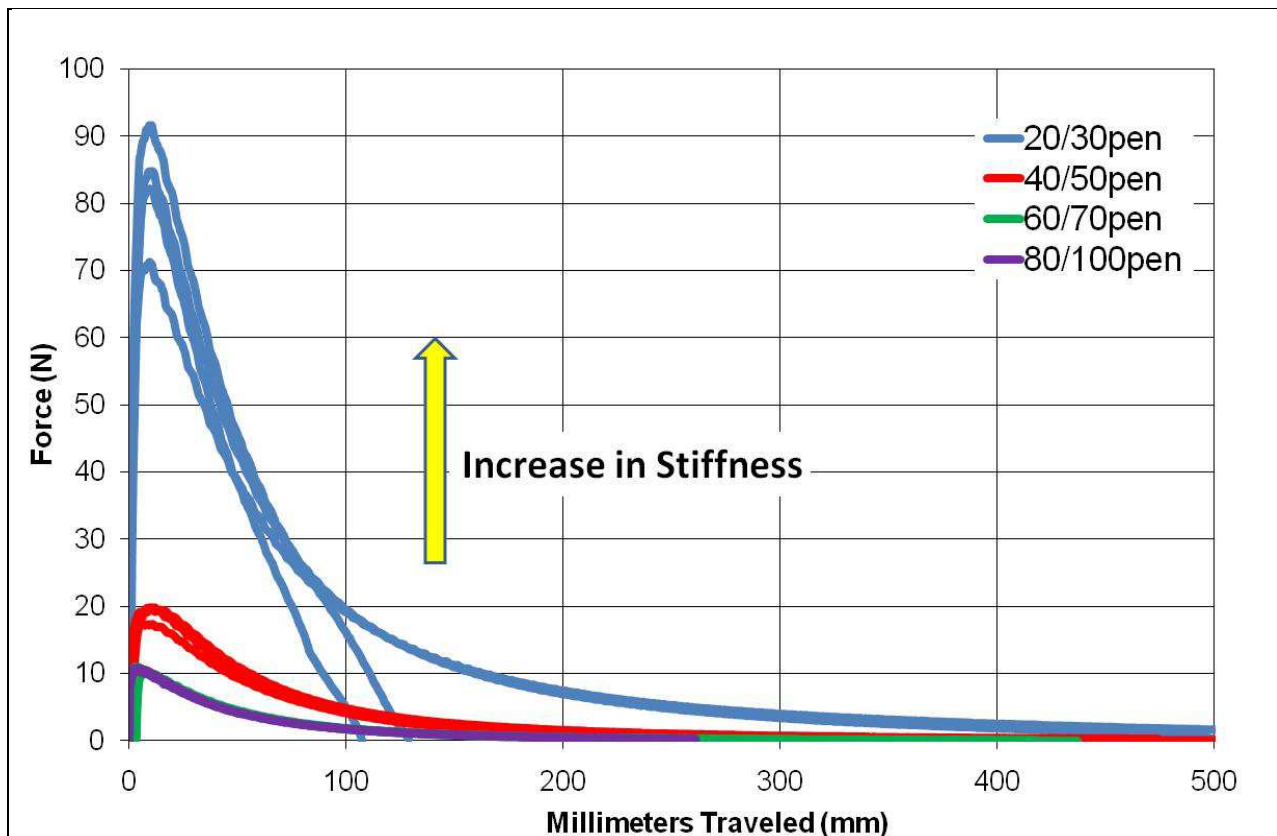


Figure 6: Force-ductility curves of unmodified bitumens at 15°C

3.3 Modified binders

The illustrated force ductility test properties in Figures 4 and 5 can be used to deduce whether the binder has been modified and the extent of modification.

Figure 7 shows the effect that an increase in SBS polymer can have on the force ductility curve of standard bitumen. In this instance, the test was conducted at a faster deformation rate in order to clearly illustrate the effect of increasing the polymer level. The increase in SBS content from 0 to 6% did not result in a dramatic increase in the maximum force or elastic phase, even though at 6% SBS the binder is no longer workable enough for routine use in road construction. But there was a notable increase in slope after 200mm where the SBS polymer network dominated the performance of the binder.

Force ductility testing is currently a requirement in Technical Guideline 1 (TG1, 2007) for S-E1, S-E2, SC-E1, SC-E2, A-E1, A-E2, A-P1, A-H1 and A-H2 modified binders. Data for

some of these binder classes has been collated, analysed and presented in sub-section 3.3.1.

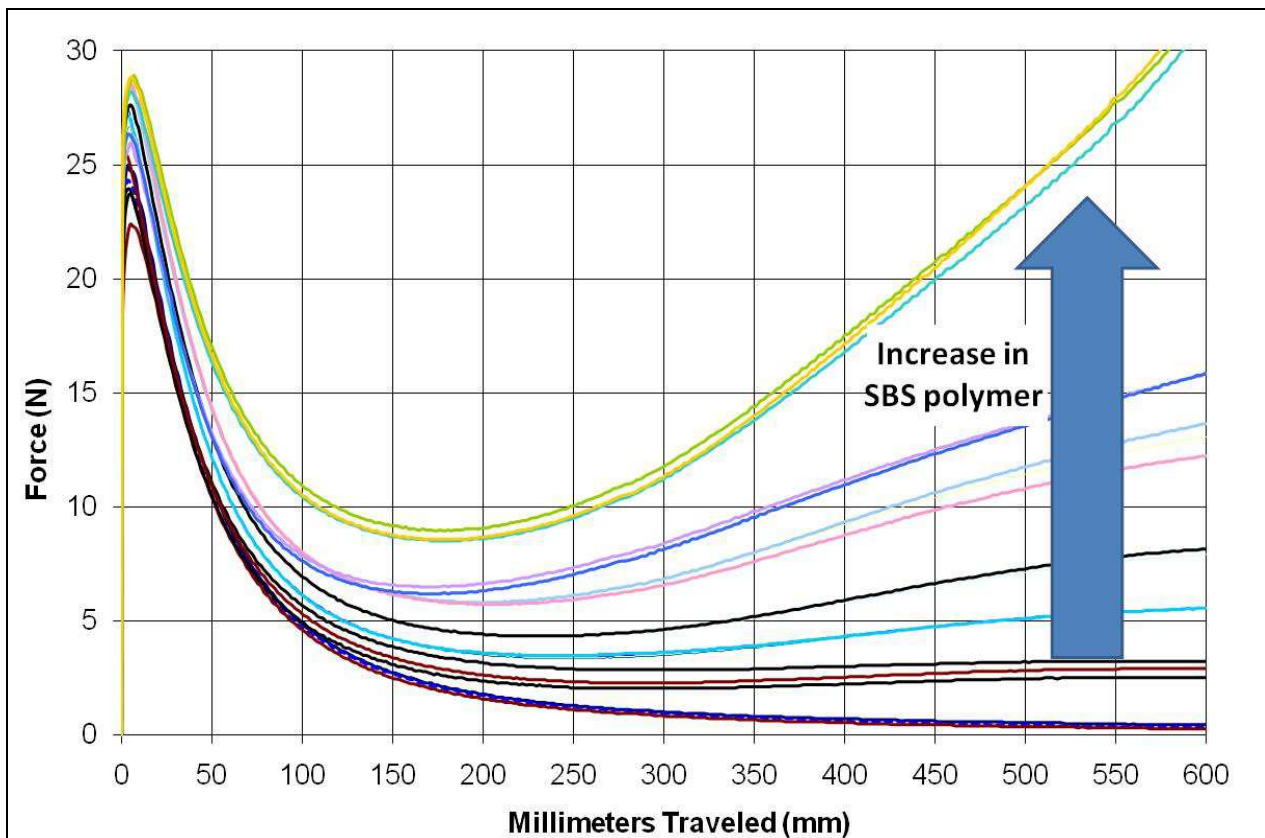


Figure 7: Force-ductility curves of modified binders with 0-6% SBS polymer at 273mm/min and 15°C

3.3.1 Modified binders of the A-E1, S-E1, A-E2 and S-E2 binder classes

The force ductility curves for modified binders of the A-E1, S-E1, A-E2 and S-E2 classes are presented in Figures 8 and 9. The force ductility curves show an increase in force after 200mm due to modifiers, and this is affirmed when this peak increases with extra modifier addition. On the other hand, extra added wax additives appear to also increase the maximum force and elastic phase properties. The wax additives are likely to be in a crystallized form *in situ* within the bitumen at this test temperature and would therefore impart a reinforcing effect that would result in higher stiffness of the binder.

The consequence of the wide guideline limits for the S-E2 and A-E2 class binders is seen in the broad range of force ductility curves shown in Figure 9. The curves confirm there is a diverse amount of additives used to achieve the set guideline requirements for these binders.

In essence, this test is able to differentiate between the types of added additive and indicate the amount of modifier present in the binder. The challenge is setting guideline limits given the diversity of additives used by bitumen suppliers nationally. But there is potential to better understand, characterise and link ductility results to binder performance.

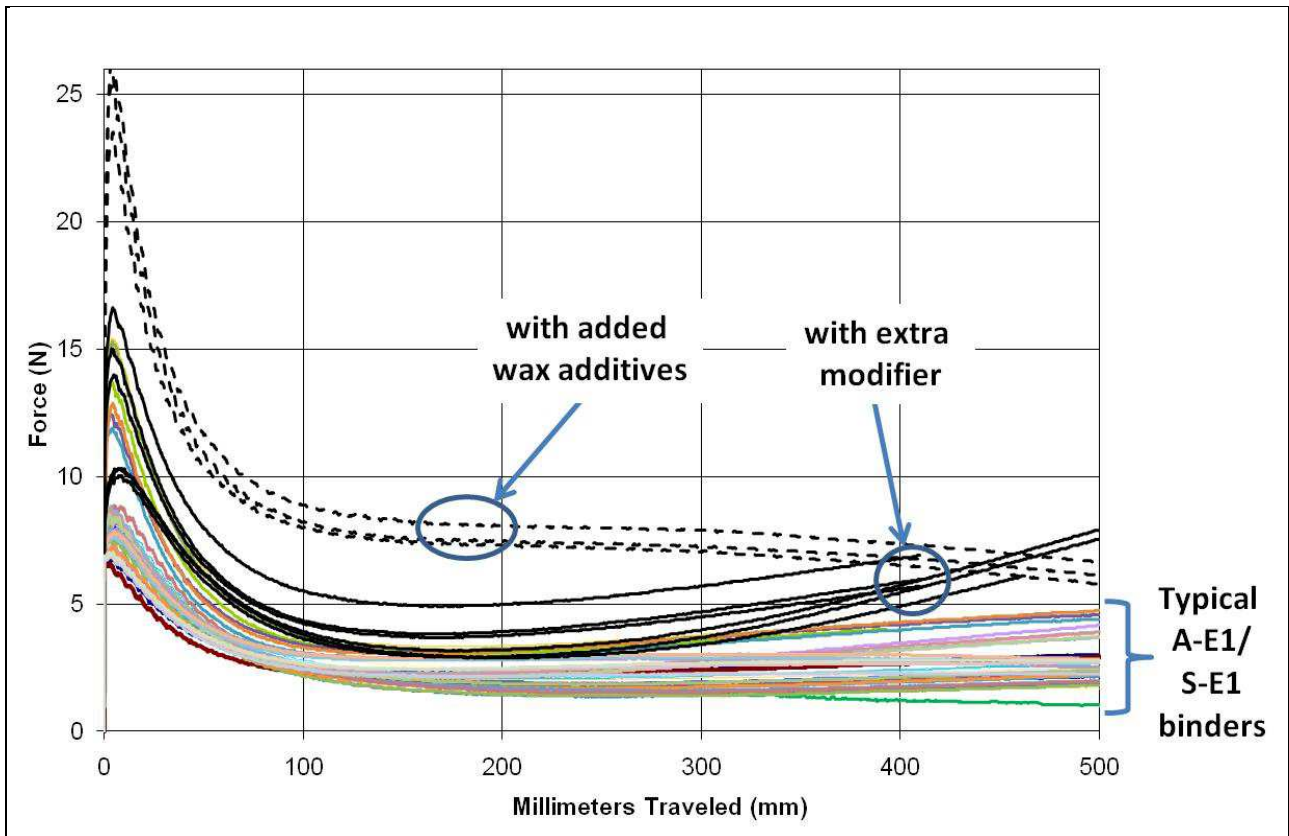


Figure 8: Force-ductility curves of S-E1 and A-E1 modified binders at 15°C

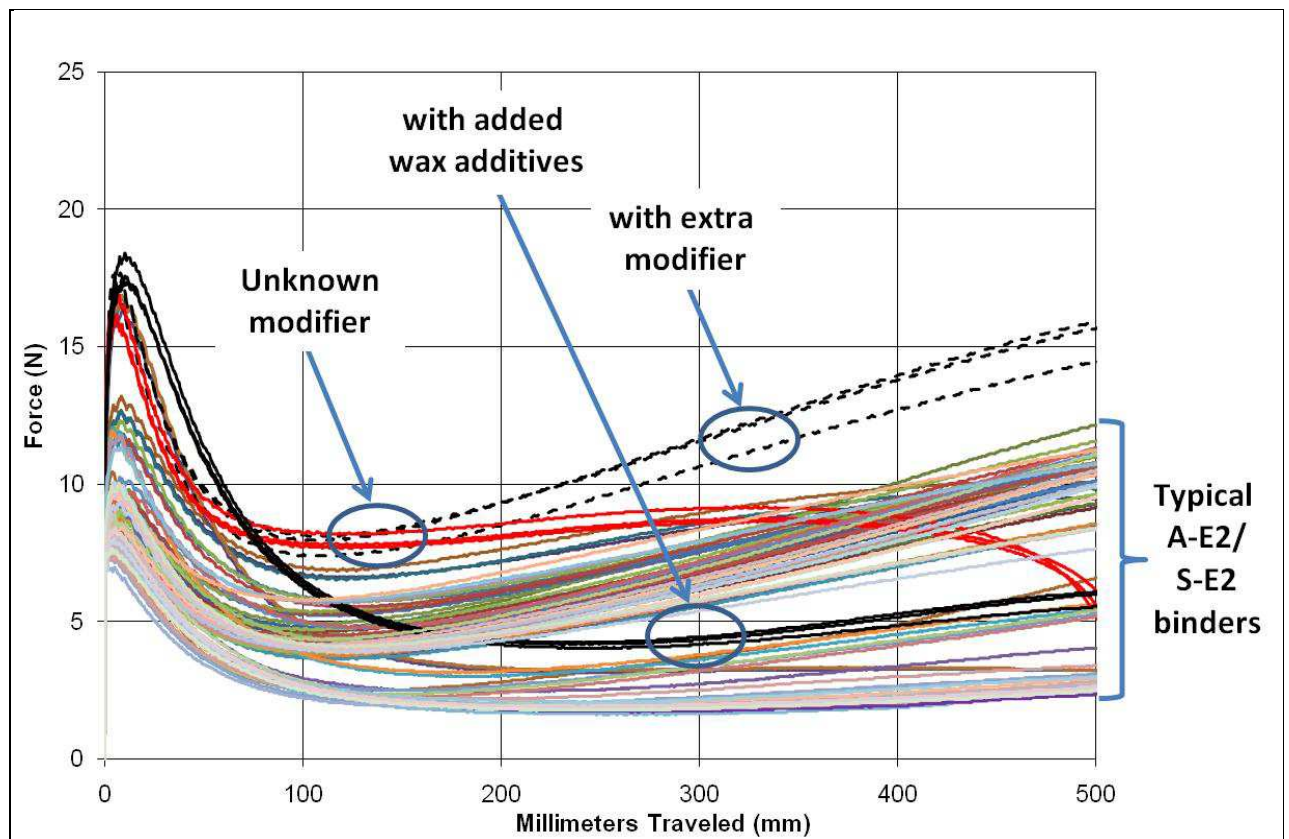


Figure 9: Force-ductility curves of S-E2 and A-E2 modified binders at 15°C

3.3.2 Modified binders with ageing

Ageing of unmodified binders typically results in an increase in stiffness due to oxidation. Aged unmodified binders would therefore generate higher force values during elongation. The effect on the force ductility curve would be an increase in the maximum force, elastic phase and total area under the force ductility curves, as observed with an increase in stiffness of unmodified binders in Figure 6. But ageing would also result in a decrease of the ductility length of these binders.

Ageing of modified binders is more complex rheologically and chemically compared to unmodified binders. The components of modified binders (base bitumen, modifiers and/or other additives) may age differently and can even result in opposing effects on the measured property (Mturi *et al.*, 2013).

In the case of SBS modified binders, ageing results in the partial loss of the proportional elastic contribution from the SBS modifier as well as the oxidation of the dominant bitumen phase. The effect on the force ductility curve is shown in Figure 10. It resulted in an increase in the primary peak due to the increase in stiffness of the base binder, and a shift in the curve shape of the second peak due to the partial loss of the elastic contribution from the SBS modifier.

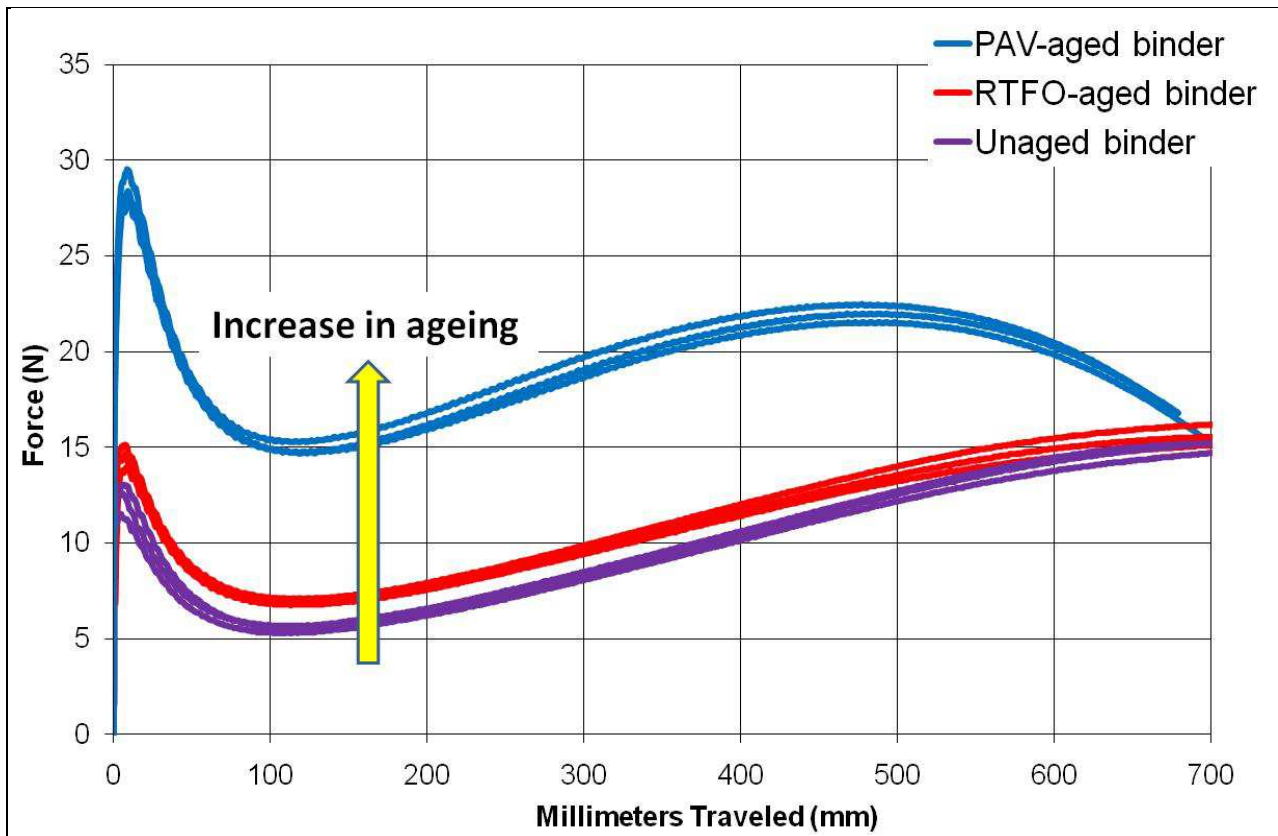


Figure 10: Force-ductility curves of an SBS modified binder with ageing at 15°C

Figure 11 shows the effect of cumulated deformation energy up to 200mm or 0.2m ($E_{0.2}$), between 200mm (0.2m) and 400mm (0.4m) ($E_{0.2} - E_{0.4}$) and the deformation energy ratio ($(E_{0.2} - E_{0.4}) / E_{0.2}$) for a modified binder with ageing.

The graph illustrates that ageing results in an increase in $E_{0.2}$ because of an increase in the primary peak due to the stiffening effect of the base bitumen. In the modifier influenced region ($E_{0.2} - E_{0.4}$), there was an initial increase in deformation energy followed by a

reduction. The deformation energy ratio can be used to evaluate the relative polymer effect (Mollenhauer *et al.*, 2011) and when it decreases with ageing as shown in Figure 11, it indicates that the modifier contribution has decreased in the ageing process.

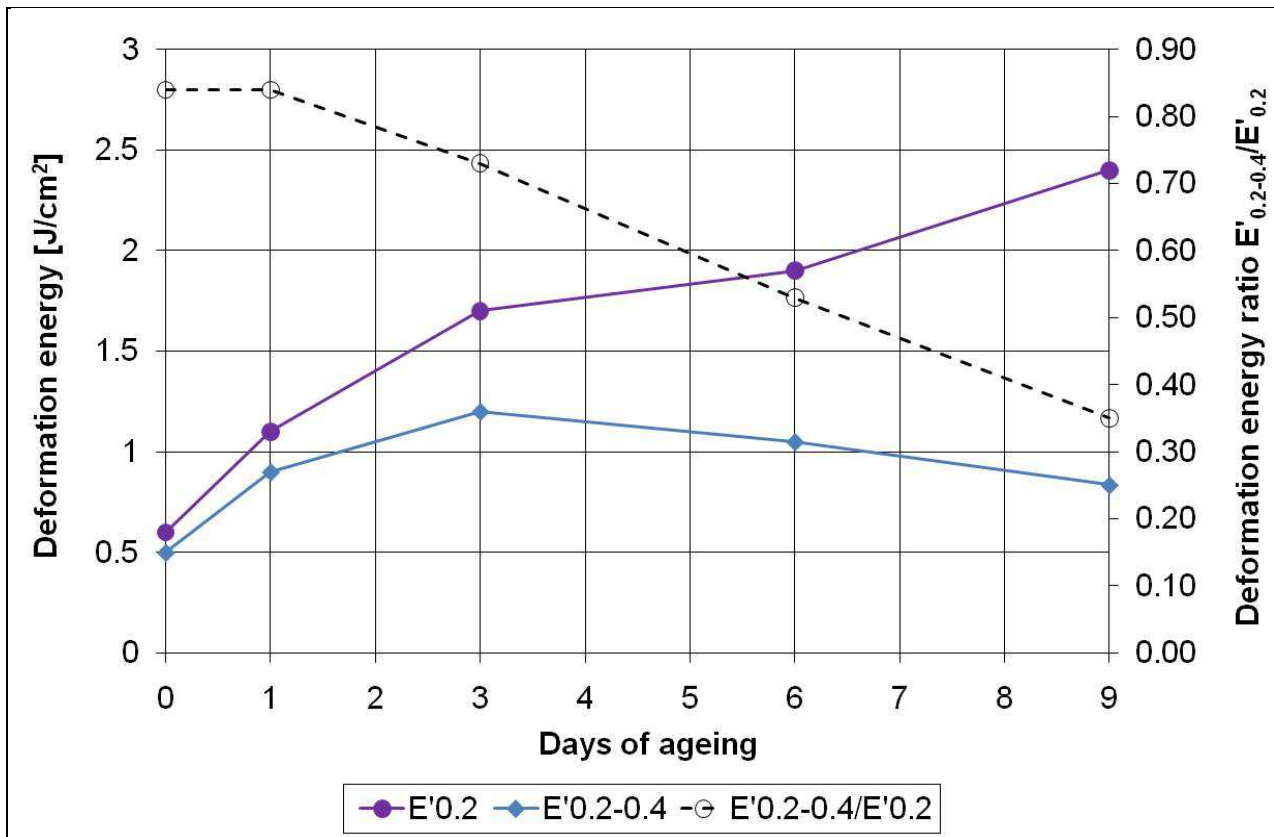


Figure 11: Effect of RILEM ageing (loose mixture aged in an oven for 9 days at 85°C) on force ductility properties of a modified binder (Mollenhauer *et al.*, 2011)

3.4 Load-relaxation ductility test results

The *in situ* binder within an asphalt pavement is subjected to multiple traffic loads. In order to simulate traffic conditions during loading and unloading cycles, the behaviour of the binder when subjected to a force (stress) and during relaxation needs to be monitored. At low temperatures, the stress relaxation ability of the binder gives an indication of its resistance to cracking.

Figure 12 shows the force-relaxation curves of an SBS modified bitumen. The test was conducted by loading a force and instantaneously removing it (unloading) to allow for the binder to relax to a minimum force. The relaxation period is dependent on the elastic and the viscous portion of the binder. For unmodified binders, the measured force instantaneously approaches zero when the deformation rate is stopped. But the relaxation period takes longer with modification and more so with a higher level of modification. This is because the elastic response is expected to relax gradually whereas the viscous flow relaxes immediately.

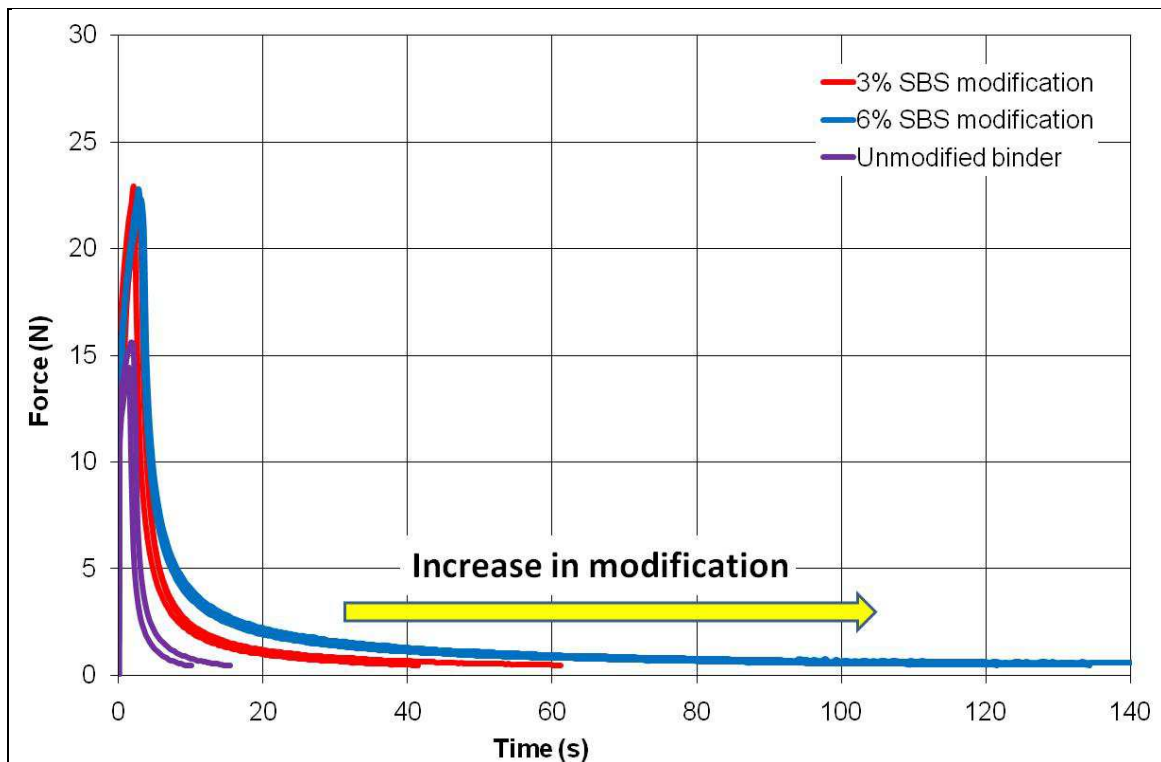


Figure 12: Force-relaxation curves from a start-stop experiment for an 80/100pen bitumen unmodified, with 3% and 6% SBS modification at 10°C

3.5 Proposed national guidelines for the force ductility test

There are complications experienced when testing modified binders at the test temperature of 5°C as recommended by TG1 (2007). They include difficulties encountered when conditioning the water bath at 5°C and also the challenge of preparing test specimens at this temperature. In most instances, ductility moulds with binder specimens disintegrate during preparation. It is proposed based on the past 5 years of successful testing of a large range of different binders that force ductility testing be carried out at 15°C for modified binders instead of the recommended 5°C.

Sub-sections 3.5.1 – 3.5.5 contain proposed performance parameters for this test method based on the results analysed in this paper.

3.5.1 *Ductility (tenacity) $E_{0.2}$*

The cumulated deformation energy up to 200mm (0.2m) can be used to differentiate between unmodified binders and give an indication of the extent of ageing.

3.5.2 *Force ductility $E_{0.2} - E_{0.4}$*

The cumulated deformation energy between 200mm and 400mm shows the presence of modification and the level of modification.

3.5.3 *Force ductility ratio $(E_{0.2} - E_{0.4}) / (E_0 - E_{0.2})$*

This ratio can be used to evaluate the relative modifier effect on the deformation energy.

3.5.4 *Primary Stress Value (or the Maximum Force)*

This is the value of the maximum force for the primary peak. For unmodified and elastomer modified bitumens (e.g. SBS modified binders), it is indicative of stiffness of the base bitumen. Ageing of a particular binder can also be detected using this parameter. It is most useful when used in conjunction with the ductility below 200mm.

3.5.5 Secondary Stress Value

This is the value of the maximum force after 200mm. It can be used in conjunction with the force ductility value to differentiate between modified binders and also indicate the extent of ageing.

4. CONCLUSION

The force ductility test results can be used to differentiate between unmodified and modified bitumens. They can provide valuable input to the type of modifier, additive as well as the extent of modification in the bitumen. The test can also be used to monitor ageing effects and stress-relaxation behaviour of bitumen in order to simulate the performance of the binder during processing and/or *in situ* within the asphalt pavement, respectively. Force ductility data can therefore be used to develop meaningful test limits in the specification of modified binders.

REFERENCES

Anderson, D, and Wiley, M, 1976. Force ductility – An asphalt performance indicator. Proceedings of Association of Asphalt Paving Technologists, 45 p.25-41.

Button, J; Little, D; Kim, Y, and Ahmed, J, 1987. Mechanistic evaluation of selected asphalt additives. Proceedings of Association of Asphalt Paving Technologists, 21 p.62-90.

Mollenhauer, K, Mouillet, V, Piérard, N, Gabet, T, Tušar, M, and Vanelstraete, A, 2011. Chemical and physical compatibility of new and aged binders from RA. “Re-Road deliverable 2.3: End of life strategies of asphalt pavements”, pub European Commission.

Mturi, GAJ, O’Connell, J, and Anochie-Boateng, JK, 2013. Limitations of current South African test methods for bituminous binders. Construction and Building Materials, 45 p.314-323.

Read, J, and Whiteoak, D, 2003. The Shell Bitumen Handbook. “Mechanical testing and properties of bitumens”, pub Shell Bitumen, UK (Fifth Edition), p.152-153 (2003).

South African National Standard 307 (SANS 307), 2005. Penetration grade bitumens. Standards South Africa, Pretoria, South Africa.

Technical Guideline (TG1), 2001. The use of modified bituminous binders in road construction. Asphalt Academy, Pretoria, South Africa.

Technical Guideline (TG1), 2007. The use of modified bituminous binders in road construction. Asphalt Academy, Pretoria, South Africa (Second Edition).

KEY WORDS

Force Ductility, Ductility, Modified Binder, Deformation Energy, TG1