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Cracking of asphalt at low temperature as related to bitumen rheology

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A laboratory investigation of the influence of bitumen rheology on low temperature behaviour of asphalt mixtures is described. Five bitumens from four sources and three different mixture types were studied. Rheological characteristics of the binders were measured using conventional methods (penetration, softening point and viscosity) as well as dynamic mechanical analysis (DMA). Low temperature properties of asphalt characterized by the fracture temperature were measured using thermal stress restrained specimen test (TSRST). Statistically significant relations between rheological characteristics of bitumens and TSRST fracture temperatures of asphalt specimens were established.

1. Introduction

Degradation of roads is caused by several traffic and/or environmental factors and appears as longitudinal and transverse unevenness of the road surface. One common indication of the deterioration of the road is the occurrence of different types of cracks, such as fatigue cracks caused by traffic loading or temperature cycling, cracks caused by frost heave, reflective cracks, and cracks created at low temperature.

Thermally induced cracking of asphalt pavement may be a problem in cold regions (low-temperature cracking) as well as in areas which experience large extremes in daily temperatures (thermal fatigue cracking). Research regarding thermal cracking of asphalt has been carried out over many years [1]. Nevertheless, knowledge in this area is still quite insufficient to control the problem. Current specifications in most countries do not take into account the problem of thermal cracking to a sufficient degree. Furthermore, in cases where requirements on thermal properties, i.e. low temperature properties of the binder, are specified, the corresponding test method is often empirical and its relation to reality questionable. The main reason for this situation is probably the fact that thermally induced cracking of asphalt is a very complex process influenced by many different types of factors, such as material, environment and pavement structure factors [2], not yet fully understood. Among material factors, properties of the binder are probably of the greatest importance. Chemical as well as rheological properties may influence the low temperature behaviour of asphalt mixtures.

In this paper, investigations with the purpose of establishing relationships, if any, between bitumen rheology and low temperature properties of asphalt, are described. The influence of bitumen chemistry and the addition of polymers to the binder is described elsewhere [3, 4].

2. Materials and methods

2.1. Binders and mixtures

Five plain bitumens from four different sources (Venezuela (Laguna), Saudi Arabia, Mexico and Russia) were used in this study. One of the Laguna binders was a B 85 bitumen, while the others were B 180. Characteristics of the bitumens (before mixing with aggregates) are given in Table I.

The aggregate consisted of a crushed granite material from Farsta, which was used in three types of mixtures, dense graded (ABT), stone mastic (ABS) and porous asphalt (ABD), respectively. Slabs were prepared in the laboratory using a mixer (Kalottikone OY, Finland) and a plate compactor (MAP, Spechbach-le-bas, France) with two rubber tyres (diameter 400 mm, width 80 mm). The mixing temperature was in the range 150–170 °C and compaction temperature 140–155 °C, depending on binder and mixture type. The slabs were compacted to void contents in accordance with Swedish requirements. From each slab, five cylindrical specimens were extracted horizontally. The diameter of the specimens tested was 58 ± 1 mm and the length 250 mm ± 2 mm. The maximal particle size was 12 mm in all mixtures and the particle size distributions are shown in Fig. 1. The nominal binder content was 6.2% by weight (ABT), 5.8% by weight (ABS) and 5.2% by weight (ABD), respectively.

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TABLE I Characteristics of bitumens used in this study

Parameter	Bitumen B 85 (Venezuela)	 B 180 (Venezuela)	 B 180 (Saudi Arabia)	 B 180 (Mexico)	 B 180 (Russia)
Pen. (25 °C, 100 g, dm)	86	181	160	164	187
Softening point (°C)	46	38	40	40	42
Dynamic viscosity at 60 °C (Ns m^{-2})	185	66	59	73	32
Kinematic viscosity at 135 °C (mm^2 s^{-1})	356	208	222	260	159

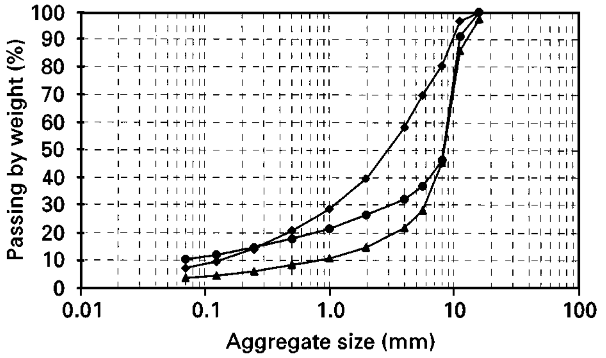

Figure 1 Particle size distribution of the aggregate. (◆) ABT 12; (●) ABS 12; (▲) ABD 12.

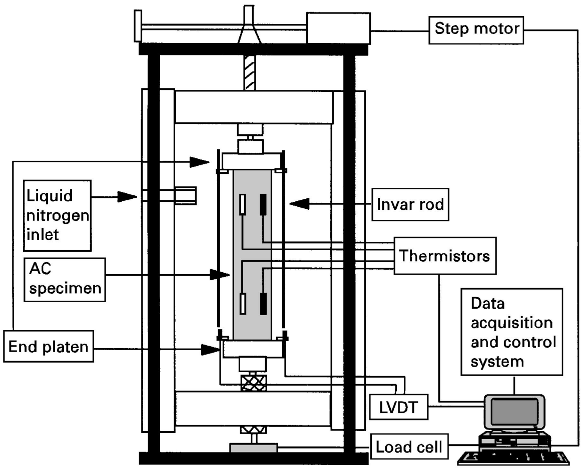

Figure 2 Schematic of the TSRST system.

2.2. Test equipments and procedures

In this study, the thermal stress restrained specimen test (TSRST) was used to determine the low temperature cracking resistance of the asphalt mixtures. After recovering the binder from all the TSRST specimens using rotary evaporator technique, the rheological properties of the binders were characterized using conventional methods (penetration, softening point and viscosity) as well as dynamic mechanical analysis (DMA).

2.2.1. Tensile stress restrained specimen test (TSRST)

The TSRST system is schematically shown in Fig. 2. The basic principle of the test system is to keep the length of the asphalt sample constant during cooling. A cylindrical specimen is mounted in the load frame. The temperature inside the environmental chamber is decreased during the test with the aid of vaporized liquid nitrogen or a refrigerating machine. As the specimen contracts, two linear variable differential transducers (LVDT) sense the movement and a signal is sent to the computer, which in turn causes the screw jack to stretch the specimen back to its original length. As the temperature continues to decrease, the thermal stress inside the sample increases until the specimen breaks. The tests were performed on unaged specimens and specimens aged up to 100 days at 85°C using a cooling rate of 10 °C h^{-1}.

2.2.2. Conventional binder tests

After TSRST, all the asphalt binders were recovered and tested using standardized procedures. The binder rheology was determined by measuring penetration at 25 °C (ASTM D 5), softening point, ring and ball (ASTM D 36), and viscosity at 135 °C (ASTM D 2170), respectively.

2.2.3. Dynamic mechanical analysis (DMA)

General concepts of DMA are shown schematically in Fig. 3. Different types of geometry can be used, such as

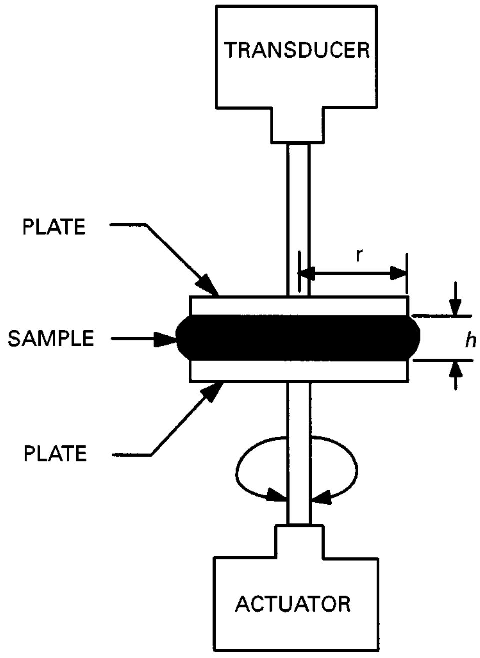

Figure 3 Parallel plate geometry with sample loaded.

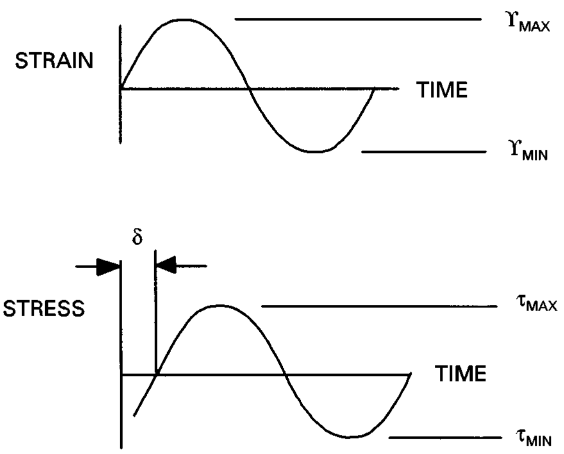

Figure 4 Basic concepts in tests using dynamic shear rheometer. $|G^*| = \tau_{\max} - \tau_{\min}/\Upsilon_{\max} - \Upsilon_{\min}$, where Υ = shear strain (%), $|G^*|$ = magnitude of complex shear modulus (P_a), τ = shear stress (P_a). δ = phase angle (°).

cone and plate, parallel plates and cup and plate. In this study, parallel plates were used. The diameter of the plates is 8 mm. About 0.1 g bitumen was applied to the bottom plate, covering the entire surface, and the plate was then mounted in the rheometer. After heating to the softening point of the bitumen, the sample was brought into contact with the top plate and trimmed, after which the final gap was adjusted to 1.5 mm. The last step of preparation resulted in a slight bulge of the bitumen specimen, which is the desired configuration.

A sine wave was applied by an actuator. The actual strain and deformation force (torque) were measured. The torque and strain readings were sent to a computer. Four temperatures (-30, -20, -10 and 0 °C) and three frequencies (0.628 rad s^{-1}/0.1 Hz, 6.28 rad s^{-1}/1 Hz and 62.8 rad s^{-1}/10 Hz) were used in this study. The sample was conditioned at the testing temperature for 15 min before the frequency sweep. The strain is chosen as small as possible to ensure working in the linear region, but large enough to allow sufficient strain readings at the highest frequency and lowest temperature. Some basic concepts are presented in Fig. 4.

Complex modulus, G^*, is a measure of a material's overall resistance to deformation in dynamic testing and can be expressed as $G^* = G' + iG'' = |G^*|\cos\delta + i|G^*|\sin\delta$. The storage modulus, G', is related to the energy stored and G'', the loss modulus, to the energy lost at deformation. The phase angle, δ, is the phase difference between the strain and stress in an oscillatory deformation and indicates the visco-elastic character of the material. If δ is equal to 0 °, the material is entirely elastic, and, if 90 °, completely viscous.

3. Test results
3.1. TSRSTs

TSRST provides information on several parameters, such as fracture temperature, fracture stress, transition temperature, and slope of the stress-temperature curve below transition temperature, as shown in Fig. 5.

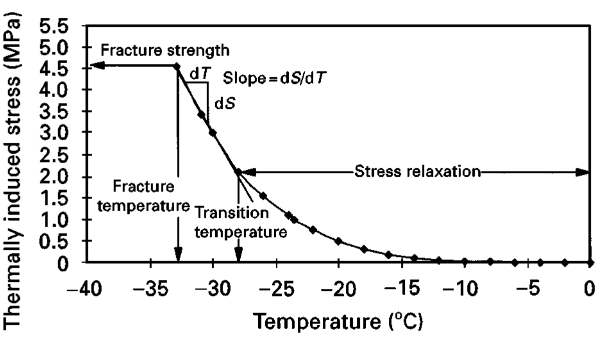

Figure 5 Typical test results of TSRST.

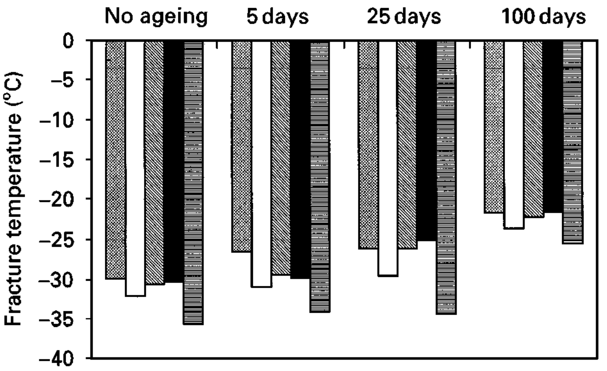

Figure 6 Effect of ageing and binder source/grade on the fracture temperature of dense graded asphalt specimens (ABT). (▨) Lagura 85; (☐) Laguna 180; (■) Saudi Arabia; (■) Mexico; (▤) Russia.

The most important parameter is fracture temperature. In this study, special attention is given to relationships between fracture temperature of asphalt mixtures and rheological characteristics of bitumens. Discussions of other TSRST parameters as well as detailed information of test results are given elsewhere [2].

The fracture temperature of dense graded asphalt mixtures is illustrated in Fig. 6. As can be seen, the fracture temperature is affected not only by the degree of ageing but also by the binder source. For unaged samples, the maximum difference in fracture temperature due to different binders is about 6 °C (Russian and Venezuelan B 85). About 2 °C of this difference might be explained by binder grade (the difference in fracture temperature of mixtures containing Laguna B 85 and Laguna B 180 was about 2 °C). Ageing results in hardening of the binder and, consequently, in an increase in fracture temperature. After 100 days' ageing at 85 °C, the increase in fracture temperature ranges from 8 to 10 °C, the mixture containing the Russian binder showing a slightly greater increase than the others. It should also be noted that the "Russian" mixtures show the best low temperature properties before ageing (fracture temperature about -35 °C). The TSRST results obtained on stone mastic asphalt mixtures were similar to those obtained on dense graded asphalt specimens.

Ageing of porous asphalt (ABD) is faster than ageing of the other two mixture types studied due to higher air void content (Fig. 7). The increase in fracture temperature after 100 days' ageing was only

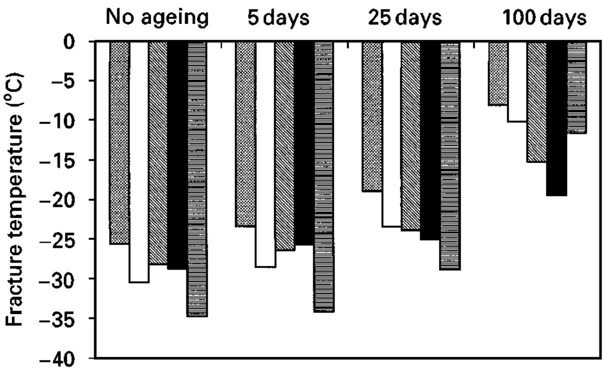

Figure 7 Effect of ageing and binder source/grade on the fracture temperature of porous asphalt specimens (ABD). See the Fig. 6 for code.

about 9 °C for specimens containing Mexico bitumen (the corresponding difference for stone mastic asphalt was 5 °C), but as high as about 23 °C for mixtures containing Russian bitumen. For unaged samples, the maximum difference in fracture temperature due to different binders (Russian and Venezuelan B 85) is somewhat larger (about 9 °C) compared to dense graded mixtures. The effect of binder grade is found to be somewhat greater in porous asphalt compared to stone mastic asphalt; the difference in fracture temperature of unaged porous asphalt mixtures containing Laguna B 85 is about 5 °C higher than the corresponding mixture containing Laguna B 180. This observation supports the common opinion that softer binders are favourable with regard to low-temperature behaviour of asphalt pavements. In this case, it should also be noted that the "Russian" mixtures show the best low temperature properties before ageing (fracture temperature about −35 °C), as was also the case for dense graded asphalt.

3.2. Dynamic mechanical analysis

A great number of measurements of rheological properties of recovered bitumens were performed using the rheometer. Fifty-nine binder samples were analysed at four different temperatures (−30, −20, −10 and 0°C) and three different frequencies (0.1, 1 and 10 Hz), i.e. more than 700 measurements were conducted. Only a selection of the results will be presented in this paper. For more detailed information, see [2].

The effect of temperature and loading rate on complex modulus (G^*) and phase angle (δ) of unaged Laguna B 85 recovered from stone mastic asphalt are presented in Figs 8 and 9. As can be seen, G^* increases when temperature decreases and/or frequency increases, while δ is influenced in the opposite direction.

3.3. Conventional tests

Penetration, softening point and viscosity test results of 59 recovered binders are given in [2].

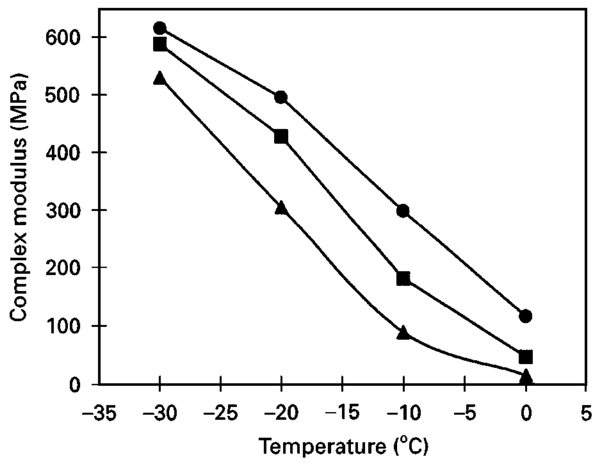

Figure 8 Effect of temperature and loading rate on complex modulus. (▲) 0.1 Hz; (■) 1 Hz; (●) 10 Hz.

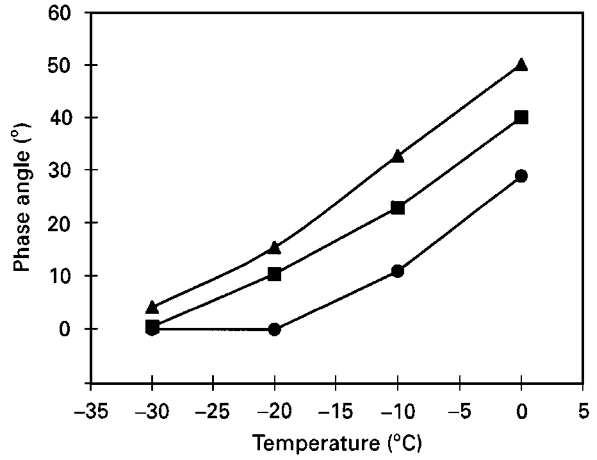

Figure 9 Effect of temperature and loading rate on phase angle. See Fig. 8 for code.

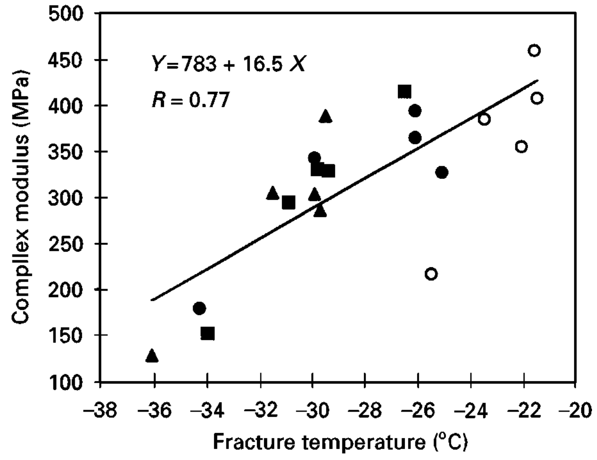

Figure 10 Complex modulus at −20 °C and 1 Hz of bitumens recovered from dense graded asphalt specimens as a function of fracture temperature. (▲) No ageing; (■) 5 days; (●) 25 days; (○) 100 days.

3.4. Regression analysis

In Fig. 10, G^* of binders recovered from dense graded asphalt specimens and tested at −20 °C and 1 Hz is shown as a function of the corresponding fracture temperature. As expected, the modulus values increase at increasing fracture temperature. The correlation is significant at a risk level of 5%.

The corresponding results on porous asphalt are given in Fig. 11. As can be observed, the points representing 100 days' ageing (shown by open circles) differ from the other points, which was also observed when analysing results from stone mastic asphalt specimens. A reason for this divergence is discussed in Section 4.

In Fig. 12, the phase angle of binders recovered from dense graded asphalt mixtures as a function of the corresponding fracture temperature is illustrated (−20 °C, 1 Hz). Figs 10 and 12 are corresponding figures. As indicated in Fig. 12, a linear relationship exists between phase angle of the binder and fracture temperature of the asphalt specimens and the relationship ($R = 0.79$) is equally strong for the complex modulus (Fig. 10). As was the case for the complex modulus, the phase angle/fracture temperature points for porous asphalt samples aged for 100 days diverge from samples aged up to 25 days, as indicated in Fig. 13.

Linear correlations between binder parameters from conventional methods (penetration at 25 °C, softening point, ring and ball, and kinematic viscosity at 135 °C) and fracture temperature of the mixtures were investigated. However, the correlation coefficients obtained were low (0.65 to 0.73).

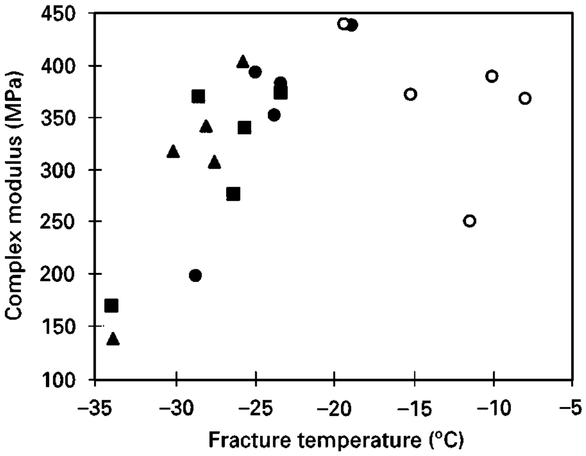

Figure 11 Complex modulus at − 20 °C and 1 Hz of bitumens recovered from porous asphalt specimens as a function of fracture temperature. See Fig. 10 for code.

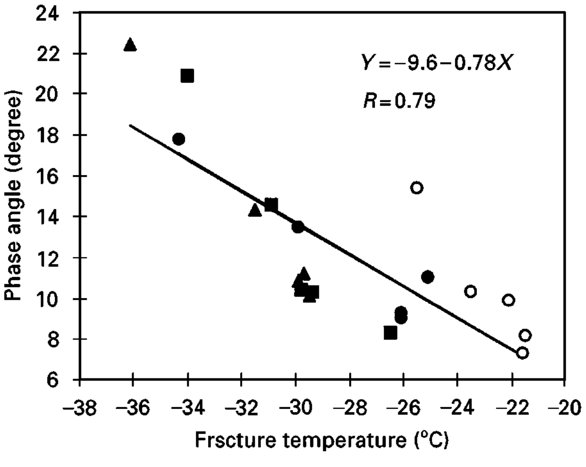

Figure 12 Phase angle at − 20 °C and 1 Hz of bitumens recovered from dense graded asphalt specimens as a function of fracture temperature. See Fig. 10 for code.

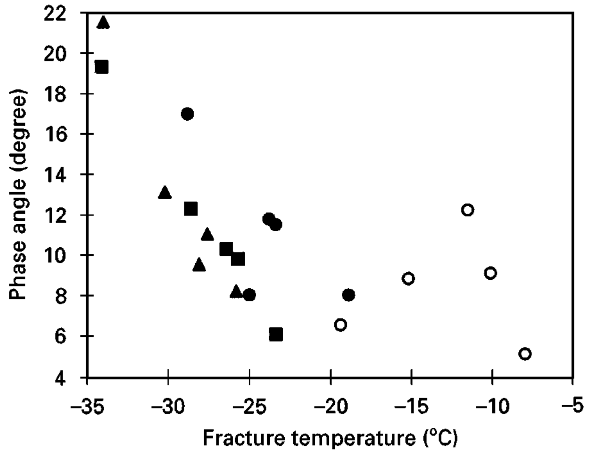

Figure 13 Phase angle at − 20 °C and 1 Hz of bitumens recovered from porous asphalt specimens as a function of fracture temperature. See Fig. 10 for code.

4. Discussion and conclusions

TSRST has proved to be an interesting tool for accelerated testing of the performance of asphalt concrete pavements at low temperature under actual field conditions [5, 6]. A field validation of TSRST has indicated that low-temperature behaviour of asphalt concrete pavements can be predicted by TSRST [7]. No complete evaluation of the variability of the TSRST procedure has been found in the literature. However, Zeng [2] has reported a mean and standard deviation of 1.2 and 0.53 °C, respectively, in fracture temperature difference between two unaged samples from a total of 33 different mixtures.

According to Jung and Vinson [6] the actual cooling rate in the field is normally about 1 to 2 °C h^{-1}. An increase in cooling rate from 1 to 10 °C h^{-1} results in an increase in fracture temperature of about 5 °C. In this project, the cooling rate was chosen as 10 °C h^{-1} to simulate the most severe field conditions. The choice of the relatively high cooling rate is also based on practical reasons; to perform the TSRST in a reasonable time (about 4 h) a cooling rate of 10 °C h^{-1} was necessary.

Rheological properties of bitumen are of fundamental importance for the performance of asphalt concrete pavements in practice. Traditionally, physical characteristics of the binder have been determined using empirical test methods (i.e. penetration and softening point). During the last decade, an increasing interest in using more scientific instruments, rheometers, for measuring the visco-elastic properties of bituminous binders has been observed. In principle, such instruments make it possible to understand the rheology of the bitumen from a more fundamental point of view. However, the science in this area is still under development; a great number of questions related to testing using rheometers are still to be answered, as was recently clearly demonstrated [8].

Regarding ageing, the air void content of the mixture is of considerable significance. Because of the high air void content, oxidative ageing occurs faster in porous asphalt compared to stone mastic and dense graded asphalt, which greatly influences the low temperature behaviour of the asphalt concrete pavement.

This investigation has demonstrated statistically significant relationships between rheological characteristics of bitumen (complex modulus and phase angle) obtained using dynamic mechanical analysis and low temperature properties of asphalt (fracture temperature), as indicated in Figs 10 to 13. However, the deviation from linearity at 100 days of ageing at 85 °C, especially for porous asphalt (Figs 11 and 13), should be observed. It is questionable whether the binder, after such a treatment, really is a bitumen in the full sense of the word. If results on samples aged for 100 days are omitted, a significant correlation (risk level 5%) between complex modulus and fracture temperature is proved for all three mixture types with correlation coefficients between 0.84 and 0.88.

To simulate the field condition, the test temperature of the rheometer should be chosen so that it is sufficiently low. DMA was performed on binders down to $-30\,^{\circ}\mathrm{C}$. However, it should be noted that, in this investigation, some test results obtained at $-30\,^{\circ}\mathrm{C}$ were unreasonable because of the problem of adhesion between the binder and testing plates.

The results of the rheological tests presented in this study indicate that rheometers may be valuable tools for predicting performance-related properties of asphalt pavements, in this case resistance to low-temperature cracking. However, much research is still needed before a more definitive opinion on this complex issue can be given.

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References

1. L. F. RADER, Proc. Assn Asphalt Paving Technol. **5** (1936) 29.
2. H. ZENG, PhD thesis, Division of Highway Engineering of the Royal Institute of Technology, 1995, Stockholm.
3. U. ISACSSON and H. ZENG, *Construction and Building Materials* **11** (1997) 83.
4. U. ISACSSON and H. ZENG, *Materials and Structures* **31** (1998) 58.
5. A. F. STOCK and W. ARAND, Proc. Assn Asphalt Paving Technol. **62** (1993) 23.
6. D. H. JUNG and T. S. VINSON, *ibid.* **62** (1993) 54
7. H. KANERVA, T. S. VINSON and H. ZENG, SHRP-A-401 (1994).
8. "The Rheology of Bituminous Binders", European Workshop organized by Eurobitume, Brussels, 5–7 April (1995).

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