Laboratory Evaluation of Asphalt Mixes Using Engineered Binders Under Static and Cyclic Thermal Stresses

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ABSTRACT

There are two main approaches to develop reliable and predictable asphalt concrete mixtures - improve the mix design by selecting a better aggregate type and gradation or improve the mix performance through the use of engineered asphalt cement. SHRP (Strategic Highway Research Program) guidelines require combining proper aggregate with the most promising engineered asphalt binder.

A comprehensive testing program at Carleton University on asphalt concrete mixes used four types of asphalt binders: PG 70-28, PG 58-40, PG 58-22 (conventional AC 85/100) and PG 52-28 (AC 150/200). Tests carried out in the environmental chamber included applying indirect tensile stresses to core specimens as well as static and cyclic direct tensile stresses to asphalt beams under severely cold temperatures.

The results of this study indicate that an engineered asphalt cement such as PG 70-28 can perform according to the design specifications and can also improve the mechanical and thermal properties of the mix by increasing its tensile strength and its resistance to thermal cracking through higher strain values at failure. For example, at a temperature of -46 C the tensile strength of mixes with engineered binders was 13 % to 85 % higher than the tensile strength of mixes with conventional binders. In addition, the strain values at failure were more than doubled for mixes with engineered asphalt binders.

RÉSUMÉ

Il y a deux approches principales pour mettre au point des enrobés de béton bitumineux fiables et prévisibles : améliorer la formulation par le choix d'un meilleur type de granulats ou améliorer la performance de l'enrobé par l'utilisation de bitume conçu par ingénierie. Les directives de SHRP (Programme de Recherche Routière Stratégique) exigent la combinaison de granulats appropriés avec le liant bitumineux dont la conception par ingénierie est la plus prometteuse.

Un programme exhaustif d'essai à l'université Carleton sur des enrobés bitumineux a utilisé quatre types de liants bitumineux : PG 70-28, PG 58-40, PG 58-22 (bitume 85/100 conventionnel) et PG 52-28 (bitume 150/200 conventionnel). Les essais ont été réalisés dans une chambre à environnement contrôlé et comportait l'application de contraintes de traction indirecte sur des carottes ainsi que des contraintes statiques et cycliques de traction directe sur des poutres de bitume sous des températures très froides.

Les résultats de cette étude montre qu'un bitume conçu par ingénierie tel que le PG 70-28 peut se comporter selon les spécifications de design et peut aussi améliorer les propriétés mécaniques et thermiques de l'enrobé en augmentant sa résistance à la traction et à la fissuration thermique au moyen de valeurs supérieures de déformation à la rupture. Par exemple, à la température de - 46 oC la résistance à la traction des enrobés était de 13 % à 85 % supérieure à la résistance à la traction des enrobés aux liants conventionnels. En outre, les valeurs de déformation à la rupture étaient plus que doublées pour les enrobés avec des liants conçus par ingénierie.

1. INTRODUCTION

The long term performance of asphalt pavements can be significantly affected by the cracks that may be induced due to severe environmental conditions. The impact of thermally induced cracks on the structural integrity of asphalt layers has been recognized by the Strategic Highway Research Program, SHRP. As a result, special attention has been given to cold temperature cracking in the newly developed Superpave Level 3 design method.

Thermal cracking in asphalt layers occurs due to (i) a severe temperature drop causing the thermal strains to exceed the limiting tensile strength of the material, or (ii) a cyclic temperature variation within the plastic zone causing irreversible damage to asphalt, leading to the loosening of aggregate particles and cracking after a relatively small number of cycles [1,2,3]. Pavement engineers and researchers have invested a great deal of time and money to develop reliable asphalt concrete mixtures which can resist the effect of severe thermal changes. At the present time, there are two main approaches to achieve this objective. The first approach is to improve the mix design through the selection of a better aggregate type and gradation. The second approach is to improve the mix performance through the use of engineered asphalt cement. According to the new design guidelines developed by SHRP, optimization of the mechanical properties of the asphalt mixture requires the use of proper aggregates in association with the most promising engineered asphalt binder.

Clearly, significant savings can be achieved if the use of engineered binders can improve the resistance of the asphalt mixture to cold temperature cracking. Therefore, evaluation of the resistance of asphalt mixes using newly developed binders to stresses and strains generated by cold temperature is an important task. The main objectives of this paper are to present the outline and results of a comprehensive testing program carried out to determine the tensile strength of beams made of asphalt mixes using a number of asphalt cements, including the newly engineered McAsphalt binders.

2. OBJECTIVES AND SCOPE

The thermal behaviour of asphalt mixes and their resistance to cold temperature cracking can be related to strains at which failure occurs. At very low temperatures the behaviour of asphalt mix usually shows brittle behaviour. To assess the cold temperature behaviour of asphalt mixes, a laboratory testing program was developed and implemented utilizing the cold temperature testing facility at Carleton University. The main objectives of the testing program are as follows :

1. To plan and carry out a comprehensive testing program on asphalt specimens using engineered as well as conventional types of asphalt binder.

2. To investigate the effectiveness of the engineered asphalt binders by performing laboratory tests on asphalt mixes, and to compare the test results with other results from similar asphalt specimens using conventional binders.

3. To provide the Canadian Paving Industry with a more reliable testing method for assessing the long term performance of asphalt binders designed to minimize cold temperature cracking.

The present paper describes a testing program that uses laboratory fabricated asphalt beams to determine the thermal behaviour and performance of asphalt mixes utilizing different types of asphalt binders. The objective of the testing program is achieved through the application of direct static and cyclic tensile stresses using the Environmental Chamber Test Facility at Carleton University, Figure 1. The direct cyclic tests are performed to the authors knowledge, for the first time, at a temperature of -46°C. The direct static tensile tests are performed at temperatures of -46°C , -34°C and 0°C.

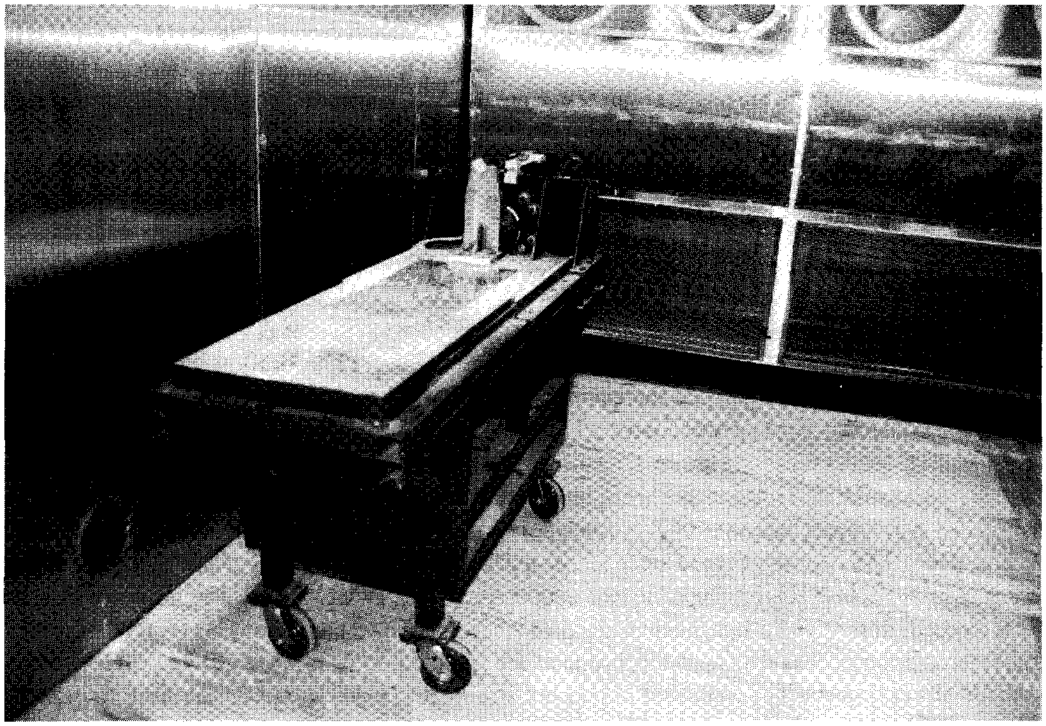

Figure 1 Inside the Environmental Chamber of the Direct Tensile Strength Test Facility

3. OUTLINE OF THE TESTING PROGRAM

The experimental investigation consisted of three stages. The first stage involved the selection of the mix design. This stage included the design and selection of an HL-3 asphalt mixture (described in MTO's Pavement Design and Rehabilitation Manual SDO-90-01, January 1990, using a maximum aggregate size of 16 mm) using four asphalt binders, PG 70-28, PG 58-40, PG 58-22 and PG 52-28, (see Appendix I). More than 120 asphalt core specimens were produced, representing five different asphalt content ratios. The 120 core samples were then utilized to determine the densities and indirect tensile strength of fabricated core specimens at -46°C. The outcome of this stage was the selection of an asphalt content ratio of 5.5 % for optimum mix design.

The next stage involved the fabrication of 96 asphalt beams or slabs from asphalt mixes designed on the basis of the results of the previous stage. The asphalt beams were constructed using special wooden moulds. The inside surfaces of the moulds were lined with stainless steel plates. Each mould was anchored to the floor of the laboratory in order to ensure sufficient and uniform application of the vibratory compaction effort. A plate vibratory compactor weighing 79 kg, and capable of applying a force of 1066 kg at 95 Hz, was used to compact the asphalt beams through a stiffened cover of the plywood mould. Beam samples were compacted for 4 minutes and kept in their moulds for 72 hours after which they were removed from the moulds and stored on a flat surface prior to testing. A masonry saw was used to cut each beam sample into two identical halves. Half of the constructed beams were used to measure the maximum tensile strength and strain at failure under constant rate of displacement. Tests were carried out at three temperatures: 0°, -34° and -46°C.

The results of the direct static tensile strength test were used to design and complete the third stage of this investigation. In order to assess the effect of the asphalt binder on the long term performance of the asphalt mixes, cyclic direct tensile strength tests were carried out at -46 °C. The testing method and program are discussed below.

3.1 Direct Static Tensile Strength Test

This stage of the testing dealt with the evaluation of the thermal behaviour of the selected mixes under severe cold temperature as low as -46 °C. Special arrangements were made to allow the utilization of liquid nitrogen to lower the temperature inside the environmental chamber to -46 °C. As described earlier, asphalt mixes with 5.5% asphalt content were used to fabricate beam specimens. For each of the four asphalt binders, 24 asphalt beams were constructed, resulting in a total of 96 beams. Static and cyclic direct tensile strength tests on asphalt concrete mixes were then carried out in the Environmental Chamber at Carleton University. The static direct tensile strength tests were carried out at three different cold temperatures: -46°C , -34°C and 0°C. The results of these tests are important since they provide these thermal properties of asphalt mixes relevant to cracking due to severe temperature drop, as well as the maximum tensile strength, maximum strain at failure and other mechanical properties related to the behaviour of asphalt mixes under severe cold temperatures. The data and test results of the static direct tests were utilized to design the direct cyclic tensile strength tests. The observed maximum strain from the static tests was used to determine the level of constant cyclic strain to be induced in the beam specimens.

The preparation and testing procedures for each beam consisted of the following steps:

1. The temperature inside the Environmental Chamber was adjusted to the test temperature 24 hours before testing. Special arrangements were made to achieve a temperature as cold as -46°C.

2. The hydraulic actuator was calibrated to apply both a static as well as a predefined cyclic displacement.

3. The beam specimen was placed on the top of the loading table. The loading table consists of a fixed and a moving steel plate. The moving plate is connected to a load cell and to an LVDT (linear variable displacement transducer) positioning system with feedback to a data acquisition computer.

4. The moving plate was placed on a Teflon sheet to minimize friction forces and the load cell was calibrated accordingly.

5. A dummy asphalt specimen was placed in the Environmental Chamber with a thermocouple connected to its centre to monitor its temperature in order to ensure that thermally uniform conditions prevail.

6. The mounting plates were glued to the underside of the specimen using high strength epoxy. The surface area of the specimen in contact with the glue exceeded twice the area of the cross section of the specimen. Since the shear stress did not exceed one half of the tensile stress, the failure was initiated by the tensile stress.

7. The specimen was pre-cooled at the test temperature for another 24 hours.

8. The plates/test specimen were fastened to the test table inside the environmental chamber for 2 hours before applying the displacement/load.

9. The displacement was applied at a selected rate until failure occurred. The recorded data included load/displacement values up to failure.

3.2 Direct Cyclic Tensile Strength Test

The results of the static tests were used to design the cyclic testing program.The test sequence is shown in Table 1. Testing began with an applied maximum cyclic displacement of 0.4 mm. Tests at this displacement were continued for a large number of cycles (30,000) or until failure, whichever occurred first. The number of cycles had to be limited to 30,000 due to time limitations placed by safety regulations. When failure did not occur in 30,000 cycles, the maximum cyclic displacement was increased to 0.6 mm and the testing was resumed until failure or for no more than 15,000 cycles, whichever occurred first. If the specimen did not fail even at the end of the 15,000 cycles, the test was continued at a maximum displacement of 0.8 mm for up to a maximum number of 7500 cycles. For specimens which did not fail at the end of these 7500 cycles, cyclic load was applied at a maximum displacement of 1 mm until failure took place. Thus, specimens that reached Level 4 (last stage) of the test program had been subjected to at least 52500 load cycles at -46 °C.

The data acquisition system recorded the load applied to the sample, the constant maximum displacement, and the number of cycles of load applications. Owing to the large volume of data that could be generated, data was recorded only at selected intervals for cycles number 1, 11, 21, 101, 111, etc. The typical duration of a cyclic test was between 3 and 5 days.

Table 1: Cyclic Tensile Strength Testing Sequence

Level	Max. Displacement (mm)	No. of Cycles
1	0.4	30,000
2	0.6	15,000
3	0.8	7,500
4	1.0	until failure

4. TEST RESULTS

In general, the results obtained from the direct tensile static and the constant displacement cyclic tests showed that engineered asphalt binders can provide thermal properties and long term performance that are superior to those obtained with conventional binders. The two engineered binders, PG 70-28 and PG 58-40, evaluated in this study sustained higher number of fatigue cycles, had higher tensile strength, and absorbed relatively higher amount of strain energy specially under severe cold temperatures, -30 °C or lower. The following sections present the results of the test program.

4.1 Direct Tensile Strength

Figures 2 to 5 show typical direct tensile strength results obtained from tests performed at 0°C, -34°C and -46°C on beam specimens having the four different asphalt binders. Figure 2 shows the effect of temperature on beam samples fabricated using PG 58-40. As shown in the figure, the engineered asphalt binder provided its highest tensile strength at the lowest temperature of -46°C. The stiffness (as represented by the slope of the stress/strain curve) was considerably higher at the test temperature of -34°C than at 0°C. However, there was virtually no difference between the stiffness at -34°C and that at -46°C. Another important observation is the fact that strain at peak stress was higher at -46°C than at -34°C. It should be noted that mixes using PG 58-40 exhibited a very ductile behaviour at 0°C which was not observed in mixes made with any of the other three binders.

Figure 3 shows results of similar tests carried out on asphalt concrete beams using engineered binder PG 70-28. It should be noted that this binder is expected to perform well at temperatures as cold as -28 °C but not at temperatures lower than -34°C. The results shown in the figure suggest that the tensile stresses and strains at temperatures of 0°C and -34°C are very close to each other and that specimens tested at these temperatures exhibit relatively higher ductility. In addition, tests performed on asphalt beams at a temperature of -46°C gave a tensile strength comparable to those obtained at the warmer test temperatures.

Figure 4 shows typical results obtained from direct tensile strength tests on beam specimens constructed from asphalt mixes using binder PG 52-28 (AC 150/200). As expected from this softer binder, the mix showed some improvement in ductility (which is proportional to strain at failure) between 0°C and -34°C. However, as the test temperature was dropped below -34°C and approached -46°C, a significant drop was observed in the strain at failure.

Figure 5 shows typical results obtained from tests performed on beam specimens using binder PG 58-22 (conventional AC 85/100). The results showed a brittle behaviour in samples tested at temperatures equal to or less than -34°C. It is seen from the figure that while the sample tested at 0°C failed at strain of 3.5 %, the other two samples failed at a strain value of 2 %. Also, the maximum tensile strength observed at 0°C was at least 35 % higher than the strength values achieved at the two lower temperatures. Clearly, a drop in tensile strength of asphalt mixes with a drop in temperature is not a favourable property, since thermal stresses tend to increase with decreasing temperatures. Therefore, the use of this binder is not recommended for producing asphalt mixes for temperatures lower than -34°C. This observation is supported by the results presented in Figure 5.

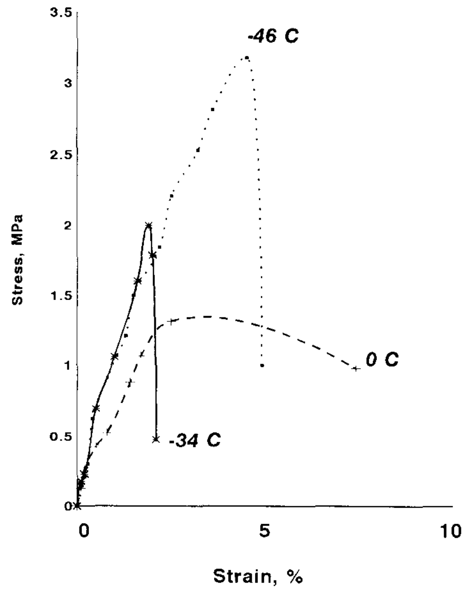

Figure 2 Typical Direct Tensile Strength Test Results for an Asphalt Mix with PG 58-40 Binder

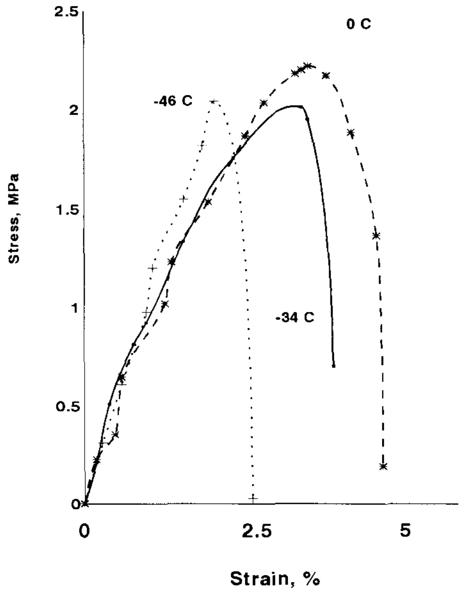

Figure 3 Typical Direct Tensile Strength Test Results for an Asphalt Mix with PG 70-28 Binder

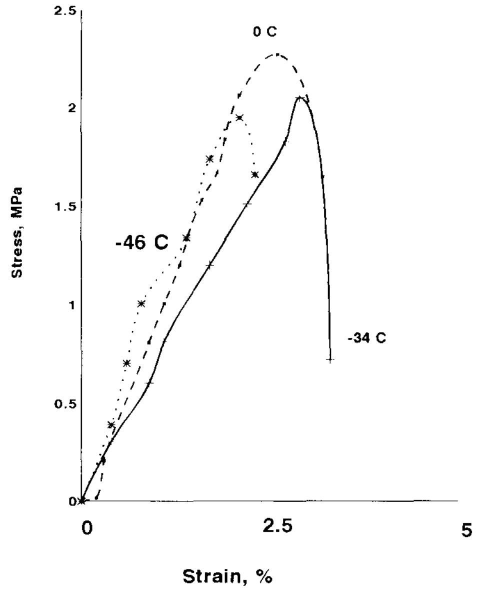

Figure 4 Typical Direct Tensile Strength Test Results for an Asphalt Mix with PG 52-28 Binder

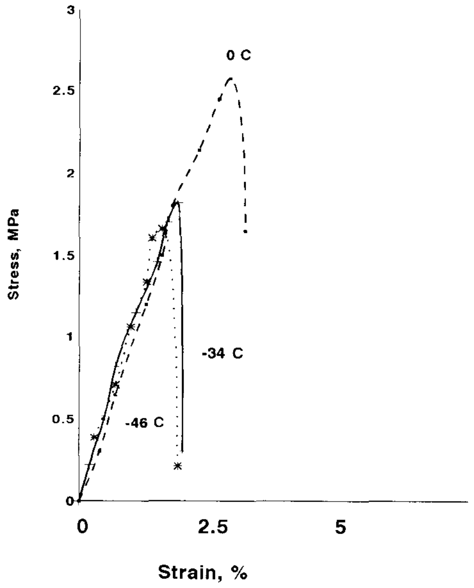

Figure 5 Typical Direct Tensile Strength Test Results for an Asphalt Mix with PG 58-22 Binder

Figures 6 and 7 and Table 2 illustrate the influence of the type of binder and test temperature on the mean values of the maximum tensile strength and stiffness up to failure. For temperatures lower than -25°C asphalt mixes made with two engineered binders PG 70-28 and PG 58-40 had higher tensile strength than mixes with conventional binders. In addition, between -25°C and 0°C, engineered binder PG 70-28 gave the highest strength. Engineered binder PG 58-40 gave the lowest strength between -20°C and 0°C. However, as shown in Figure 2 (which represents typical results) and Table 2 (which shows the average results of three test samples), mixes using this binder had the highest strain at peak stress.

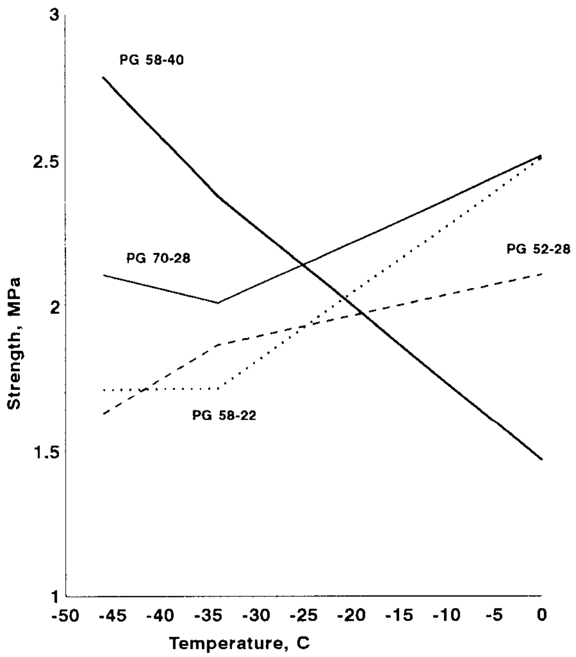

Figure 6 Effect of Temperature and Binder Type on Average Tensile Strength of Asphalt Mix

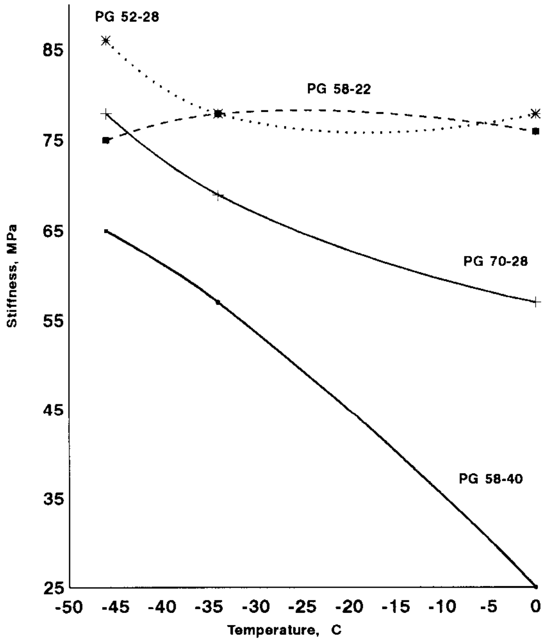

Figure 7 Effect of Temperature and Type of Binder on the Tensile Stiffness of Asphalt Mix

Figure 7 presents the variation of stiffness (calculated by dividing the mean of maximum stresses by the mean of the strains at peak stress) with temperature. The engineered asphalt binders PG 58-40 and PG 70-28 exhibit significantly lower stiffness and hence give greater ductility than the conventional binders throughout the temperature range -46°C and 0°C. It is also important to note that the stiffness of the engineered binders showed a steady and nearly linear increase as the temperature decreased. This behaviour is the result of improvement in the mix behaviour. In contrast, the thermal properties of the conventional binders (PG 48-22 and PG 52-28) appear to deteriorate as the temperature dropped from 0°C to -46°C.

The results given in Table 2 indicate that the thermal behaviour of the PG 52-28 (conventional 150/200) is slightly better (except at -34°C) than that of the PG 58-22 (conventional AC 85/100). Clearly, both conventional binders show a higher degree of brittleness at temperatures lower than -34 °C as indicated by the low strain values at failure,i.e. 1.9% and 2.3% respectively.

Table 2: Mean Stiffness* (MPa) and Average Maximum Strain Values of Polymer-Modified (PG 58-40 and PG 70-28) and Conventional Asphalts**

Temperature	PG 58-40	PG 70-28	PG 58-22	PG 52-28
0 ° C	25 (6.0%)	57 (4.4%)	78 (2.7%)	76 (3.3%)
-34 °C	57 (4.2%)	69 (2.9%)	78 (2.4%)	78 (2.2%)
-46 °C	65 (4.3%)	78 (2.7%)	86 (1.9%)	75 (2.3%)

* Mean stiffeness defined as the average of peak stress divided by strain at peak stress of three samples

** values in brackets are strain

4.2 Cyclic Displacement Tests

The cyclic displacement tests were performed at temperature of -46°C. It should be mentioned that, to the authors' knowledge, this is the first time that asphalt beams have been subjected to cyclic displacement at such low temperatures. The results of the test support the conclusions and findings obtained from the static direct tensile strength tests. The mixes using PG 58-40 sustained the highest number of cyclic displacement as well as the largest maximum displacement. The data show that PG 58-40 failed at level 4, or after application of 1.0 mm displacement. On the other hand, the PG 70-28 test samples failed at level 3, or after cycles of 0.8 mm displacement. The PG 52-28 test samples failed at level 2 or after cyclic displacement of 0.6 mm, while the PG 58-22 test samples could not sustain more than a few hundred cycles at level 1 or the lowest displacement of 0.4 mm. Figures 8 to 11 show typical test results obtained from the cyclic displacement tests.

Figures 8a to 8c show that despite the relatively large number of cycles, the mixes made of PG 58-40 essentially behaved linearly elastically with very little hysteretic energy dissipation. This appears to be also the case in the early cycles at level 4 until the mix begins to behave as a viscous material, with a well-defined yield plateau. However, despite the loss of stiffness at this higher level of displacement, there is no evidence of hysteresis. This implies no accumulation of damage.

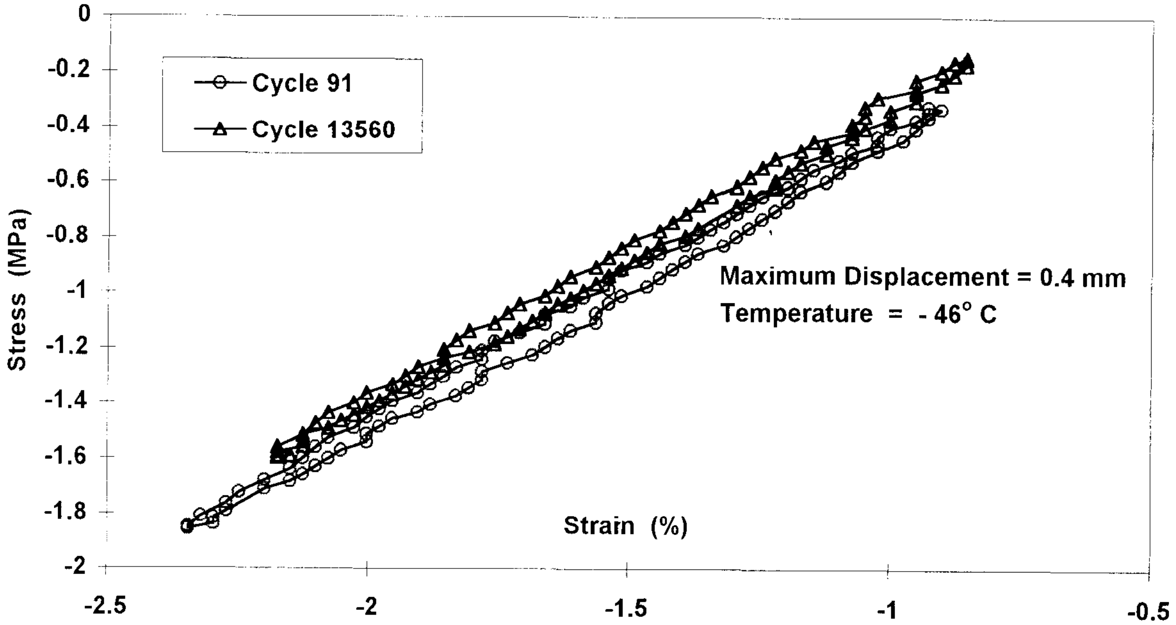

Figure 8a Typical Tensile Strength Cyclic Test Results at Level 1 Displacement of PG 58-40 Binder Mix

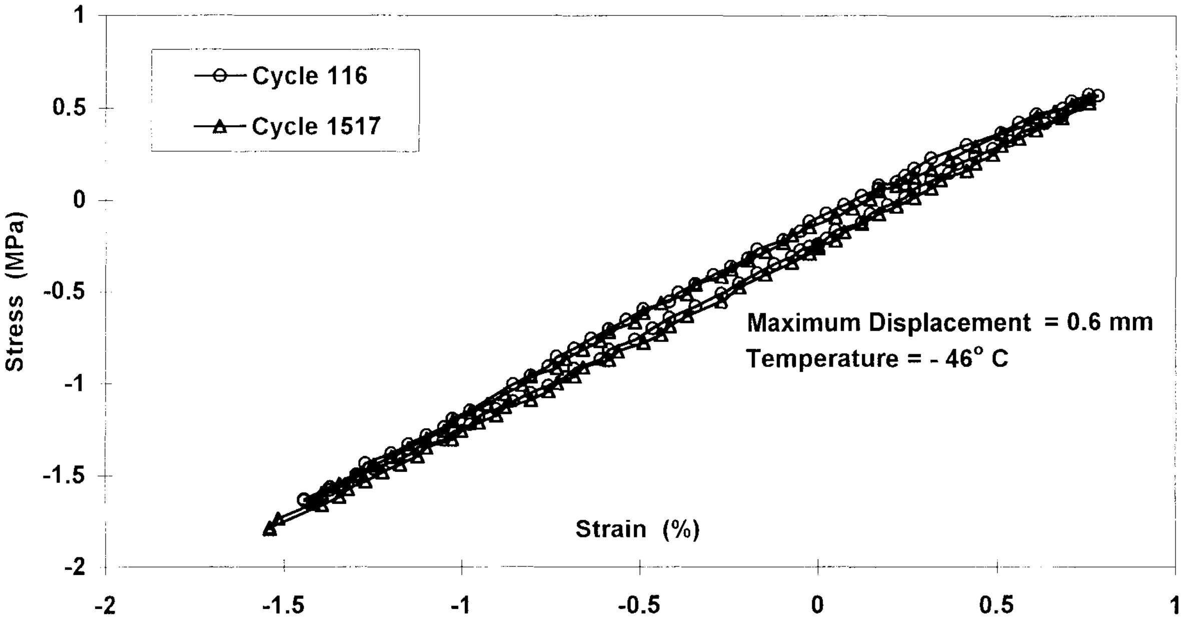

Figure 8b Typical Tensile Strength Cyclic Test Results at Level 2 Displacement of PG 58-40 Binder Mix

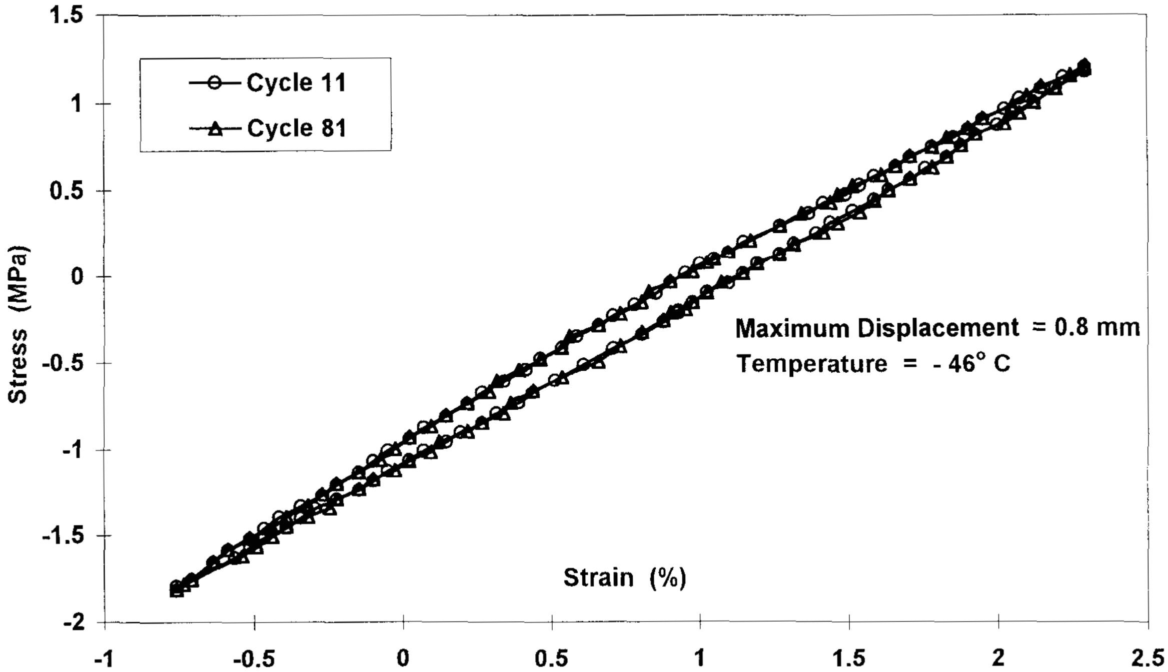

Figure 8c Typical Tensile Strength Cyclic Test Results at Level 3 Displacement of PG 58-40 Binder Mix

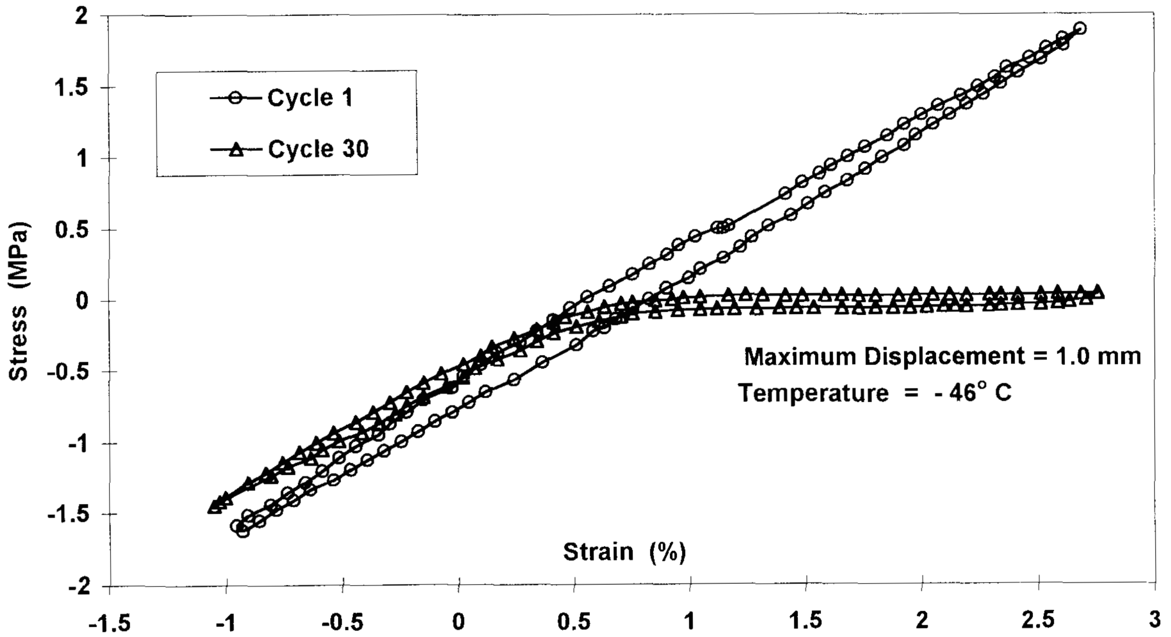

Figure 8d Typical Tensile Strength Cyclic Test Results at Level 4 Displacement of PG 58-40 Binder Mix

The same behaviour is exhibited by mixes from PG 70-28 up to level 2, but at level 3 complete failure occurred, Figures 9a to 9c.

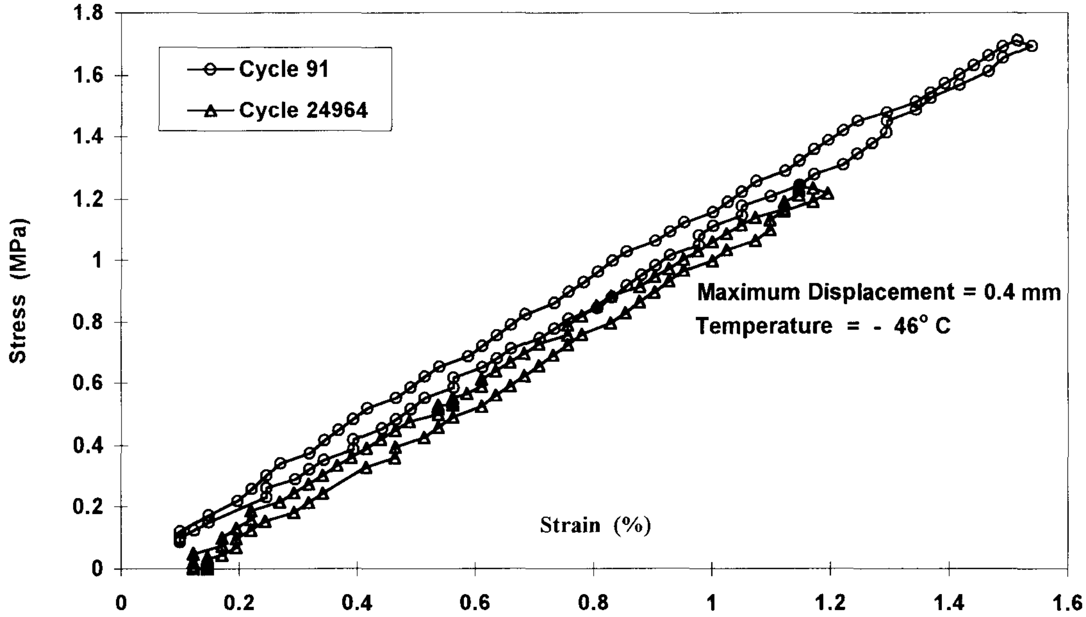

Figure 9a Typical Tensile Strength Cyclic Test results at Level 1 Displacement of PG 70-28 Binder

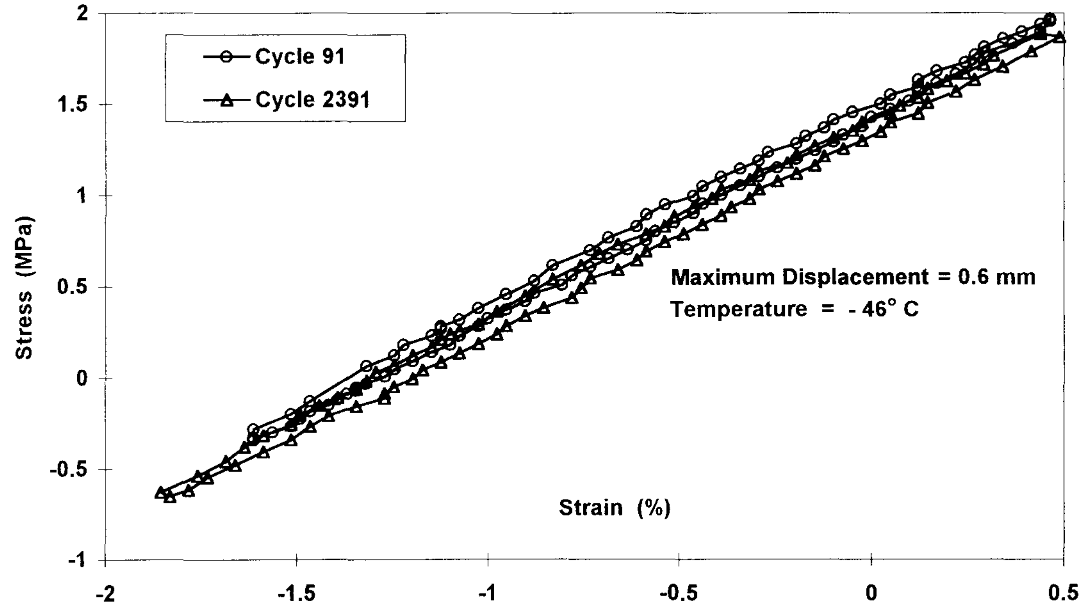

Figure 9b Typical Tensile Strength Cyclic Test Results at Level 2 Displacement of PG 70-28 Binder Mix

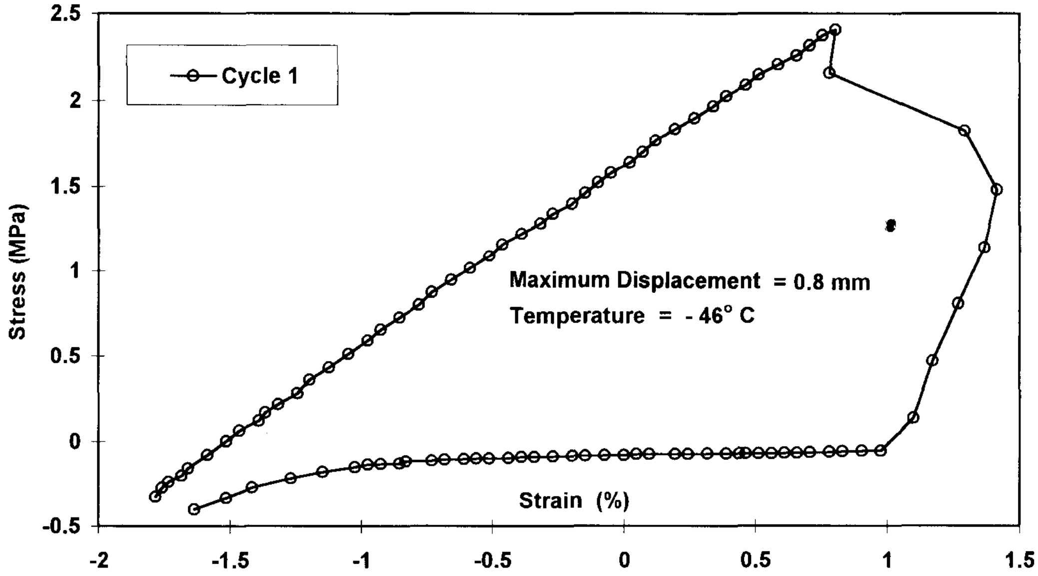

Figure 9c Typical Tensile Strength Cyclic Test Results at Level 3 Displacement of PG 70-28 Binder Mix

Figure 10a illustrates the response of the mix made with PG 52-28 at Level 1. Although this curve shows some hysteretic behaviour and reduction in stiffness, overall it is comparable to the response of the other mixes at the same level. But in Figure 10b, the same mix becomes viscous after 4313 cycles at level 2. Recall that the mix from PG 58-40 did not reach viscous behaviour until level 4.

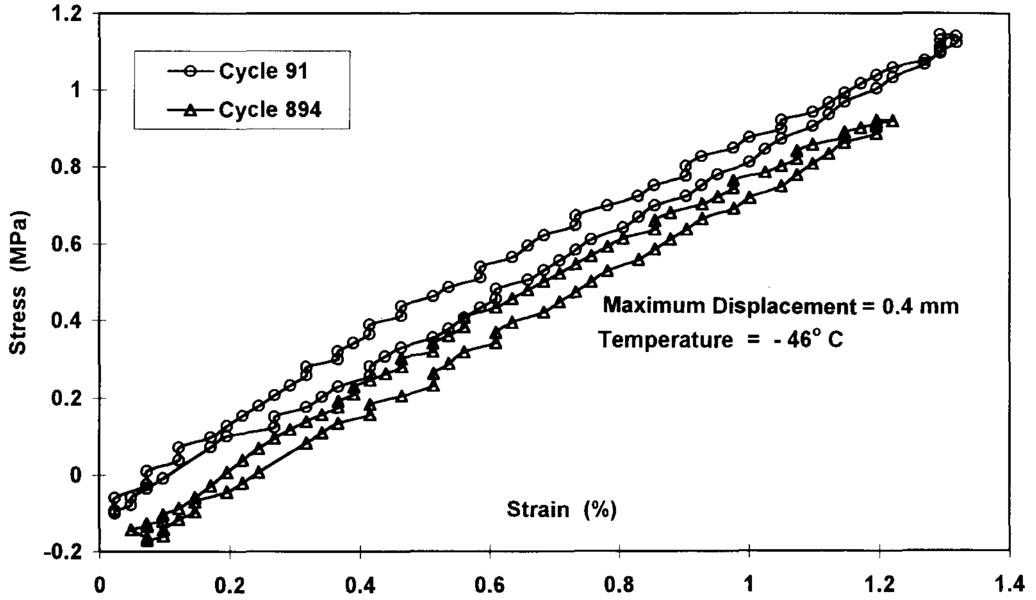

Figure 10a Typical Tensile Strength Cyclic Test Results at Level 1 Displacement of PG 52-28 Binder Mix

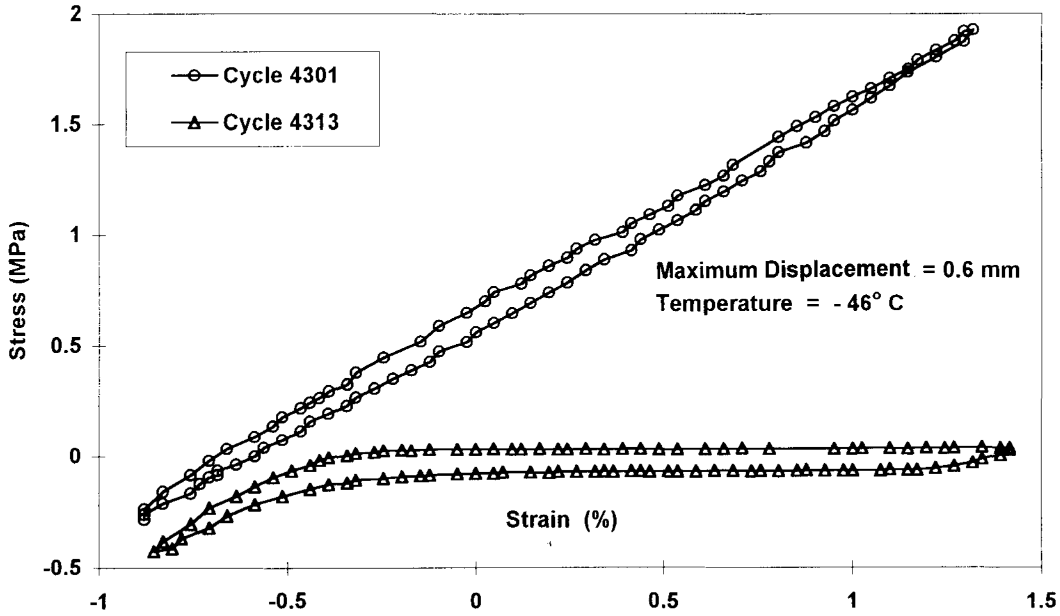

Figure 10b Typical Tensile Strength Cyclic Test Results at Level 2 Displacement of PG 52-28 Binder Mix

Finally, Figure 11a shows the cyclic stress-strain response of the mix made with PG 58-22 at Level 1. The loss of stiffness as exhibited by the plateau in the curve is evident at this low level of imposed displacement. The higher level of energy dissipation (i.e. the area bounded by the hysteretic curve) also implies greater accumulation of damage than in the other mixes at comparable level. Figure 11b shows a PG 58-22 sample failed after the application of only one cycle of 6-mm displacement.

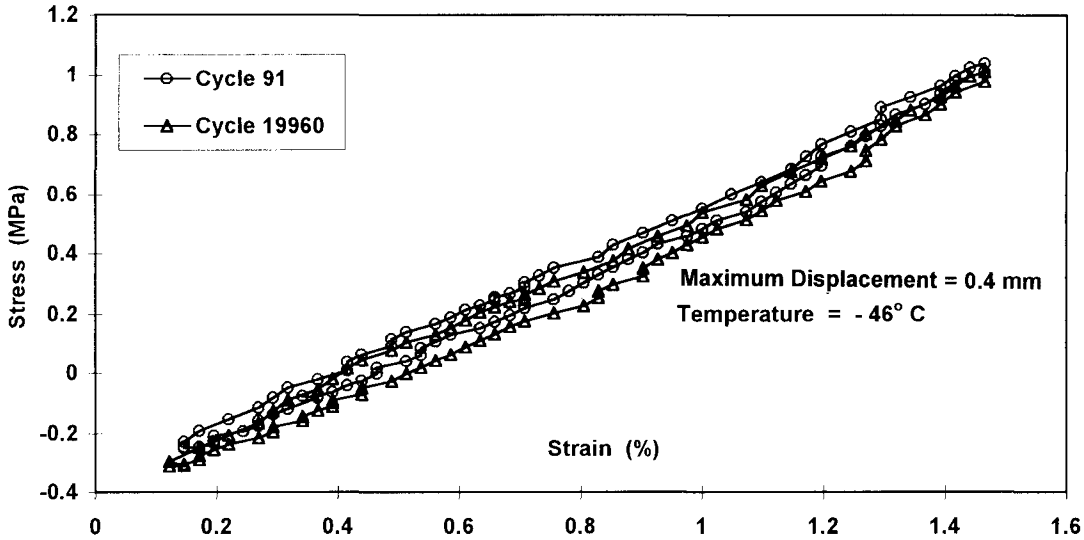

Figure 11a Typical Tensile Strength Cyclic Test Results at Level 1 Displacement of PG 58-22 Binder Mix

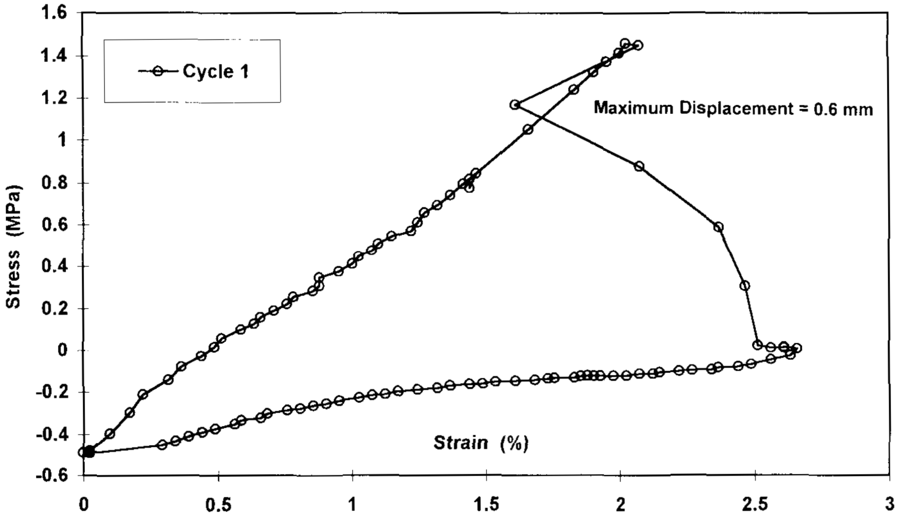

Figure 11b Typical Tensile Strength Cyclic Test Results at Level 2 Displacement of PG 58-22 Binder Mix

Figure 12 shows the relationship between the average number of cycles and the applied maximum displacement for each of the four binders. As seen in the figure, the two engineered binders, PG 70-28 and PG 52-28 provided asphalt mixes which could sustain the highest number of cycles at -46°C. On the other hand, asphalt samples made of the conventional binders failed at significantly lower number of load cycles. It should be pointed out that the current results agree with the SHRP grades.

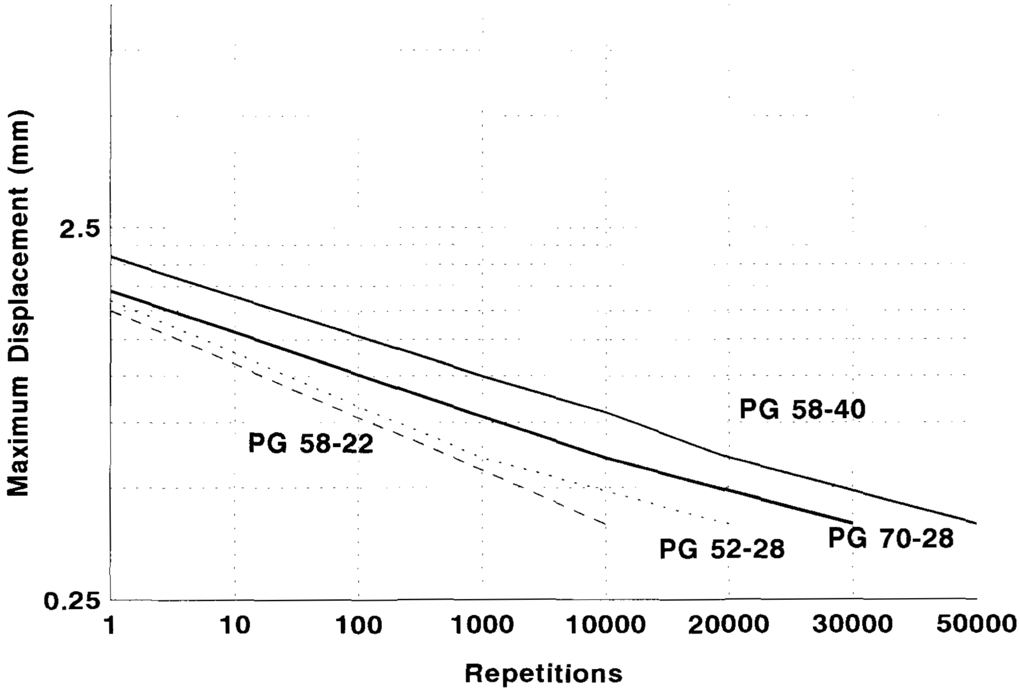

Figure 12 Results of Cyclic Displacement Tests on Mixes with Different Binders at -46°C

5. SUMMARY AND CONCLUSIONS

The results and observations presented in this paper validate the SHRP grades as shown by the superior thermal properties and long term performance of the two engineered binders. Also, the results show that while PG 70-28 and PG 52-28 have the same low end performance temperature, PG 70-28 performed better than the conventional PG 52-28 (AC 150/200). These improved thermal properties are explained by the fact that PG 70-28 is a polymer modified binder. In addition to these general conclusions the results of the testing program support the following conclusions:

1. Engineered asphalt binders such as PG 58-40 and PG 70-28, which are produced by McAsphalt, can perform according to their designed specifications. This is supported by the higher tensile strength, higher strain at failure and the lower stiffness under severe cold temperatures.

2. The long term performance of the mixes using either PG 70-28 or PG 58-40 was shown to be superior to that of the softer PG 52-28 and more resistant to thermal stresses than the brittle PG 58-22.

3. The test results support the grading system suggested by SHRP for its new Superpave mix design method.

4. The testing methods and procedures presented in the paper can be adopted to provide a reliable assessment of the thermal behaviour of conventional and engineered asphalt binders.

Finally, it is important to note that the PG 58-40 used in this investigation is the same asphalt binder which was used in the construction of a section in Petawawa test site which is an official FHWA SPA-9 test site. It is hoped that results from that field section will confirm the findings of this laboratory study.

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APPENDIX A

SHRP (STRATEGIC HIGHWAY RESEARCH PROGRAM) TEST DATA ON THE FOUR ASPHALT CEMENTS USED IN THE STUDY

Table A1: Properties of the PG 58-22 (AC 85/100) used in the Study

Test Type	Test Results	Specifications
Tests on Unaged Material		
Brookfield viscosity, 135°C, mPa.s	0.321	3 max
Flash Point, Cleveland Open Cup (COC), °C	260 +	230 min
G*/sin delta @ 58°C, 10 rad/sec, kPa	1.93	1.0 min
Tests on RTFO Residue		
% Loss Weight	.232	1.0 max
G*/sin delta @ 58°C, 10 rad/sec, kPa	**5.62**	**2.2 min**
Tests on PAV (after RTFO) (Run @ 100°C) Residue		
G* X sin delta @ 22°C,10 rad/sec, kPa	4793	5000 max
Bending Beam		
Creep Stiffness, S, 60s, -12°C, kPa	121000	300000 max
Slope, m, 60 s, -12°C	0.354	0.3 min

Table A2: Properties of the PG 52-28 (AC 150/200) used in the Study

Test Type	Test Results	Specifications
Tests on Unaged Material		
Brookfield viscosity, 135°C, mPa.s	0.211	3 max
Flash Point Cleveland Open Cup (COC) °C	260 +	230 min
G*/sin delta @ 58°C, 10 rad/sec, kPa	1.61	1.0 min
Tests on RTFO Residue		
% Loss Weight	.238	1.0 max
G*/sin delta @ 58°C,10 rad/sec, kPa	3.63	2.2 min
Tests on PAV (after RTFO) (Run @ 100 °C) Residue		
G* X sin delta @ 22°C,10 rad/sec, kPa	3613	5000 max
Bending Beam		
Creep Stiffness, S, 60s, -12°C, kPa	150000	300000 max
Slope, m, 60 s, -12°C	0.360	0.3 min

Table A3: Properties of the PG 70-28 used in the Study

Test Type	Test Results	Specifications
Tests on Unaged Material		
Brookfield viscosity, 135°C, mPa.s	0.725	3 max
Flash Point, Cleveland Open Cup (COC) °C	260 +	230 min
G*/sin delta @ 58°C,10 rad/sec, kPa	1.33	1.0 min
Tests on RTFO Residue		
% Loss Weight	.141	1.0 max
G*/sin delta @ 58°C,10 rad/sec, kPa	3.38	2.2 min
Tests on PAV (after RTFO) (Run @ 100 °C) Residue		
G* X sin delta @ 22°C, 10 rad/sec, kPa	1246	5000 max
Bending Beam		
Creep Stiffness, S, 60s, -12°C, kPa	114900	300000 max
Slope, m, 60 s, -12°C	0.351	0.3 min

Table A4: Properties of PG 58-40 used in the Study

Test Type	Test Results	Specifications
Tests on Unaged Material		
Brookfield viscosity, 135°C, mPa.s	0.880	3 max
Flash Point, Cleveland Open Cup (COC), °C	230 +	230 min
G*/sin delta @ 58°C, 10 rad/sec, kPa	1.724	1.0 min
Tests on RTFO Residue		
% Loss Weight	.443	1.0 max
G*/sin delta @ 58°C, 10 rad/sec, kPa	3.201	2.2 min
Tests on PAV (after RTFO) (Run @ 100°C) Residue		
G* X sin delta @ 22°C, 10 rad/sec, kPa	1345	5000 max
Bending Beam		
Creep Stiffness, S, 60s,-12°C, kPa	258100	300000 max
Slope, m, 60 s, -12°C	0.316	0.3 min\