Comparison of Mechanical Properties of Asphalt Concrete Mixes with Aged Asphalt Cements

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ABSTRACT

Over the past 50 years, pavement engineers and researchers have invested much effort and resources to develop reliable asphalt concrete mixtures. This has led to (a) using better aggregate type and gradation and (b) selecting asphalt cement based on performance related criteria. The Canadian environment requires the use of an asphalt cement that provides resistance to low-temperature cracking in cold winter temperatures and to rutting in the elevated temperatures of summer. An earlier study in Carleton University showed that a particular Styrene Butadiene Styrene (SBS) polymer modified asphalt cement could produce such desired improvements in the asphalt cement quality. .

This paper focuses on testing asphalt concrete mixtures produced using three different PG 58-34 asphalt cements which had been processed in the Pressure Aging Vessel (PAV) before being used to manufacture asphalt concrete specimens.

This paper presents the details and results of the laboratory testing program: indirect tensile strength and shear strength in dry conditions and after conditioning for moisture damage, and static and cyclic direct tensile strength at low temperatures. The test results showed the SBS polymer modified asphalt cement improved resistance to rutting and cracking.

RÉSUMÉ

Depuis les dernières 50 années, les ingénieurs de chaussées et les chercheurs ont mis beaucoup d'efforts et de ressources pour développer un enrobé de béton bitumineux fiable. Cela a conduit à - a) une utilisation de meilleurs types et granulométries de granulats et – b) un choix de bitume basé sur des critères reliés à la performance. L'environnement canadien exige l'utilisation d'un bitume qui fournit une résistance à la fissuration à basse température lors des températures des hivers froids et à l'orniérage lors des températures élevées de l'été. Une étude antérieure à l'Université Carleton a montré qu'un bitume particulier modifié au polymère de styrène butadiène styrène (SBS) peut produire de telles améliorations désirées dans la qualité du bitume.

Cet exposé se concentre sur les essais des enrobés de béton bitumineux produits avec trois bitumes PG 58-34 différents qui ont subit le vieillissement au récipient sous pression (PAV) avant d'être utilisé pour la fabrication des échantillons de béton bitumineux.

Cet exposé présente les détails et les résultats du programme d'essai en laboratoire : résistance à la traction indirecte et résistance au cisaillement dans les conditions sèches et après conditionnement aux dommages de l'humidité, ainsi que la résistance statique et cyclique à la traction directe à basses températures. Les résultats d'essais montrent que le bitume modifié au polymère SBS accroît la résistance à l'orniérage et à la fissuration.

1. INTRODUCTION

Long-term performance of asphalt concrete pavement is the most important factor for evaluating the quality of the asphalt concrete mixtures. The two main approaches that have been followed to achieve this objective are (*a*) use of aggregates with better characteristics and gradation and (*b*) better selection of the asphalt cement for the job on hand. This latter approach has been the subject of a research effort by Strategic Highway Research Program (SHRP), which resulted in the current AASHTO MP1 Specification to categorize asphalt cements into performance grades (PG). This new system categorizes the asphalt cements based on the maximum and minimum pavement design temperatures. On evaluating the use of the PGAC system in the region of Ottawa-Carleton, Corbett and Lee [0] reported that proper selection of asphalt cement increases the pavement service life and reduces the maintenance cost. Based on the premise that proper selection of asphalt cement will lead to improved performance of the asphalt concrete mixture, a concentrated research effort has been directed toward improving the properties of asphalt cements [2]. Results of recent research studies showed that improving the qualities of the asphalt cements may indeed lead to improving the long term performance of asphalt concrete mixes [3,4,5].

A previous laboratory study was carried out at Carleton University to compare the expected long-term pavement performance of asphalt concrete mixtures that were manufactured using Conventional Asphalt Cement (CAC), air Oxidized Asphalt Cement (AOA), and a particular Styrene Butadiene Styrene (SBS) Polymer Modified Asphalt Cement PMA [5]. The results showed that the use of a particular PMA in asphalt concrete mixtures would lead to significant improvement in the long-term performance of the pavement, as indicated by resistance to static and cyclic tensile stresses. It should be mentioned that the asphalt concrete specimens tested in the 1997 study were manufactured using unaged (fresh) asphalt cements. Starting in December 2000, a second-phase complementing the original study was carried out to compare the performance of asphalt concrete specimens manufactured using three aged asphalt cements (all are categorized as PG 58-34) to manufacture asphalt concrete specimens, with one important change - that the three asphalt cements were processed in the Pressure Aging Vessel (PAV) to simulate the effect of in-service aging. The following sections present the scope and objectives of this study as well as the outline and results of the experimental program.

2. SCOPE AND OBJECTIVES

The scope of this project was limited to testing three types of asphalt cements (CAC, AOA, and PMA), where the particular PMA was produced using Styrene Butadiene Styrene (SBS) polymer [2]. All three asphalt cements were categorized as PG 58-34 and were processed in a Pressure Aging Vessel (PAV) at 100 °C, 2070 kPa for 20 hours.

A standard Ontario Ministry of Transportation (MTO) hot-laid mix for heavy traffic roads, namely HL-4, was used to manufacture all testing specimens [6]. The specifications for HL-4 aggregate gradation and the job mix formula (JMF) used in this study are shown in Figure 1. The optimum asphalt content selected for this research project was 5.5%, which was similar to that used in the research project undertaken in 1997. Considering the severe low temperatures in the Canadian winter, testing was conducted at room temperature (20 to 25 °C) in addition to three cold temperatures (0, –34, and –46 °C).

The main objectives of this study were:

- To plan and carry out a comprehensive testing program on asphalt specimens using PAV processed conventional, air-oxidized and polymer modified asphalt cements, and
- To compare the expected field performance of a standard MTO/OPSS HL-4 mix with different PGAC types based on the results of laboratory testing.

3. OUTLINE OF EXPERIMENTAL PROGRAM

As mentioned before, in this study the performance of asphalt concrete mixtures made of three different types of asphalt cement was evaluated. This evaluation was carried out by testing core and slab specimens using each of the asphalt cement types. Different testing protocols were used for the evaluation. First, mix core specimens were tested for indirect tensile strength, shear strength, and moisture sensitivity. Slab specimens were then tested for direct tensile strength and fatigue resistance to cyclic direct tensile stress. The grading of the asphalt cements and processing in the PAV were carried out by McAsphalt Industries Limited and the entire experimental program, including specimen fabrication and data analysis, was carried out at Carleton University. The experimental program consisted of five stages, which are explained in the following sections. (See Table 1 for details.)

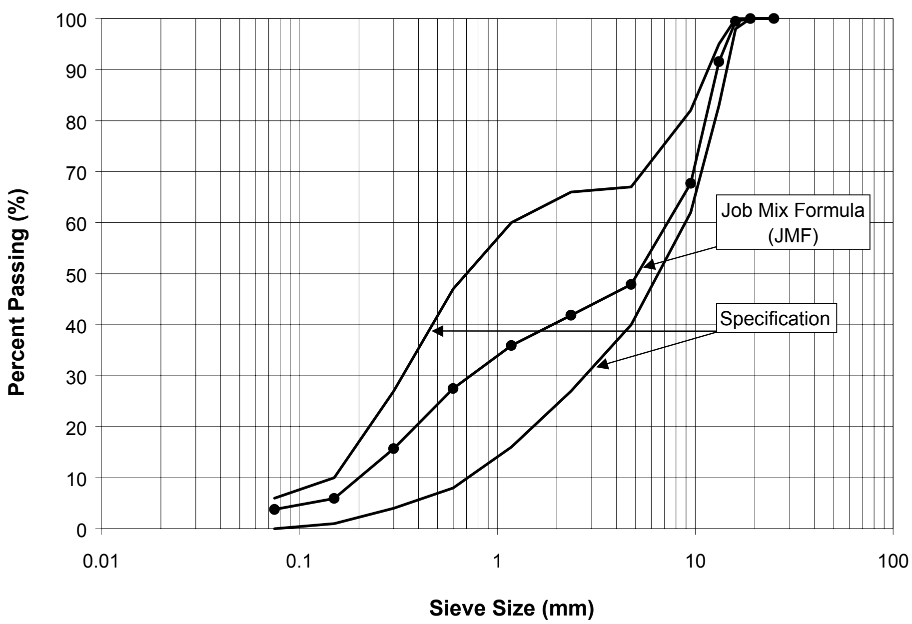


Figure 1: Specifications and Job Mix Formula (JMF) for Aggregate Gradation in HL-4 Mix.

3.1 Stage 1: Specimen Preparation

The first stage involved the fabrication of the specimens required for the testing program. In this stage, a total of thirty cores (10 cores per asphalt cement type) with 100-mm diameter were manufactured to determine the indirect tensile strength, shear strength, and moisture sensitivity of the asphalt concrete as outlined in Stages 2 and 3, respectively. These cores were manufactured using Marshall hammer and applying 75 blows on each side according to the MTO/OPSS 1149 specifications for the HL-4 standard mix. The dimensions of each core were then recorded, and its bulk relative density was determined. In addition to the core specimens, a total of 56 slabs (20 slabs for each of AOA and CAC and 16 for PMA) were manufactured to determine the direct tensile strength and fatigue resistance to cyclic direct tensile stress using specialized equipment. It should be noted that, as discussed in Stages 4 and 5, the desirable number of slabs was 18 per asphalt cement type but the actual number of slabs made of each PGAC type was controlled by the amounts of PAV processed asphalt cement available. The dimensions of each slab were 250 mm long, 75 mm wide, and 75 mm deep. The test slabs were cut out from a larger slab, which was constructed using a wooden mould and compacted with a plate vibratory compactor.

Table 1: Summary of the Experimental Program.

Stage	Test	Specimen Type	Testing Temperature	Number of Specimens Tested		
				CAC	AOA	PMA
2	ITS Shear strength	Cores	Room temperature	3 § 2 §	3 § 2 §	3 § 2 §
3	ITS Shear strength	Cores	Room temperature	3 ‡ 2 ‡	3 ‡ 2 ‡	3 ‡ ‡
4	SDTS	Slabs	0 °C –34 °C –46 °C	3 3 4	3 3 3	2 2 3
5	CDTS	Slabs	0 °C –34 °C –46 °C	3 4 3	3 4 4	3 3 3

§ Dry specimens.
‡ Moisture conditioned specimens.
Note: ITS = Indirect Tensile Strength; SDTS = Static Direct Tensile Strength; CAC = Conventional Asphalt Cement; AOA = Air Oxidized Asphalt Cement; PMA = Polymer Modified Asphalt Cement

3.2 Stage 2: Indirect Tensile and Shear Strengths

The second stage involved quantifying the mechanical properties of the core specimens corresponding to the three asphalt cement types by measuring their static indirect tensile strength (ITS), and shear strength (SS). Ten specimens corresponding to each asphalt cement type were divided into four subsets with approximately equal mean bulk relative density. The first subset consisted of three specimens that were tested for ITS in dry condition, and the second subset consisted of two specimens that were tested for SS in dry condition. Finally, the third and fourth subsets consisted of three and two specimens, respectively, and were used to evaluate the mixes' moisture sensitivity as discussed in Stage 3. The testing in stage 2 and stage 3 was performed at room temperature (25 °C).

3.3 Stage 3: Moisture Sensitivity

The third stage dealt with evaluating the moisture sensitivity of the asphalt mixes using the different asphalt cement types. Half of the core specimens, third and fourth subsets as outlined in Stage 2, were conditioned in warm water (60°C) according to the MTO specifications LS-283 [8]. This conditioning required subjecting the specimens to vacuum saturation at 25°C for one hour followed by immersion in hot water bath for 24 hours. Finally, three (3) specimens in Stage 3 were tested to determine the ITS of the mix and two (2) specimens per asphalt cement type were tested to determine the shear strength (SS).

3.4 Stage 4: Static Direct Tensile Strength (SDTS)

The fourth stage dealt with evaluating the resistance of the asphalt pavement to low-temperature cracking using static direct tensile strength (SDTS) of asphalt slabs. A total of 27 slabs were subjected to a direct tensile stress at the three different temperatures of 0°, –34°, and –46 °C (2 to 4 slabs per asphalt cement type per temperature). Both the SDTS and maximum strain at failure were measured.

3.5 Stage 5: Fatigue Resistance to Cyclic Direct Tensile Stress (CDTS)

In the fifth stage, the resistance of asphalt pavements to fatigue cracking resulting from exposure to cyclic low and high temperatures was measured. The remaining slabs (3 to 4 slabs per asphalt cement type per temperature) were tested under cyclic tensile stress. The cyclic loading was displacement-controlled, where the results obtained from Stage 4 were employed to fine-tune the applied displacements. The loading in this stage was applied using cyclic application of a 0.4-mm displacement for 22,500 cycles, followed by a 0.6-mm displacement for 15,000 cycles, a 0.8-mm displacement for 10,000 cycles, and a 1.0-mm displacement until failure. The test is terminated if a specimen fails before reaching the 1-mm (10000 cycles) displacement level. It should be noted that the cyclic-displacements test initiates with a relatively small displacement (0.4 mm) to introduce sample damage. The displacement levels above 0.4 mm are significant enough to estimate performance under cyclic-fatigue because of micro/macro damage to the sample. On the other hand, the gradual increase in the applied displacement was designed accelerated testing.

4 TEST RESULTS

4.1 Indirect Tensile Strength (ITS) Test

The ITS of the asphalt mix can be used as an indication of the pavement's resistance to cracking due to heavy traffic loads. Also, it has been adopted by many agencies, such as the American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASM), as the main test for mix resistance to moisture damage. In addition, since the ITS depends mainly on the strength of the binder, it is an appropriate test in comparing asphalt concrete mixes with different asphalt cement types. To determine the ITS, a vertical load is applied along the diametrical plane of the core specimen as shown in Figure 2. The vertical displacement and the corresponding load until failure are recorded by a computer-based data acquisition system attached to the loading machine. The ITS is calculated as a function of the maximum load at failure and the dimensions of the specimen's cross section using the following equation:

$$\mathrm{ITS} = \frac{2\,P}{\pi\ H\ D} \tag{1}$$

where: ITS = indirect tensile strength (MPa),
P = maximum applied load at failure (N),
H = height of specimen (mm), and
D = diameter of specimen (mm).

As mentioned earlier, three cores per asphalt cement type were tested for ITS under dry conditions, and the results are presented in Table 2. Figure 3 shows a summary of the average, minimum, and maximum ITS results of dry and conditioned specimens. As shown in the table and figure, on average, the PMA had an ITS of 1.29 MPa as compared to 1.12 MPa for the CAC and 1.16 MPa for the AOA. This represents an increase of 15.2% and 11.2% respectively. The same tests were repeated after the specimens had been moisture conditioned. Again, the PMA has a higher ITS than the AOA and CAC. On average, the PMA has an ITS of 1.10 MPa as compared to 0.87 MPa for the CAC and 0.98 MPa for the AOA (Table 2). This represents an increase of 26.4% and 12.2% respectively. The table also shows the ranking of the pavements according to their expected resistance to load cracking, where PMA has the highest resistance both in dry conditions and after exposure to moisture damage.

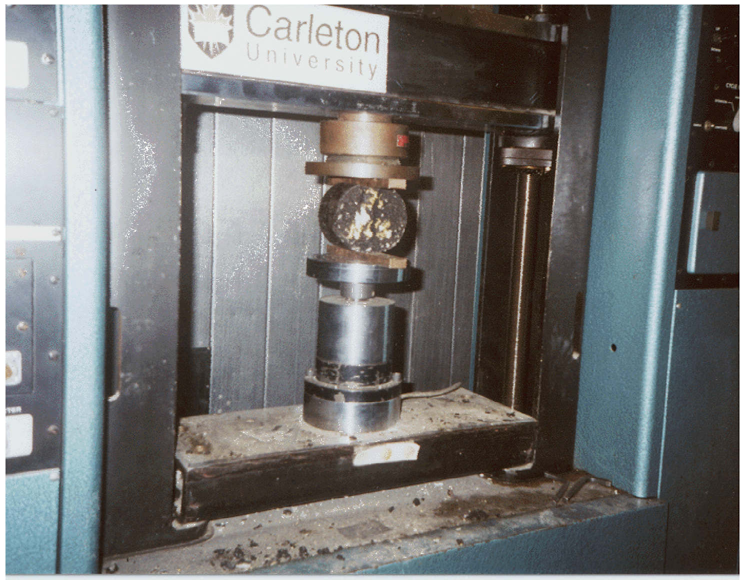
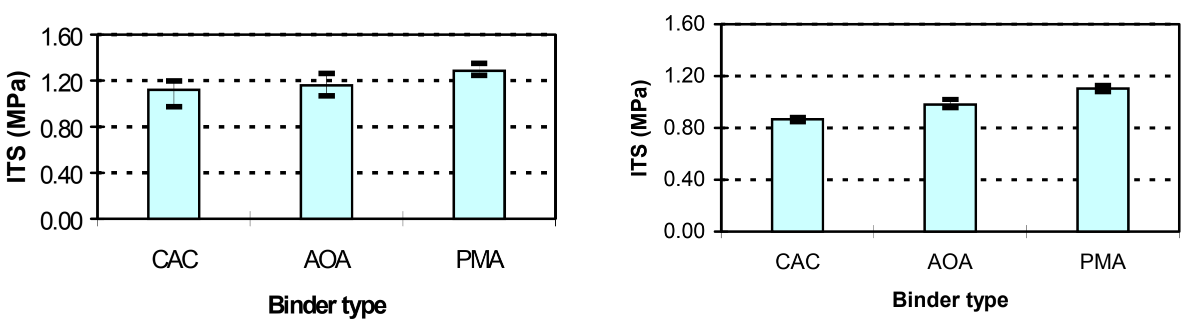


Figure 2: Setup of Indirect Tensile Strength Test.



(*a*) Dry Specimens. (*b*) Moisture Conditioned Specimens.

Figure 3: Indirect Tensile Strength (ITS) of Dry and Moisture Conditioned Specimens.

Table 2: Indirect Tensile Strength (ITS) Test Results.

Asphalt Cement Type	Specimen	*P* (N)	*H* (mm)	*D* (mm)	ITS (MPa)	Mean ITS (MPa)
(*a*) Dry Specimens – First Subset.						
CAC	3	10285.6	54.0	101.2	1.20	1.12
	7	9464.1	61.0	101.6	0.97	
	10	11241.1	59.5	101.3	1.19	
AOA	1	12413.6	61.8	101.3	1.26	1.16
	3	10296.6	60.6	101.4	1.07	
	5	10796.1	59.0	101.3	1.15	
PMA	2	12007.8	59.8	101.4	1.26	1.29
	3	11506.0	58.0	101.3	1.25	
	7	12930.5	60.0	101.6	1.35	
(*b*) Moisture Conditioned Specimens – Third Subset.						
CAC	6	8300.5	59.0	101.5	0.88	0.87
	8	8699.3	64.5	101.3	0.85	
	9	8285.1	59.5	101.6	0.87	
AOA	7	10112.7	62.2	101.5	1.02	0.98
	8	9277.6	61.0	101.2	0.96	
	9	9161.5	59.6	101.3	0.97	
PMA	5	10140.9	59.3	101.0	1.08	1.10
	6	10088.6	57.3	101.7	1.10	
	8	11148.8	62.0	101.5	1.13	

P = maximum applied load at failure; H = height of specimen; D = diameter of specimen;
CAC = conventional asphalt cement; AOA = air oxidized asphalt cement;
PMA = polymer modified asphalt cement

4.2 Shear Strength Test

Shear flow is a major contributor to rutting of asphalt pavement. Considerable research work has been carried out in Carleton University to relate the pavement's rutting resistance to shear strength and shear modulus. Based on this research, shear properties of asphalt mixes in the lab can be measured by applying a direct torque along the axis of a core specimen (Figure 5). The specimens were glued (using a Two-Ton Clear Epoxy – Glue Number 14360 manufactured by Devecon) between two steel plates, and left to dry for twenty-four hours in a vertical position. The torque moment and the angle of twist were measured. The maximum shear strength, SS, and shear modulus, *G*, could then be calculated using the elastic torsion equations:

$$\mathrm{SS} = \frac{T\ R}{J} \tag{2}$$

$$G = \frac{T\ H}{\theta\ J} \tag{3}$$

where: SS = maximum shear strength (MPa)
R = specimen radius (mm)
G = shear modulus (N/mm^2)
θ = angle of twist (radian).
T = maximum torque at failure (N.mm)
J = polar moment of inertia (mm^4) = $\pi R^4/2$
H = specimen height (mm), and

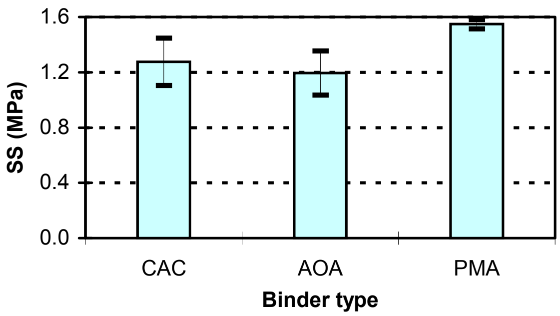
Table 3 and Figure 4 show that, under the dry condition, the PMA has on average a maximum SS of 1.55 MPa followed by CAC at 1.28 MPa and AOA at 1.20 MPa. This represents an increase in the maximum SS of the PMA of 21.1% and 29.2% over the maximum SS of the CAC and the AOA respectively. Similarly, under the saturated condition, the PMA has recorded an increase in the maximum SS of 9.3% and 7.3% over the maximum SS of the CAC and AOA, respectively. As for the shear modulus, *G*, Table 3 shows also that the average *G* of the PMA under the dry condition was 11.29 MPa as compared to 6.34 and 7.76 MPa for the CAC and AOA, respectively. This represents an increase in shear modulus of the PMA of 78.1% and 45.5% over the shear modulus of the CAC and AOA, respectively. Similarly, under the saturated condition, the PMA has recorded an increase in the shear modulus of 73.8% over the CAC and 29.4% over the AOA. Further, the table shows that PMA receives the highest ranking for rutting resistance based on shear strength and shear modulus criteria both in the dry condition and after exposure to moisture damage.

Comparing the difference in shear properties and ITS for the three mixes indicates that mixes using PMA exhibit greater gain in the shear properties (especially shear modulus), and thus greater resistance to rutting.

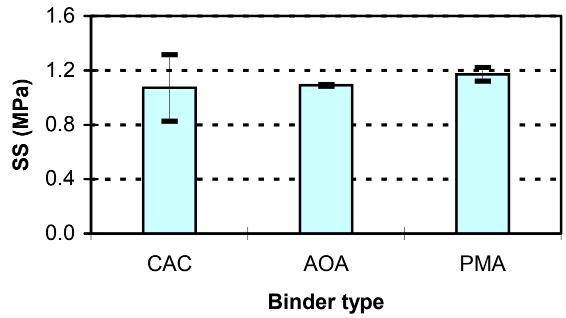
Table 3: Results of Shear Strength (SS) and Modulus (*G*) Testing of Lab-Prepared Specimens.

Asphalt Cement Type	Specimen	Torque (N.mm)	J (mm^4)	SS (MPa)	θ (radian)	G (MPa)	Mean SS (MPa)	Mean G (MPa)
(*a*) Dry Specimens – Second Subset.								
CAC	1	220000	10015304.1	1.10	0.262	4.15	1.28	6.34
	5	300000	10543650.6	1.45	0.218	8.54		
AOA	4	280000	10502282.7	1.36	0.192	8.33	1.20	7.76
	6	210000	10256625.9	1.03	0.174	7.19		
PMA	1	300000	9935818.0	1.51	0.157	11.33	1.55	11.29
	4	320000	10216106.0	1.58	0.166	11.25		
(*b*) Moisture Conditioned Specimens – Fourth Subset.								
CAC	2	170000	10419912.3	0.83	0.218	3.73	1.07	5.62
	4	270000	10419912.3	1.32	0.192	7.52		
AOA	2	220000	10256625.9	1.08	0.157	7.92	1.09	7.55
	10	225000	10419912.3	1.10	0.174	7.17		
PMA	9	250000	10378909.2	1.22	0.157	9.31	1.17	9.77
	10	230000	10399395.6	1.12	0.131	10.23		

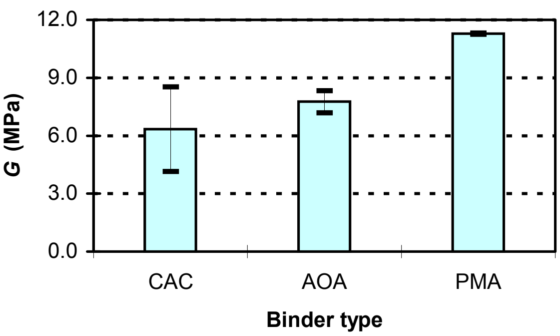
J = polar moment of inertia; θ = angle of twist;
CAC = conventional asphalt cement; AOA = air oxidized asphalt cement;
PMA = polymer modified asphalt cement



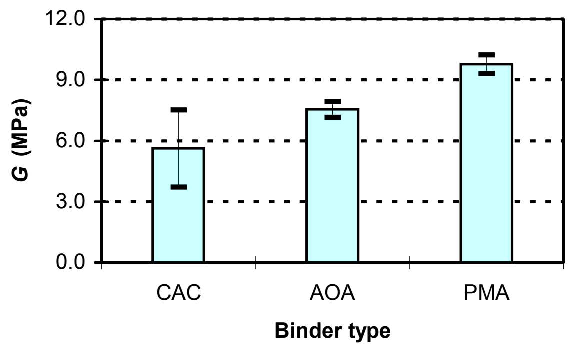
(*a*) SS of Dry Specimens.



(*b*) SS of Conditioned Specimens.



(*c*) *G* of Dry Specimens.



(*d*) *G* of Moisture Conditioned Specimens.

Figure 4: Shear Strength (SS) and Modulus (*G*) of Dry and Moisture Conditioned Specimens.
CAC = conventional asphalt cement; AOA = air oxidized asphalt cement;
PMA = polymer modified asphalt cement

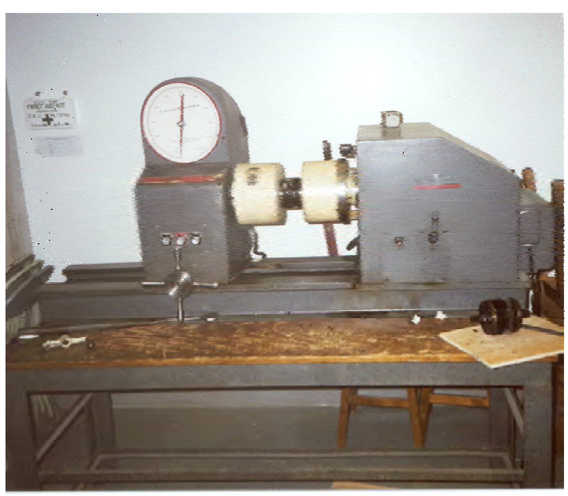


Figure 5: Setup of Shear Strength Test.

4.3 Moisture Sensitivity

Moisture sensitivity of asphalt concrete mixes can be examined by measuring the loss of strength due to conditioning in water. Therefore, the ratio of ITS, SS, or *G* can be measures of moisture sensitivity. However, it should be noted that the strength ratio is traditionally used as an indication of whether the mix should be accepted or rejected. Using this ratio to rank the mixes may be misleading especially if a mix has a higher strength after conditioning but lower strength ratio. Therefore, the strength ratio is used here to examine if the mix with each asphalt cement type would pass or fail the moisture sensitivity test. On the other hand, the retained strength (MPa) after conditioning is used to rank the mixes' resistance to moisture damage. The three mixes corresponding to the different asphalt cement types in this study had strength ratios greater than 70%, which is the common cut-off ratio for accepting or rejecting a mix based on moisture sensitivity. However, by referring back to Table 2 and Table 3, it can be clearly shown that PMA specimens had higher retained strength than the CAC and AOA specimens. Subsequently, it should be expected that pavements made with PMA would exhibit better long-term performance while being exposed to environment based moisture damages.

4.4 Static Direct Tensile Strength (SDTS) Test

The direct tensile strength test was performed on the slab specimens by applying a uniaxial load using a built-in-house loading frame.

Figure 6 shows a schematic of the setup, which was the same for static and cyclic direct strength, and Figure 7 shows a picture of a tested specimen. As shown in the Figures, to apply the uniaxial load, the bottom of the longer side of each specimen (250 mm) was glued to two separate mounting steel plates, where each plate covered slightly less than half of the specimen's length. The first of these mounting plates was then fastened to a fixed plate of the loading table, while the second mounting plate was fastened to a mobile plate in the same loading table). The mobile plate was in turn connected to a loading cell and LVDT positioning system that provided a feedback to a computerized data acquisition system. Finally, to maintain the required temperature during the test, the loading table was kept inside an environmental chamber in the Carleton University laboratory. The chamber can maintain a constant temperature ranging from +40 to –40 °C (see Figure 8). Special arrangements were made utilising liquid nitrogen to lower the temperature inside the chamber to -46 °C. The preparation and testing procedure for each specimen was as follows:

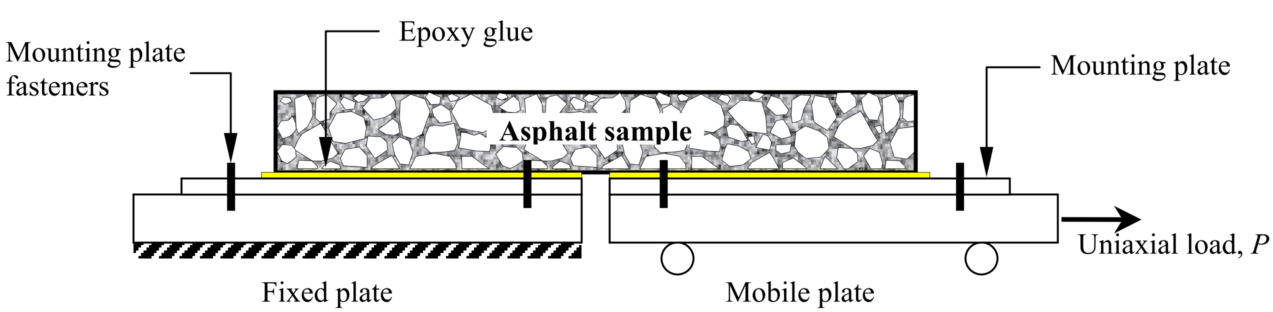


Figure 6: Schematic of Static/Cyclic Direct Tensile Strength Test.

Figure 7: Specimen in Static/Cyclic Direct Tensile Strength Test.

Figure 8: Thermostat of Environmental Chamber.

- The specimens were prepared as described earlier (Section 3.1. Stage 1: Specimen Preparation).
- The mounting plates were glued to the specimen using a high strength epoxy, which is advertised for use at very low temperatures. At -46 °C most of the samples displayed interfacial failures between the glue and hot-mix asphalt under dynamic fatigue testing.
- The plates with the specimens were pre-cooled in an industrial freezer at the test temperature for 24 hours.
- The temperature inside the environmental chamber was adjusted to the required test temperature 24 hours before testing.
- The hydraulic actuator was calibrated to apply a displacement that increased gradually at a constant rate of 50 mm/min. When such a slow rate is applied till failure, the loading can be considered static.

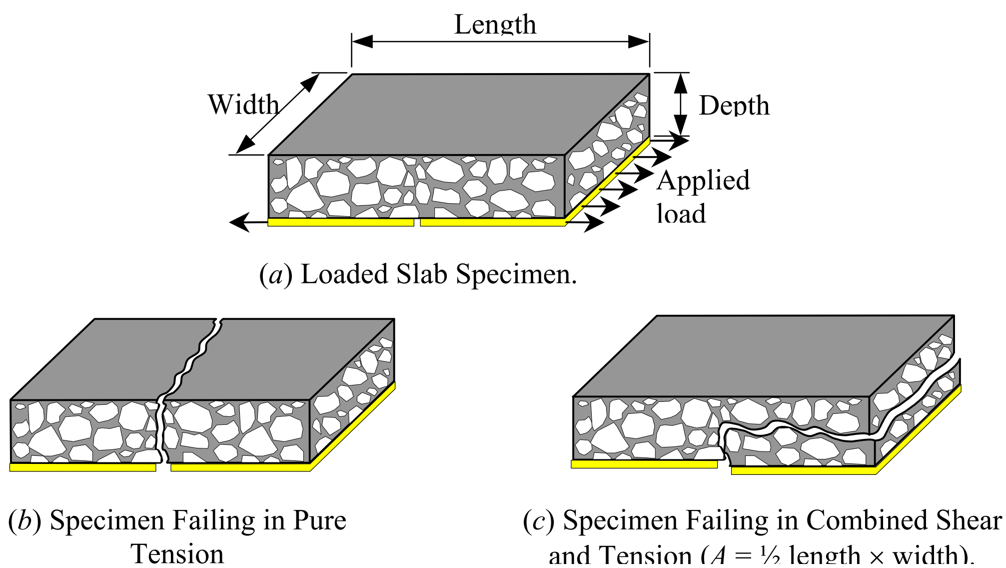
- The plates with the test specimen were fastened to the test table inside the environmental chamber, and the displacement was applied at the selected rate until failure. The data acquisition system recorded the load and displacement values up to failure.
- The data were used to calculate the SDTS and the secant modulus at failure (M), which is analogous to the modulus of elasticity, as follows:

$$\mathrm{SDTS} = \frac{P}{A} \tag{4}$$

$$M = \frac{\mathrm{SDTS}}{\varepsilon_{\max}} \tag{5}$$

where: SDST = direct tensile strength (MPa),
P = maximum applied load at failure (N),
A = failure area (mm^2),
ε_{max} = maximum strain at failure, and
M = secant modulus at failure (MPa).

- In calculating the strain corresponding to a given displacement, the value of the displacement was divided by one-third of the slab length. In reality, the strain is non-uniform across the entire slab length because of fixing the dimensions at the bottom, which was glued to the steel plates. It should be noted that because the slabs of the different asphalt cements have the same nominal dimensions, the effect of such approximation should not influence the results if they are used only to compare the different mixes.
- It was also noted that although most specimens had failed in a pure tensile mode across the cross section (A = width × depth), a few specimens failed in a combined tensile and shear mode across half of the specimen's length (Figure 9). As shown in the figure, the failure area in this latter case was taken as A = ½ length × width.



(*a*) Loaded Slab Specimen.

(*b*) Specimen Failing in Pure Tension

(*c*) Specimen Failing in Combined Shear and Tension (A = ½ length × width).

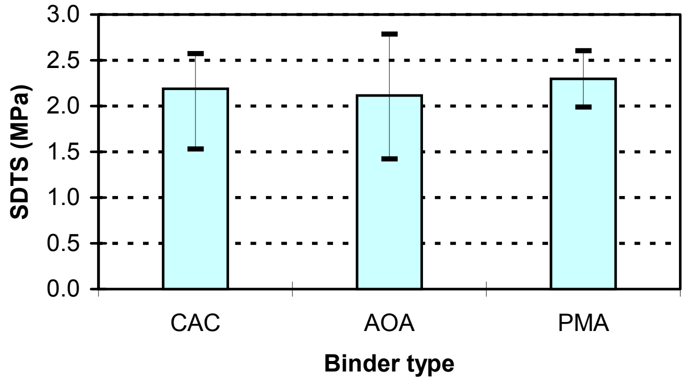
Figure 9: Failure Mode and Failure Area (*A*) in Static Direct Tensile Strength (SDTS) Tests.

As outlined earlier, a total of 26 slabs were subjected to a direct tensile stress at the three different temperatures of 0, –34, and –46 °C. One of the specimens failed at the interface between the glue and the steel plates, and therefore its results were discarded as the failure was not in the asphalt concrete, but rather in the glue system. Therefore, the results of only 25 specimens are reported (Table 4 and Figure 10). As shown in the table and figure, the PMA specimens had the highest strength and modulus at all temperatures. In addition, the change of either strength or modulus due to the drop in temperature was very minimal for the PMA specimens, while the CAC specimens experienced a significant drop in both the strength and modulus. As a result, the difference in the strength and modulus between the PMA specimens and CAC or AOA specimens increases gradually from 5-13% at 0 °C to 16-59% at –34 °C and to 38-118% at –46 °C. Such a trend suggests asphalt concrete mixes with PMA will have the advantage of a better resistance to low-temperature cracking. Clearly, the better qualities and higher resistance are becoming more evident as the pavement temperature drops from 0 °C to –34 °C to –46 °C.

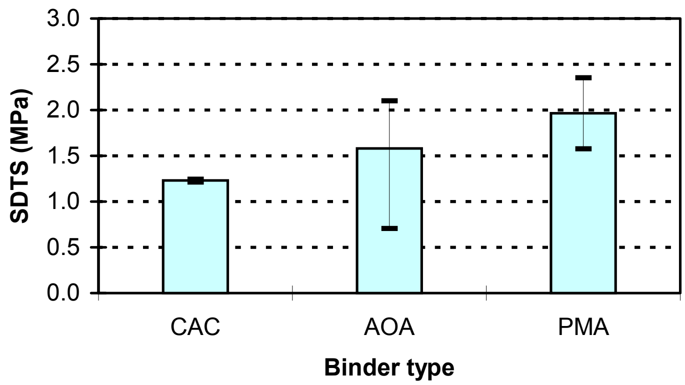
Table 4: Static Direct Tensile Strength (SDTS) Test Results.

Asphalt Cement Type	Specimen	ε_{max}	SDTS (MPa)	*M* (MPa)	Mean SDTS (MPa)	Mean *M* (MPa)
(*a*) Testing temperature = 0 °C.						
CAC	33	0.037	2.57	69.86	2.19	66.93
	41	0.029	1.53	52.73		
	53	0.031	2.46	78.20		
AOA	14	0.026	2.14	81.24	2.11	67.56
	31	0.032	1.42	45.07		
	54	0.036	2.79	76.37		
PMA	42	0.030	2.61	86.02	2.30	75.40
	52	0.031	1.99	64.78		
(*b*) Testing temperature = –34 °C.						
CAC	11	0.024	1.25	52.26	1.23	51.77
	12	0.024	1.21	51.28		
AOA	11	0.035	2.10	59.28	1.58	52.86
	12	0.014	0.71	51.88		
	21	0.041	1.93	47.43		
PMA	21	0.033	2.35	72.22	1.96	61.43
	43	0.031	1.58	50.63		
(*c*) Testing temperature = –46 °C.						
CAC	13	0.030	1.17	39.37	0.98	48.18
	14	0.015	0.86	58.84		
	22	0.015	0.87	58.10		
	31	0.028	1.01	36.41		
AOA	13	0.024	1.42	60.46	1.47	66.35
	22	0.021	1.47	69.18		
	23	0.022	1.54	69.41		
PMA	22	0.030	2.19	72.42	2.14	91.78
	23	0.023	2.35	101.38		
	54	0.018	1.88	101.55		

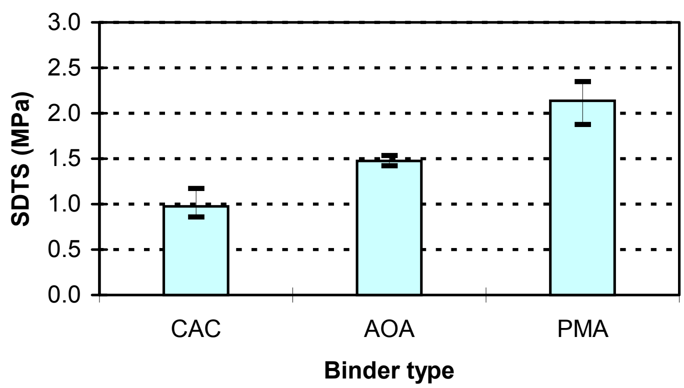
M = secant modulus at failure; CAC = Conventional Asphalt Cement;
AOA = Air Oxidized Asphalt Cement; PMA = Polymer Modified Asphalt Cement



(*a*) Testing temperature = 0 °C.



(*b*) Testing temperature = –34 °C.



(*c*) Testing temperature = –46 °C.

Figure 10: Static Direct Tensile Strength (SDTS) of Slab Specimens.
CAC = Conventional Asphalt Cement; AOA = Air Oxidized Asphalt Cement;
PMA = Polymer Modified Asphalt Cement

Table 5: Number of Cycles to Failure in Cyclic Direct Tensile Strength (CDTS) Test.

Testing Temperature	Asphalt Cement Type	Number of Cycles and Cyclic Displacement			
		0.4-mm	0.6-mm	0.8-mm	1.0-mm
0° C	CAC§	22500	7829	--	--
	AOA	21710	--	--	--
	PMA	22550	16247	--	--
–34° C	CAC	22500	4	--	--
	AOA	22500	11	--	--
	PMA	22841	14998	12	--

§ Average number of cycles for two specimens.
CAC = Conventional Asphalt Cement; AOA = Air Oxidized Asphalt Cement;
PMA = Polymer Modified Asphalt Cement

4.5 Fatigue Resistance to Cyclic Direct Tensile Stress (CDTS) Test

The resistance of asphalt pavements to fatigue cracking was evaluated in this study by applying a cyclic displacement to slab specimens until failure. As mentioned before, the cyclic displacement at a predetermined number of cycles was gradually increased as the test progressed to accelerate the specimen's failure. Each specimen was subjected first to a 0.4-mm displacement for 22,500 cycles, followed by a 0.6-mm displacement for 15,000 cycles, a 0.8-mm displacement for 10,000 cycles, and a 1.0-mm displacement until failure. However, the test was terminated if the specimen failed earlier than the final 10,000 cycles at 1.0 mm. The specimens were prepared similar to the SDTS test, and the same loading table and data acquisition system were also used in the CDTS test. However, the data acquisition system in this case was used to record the minimum and maximum displacements and the corresponding load for every tenth cycle.

A total of 31 slabs were tested at the three temperatures of 0, –34, –46 °C. Due to a number of difficulties associated with the failure of the glue at the interface of the tested specimens, only results of completed tests are summarised in Table 5. Based on these results, the following comments can be made:

- The PMA specimen had the highest fatigue resistance at both 0 and –34 °C.
- Variation in the fatigue resistance in the CAC and AOA specimens at the different temperatures is considerably larger than that for PMA specimens.
- At –34 °C, the PMA specimen failed at a higher displacement of 0.8 mm.
- The PMA specimens failed after more than twice the number of fatigue cycles of the other two mixes at 0 °C.
- Clearly as the temperature of the test reached - 34°C, the CAC and AOA failed much earlier than the PMA specimens.

5 SUMMARY AND CONCLUSIONS

This paper presented the experimental outline and results of a study carried out to complement an earlier study (1997) on comparing the long-term performance of asphalt concrete pavements with the SBS polymer-modified asphalt cement relative to asphalt concrete with conventional and air-oxidized PGACs. The earlier study showed that the asphalt concrete with the PMA provided higher resistance to rut resistance, low temperature and fatigue cracking. In this study, core and slab specimens of asphalt concrete with the PMA, AOA, and CAC were tested for indirect tensile strength, shear strength, moisture sensitivity, static direct tensile strength, and fatigue resistance to cyclic direct tensile stress. All asphalt cements were graded according to the current AASHTO MP1 specification and were then processed in the pressure-aging vessel to simulate in-service aging.

A total of 30 cores and 56 slabs were prepared at Carleton University using the three different asphalt cement types. The core specimens were tested for ITS and shear strength in dry conditions and after being conditioned for moisture sensitivity testing according to standard procedures. The results showed that the PMA specimens had higher ITS, shear strength, and shear modulus in the dry condition than AOA and CAC specimens thus suggesting that pavements with the PMA would have higher resistance to both load cracking and rutting even after aging in the field. In addition, the conditioned PMA specimens retained higher ITS, shear strength, and shear modulus than AOA and CAC specimens indicating that the performance of PMA pavements would be better if the aging pavement had experienced moisture damage. The slab specimens were tested for SDTS and CDTS at three low temperatures of 0, –34 and –46 °C. The results of both tests suggested that using the PMA for asphalt concrete pavements would result in an advantage of increased resistance to low-temperature and fatigue cracking.

In general, the results of this study complement the earlier Carleton study which showed that using the polymer-modified asphalt cement would significantly improve the performance of asphalt concrete pavements. Furthermore, the results of both studies indicate that using PMA in the design and construction of asphalt concrete mixes for low temperature applications will result in asphalt pavements with longer service life and lower maintenance and rehabilitation costs.

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