Evaluation of In-Situ Shear Stiffness of Asphalt Concrete Mixtures

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ABSTRACT

In cooperation with the Ontario Ministry of Transportation and the United States Transportation Research Board, researchers at Carleton University in Ottawa, Canada have developed the In-Situ Shear Stiffness Test (InSiSST) – a new field test facility for measuring shear stiffness of compacted asphalt concrete surface layers. To date, various field-testing programs have been conducted to evaluate the in-situ shear stiffness of asphalt concrete mixes using the newly developed InSiSST.

In this paper, a brief overview of the InSiSST facility is presented, together with the results of testing completed in Ottawa, Bancroft, Toronto, and at the Long Term Pavement Performance (LTPP) SPS-9A test site located in Petawawa, Ontario. The Petawawa site (870900) is of particular interest as four of the six test sections consist of SuperPave asphalt mixes, while the remaining two sections were designed using the Marshall method.

The results of field testing at these locations has indicated that the InSiSST is both sensitive to differences in asphalt mix shear stiffness and is able to rank mix performance between different mixes in terms of measured permanent deformation. With continued refinement and testing, is expected that InSiSST will become a valuable test facility for the design and quality control of hot mix asphalt concrete pavements.

INTRODUCTION

Permanent deformation of asphalt concrete (AC) surfaces, commonly known as rutting, is one of the widely observed surface distresses in asphalt concrete pavements. Previous research has shown that the shear properties of the AC surface mix are fundamental in resisting rutting (*1*). The Strategic Highway Research Program (SHRP) has acknowledged the importance of shear properties of both the binder and the AC mix, and has incorporated them in the SuperPave mix design methods developed to improve long-term performance of asphalt mixes in the field.

Currently, shear properties of AC mixes are predominantly evaluated through laboratory testing. Although laboratory investigations attempt to simulate field conditions by providing higher control over the testing conditions, the actual response of an AC mix can only be tested in the field. Furthermore, specimen contamination due to poor handling and/or special preparation can affect laboratory analyses to such an extent that the measured properties may not accurately represent field conditions.

Researchers at Carleton University, Ottawa, Ontario, have been working on evaluating the in-situ shear stiffness of AC mixes using an innovative approach, through the application of a concentrated torsional moment to the surface of the AC pavement. In 1995, Abd El Nabi (*2*) introduced a first generation prototype test device to evaluate the in-situ shear stiffness of AC mixes. Although this prototype device had its limitations, preliminary testing yielded promising results relating the maximum applied torque to the shear properties of AC mixes. These promising results encouraged the development of a more sophisticated testing equipment. In 2001, in cooperation with the Ontario Ministry of Transportation and the United States Transportation Research Board, a new testing facility termed the In-Situ Shear Stiffness Test (InSiSST™) was introduced (*3,4,5*).

The InSiSST™ facility uses the same concept used in the first prototype device, but with higher control, more accurate data acquisition capabilities and operational simplicity. Shake up testing for the InSiSST™ was carried out in Bancroft, Toronto, and on Carleton University Campus in Ottawa, Ontario. Field-testing was carried out at the LTPP SPS-9A 870900 test site near Petawawa, Ontario to evaluate the in-situ shear stiffness of AC surface mixtures at the different sections located at that site. At this test site, six test sections with identical pavement structures, but with different AC surface mixtures were tested.

In this paper a general description of the InSiSST is presented together with the shake up testing and the analysis results of the field-testing at the LTPP SPS-9A 870900 test site.

THE INSISST FACILITY

The In-Situ Shear Stiffness Testing (InSiSST™) facility, shown in Figure 1, is trailer-mounted testing equipment, developed at Carleton University to measure the in-situ shear stiffness of AC surface mixtures. The InSiSST facility utilises an electric motor and a gearbox as the load cell to apply a forced circumferential displacement to a steel plate bonded to the pavement surface, forcing a circular area of the pavement to rotate about an axis normal to the surface. The motor/gearbox combination is mounted vertically on a steel platform attached to a positioning system that allows for the horizontal positioning of the motor/gearbox combination. The positioning system is mounted to a box-tube frame, attached to the trailer frame via four jacks controlling the vertical movement of the motor/gearbox combination.

During transportation of the InSiSST™, the jacks are retracted upwards to hold the frame. Once driven into position, the jacks are extended to lower the test frame to the ground and continue extending until the test frame supports the entire weight of the trailer, preventing reactionary movement of the frame during testing. A laptop computer provides control of the test procedure and data acquisition. The test is strain controlled via a closed-loop system with instantaneous force and deformation measurements collected on the computer during the test procedure. A generator is mounted to the rear of the trailer to provide electricity for the InSiSST, thus allowing the facility to be completely self-sufficient.

Testing using the InSiSST facility is carried out by first fastening a steel plate to the pavement surface using epoxy. The facility is then driven to site and the testing frame is lowered in position such that the whole facility lifts off the ground. The motor/gearbox combination is positioned over the sample and the data acquisition system is set into place. The torque is then applied until the sample is failed. Figure 2 shows the application of the torque to the pavement surface during testing, while Figure 3 shows the AC mix sample after the completion of testing.

The InSiSST facility is equipped with a data acquisition system to record the instantaneous torque and the motor speed. The torque is measured directly using the torque cell and can be recorded at time intervals as small as 50-milliseconds. The angular displacement is calculated using the recorded motor speed, assuming constant strain loading conditions. Figure 4 shows a typical relationship between the applied torque and the corresponding angular displacement. As can be noted from the figure, the first section of the curve is irregular and requires correction. The irregularity results from the time required for the motor to pick up its speed and the small movement in the rubber pad used to increase the friction between the steel frame and the pavement surface.

Following the irregular start, the actual relationship between the torque and angular displacement is observed. At this stage of loading, the motor has reached a stable rate and the gearbox has maintained its inertia. The only resistance at that point is the resistance of the pavement material. The values of the angular displacement are corrected by extending the straight line, or common tangent, backward to intersect the horizontal axis at point O’. The origin is then shifted to the right from point O to point O’ and the angular displacement values are adjusted accordingly. The modified vertical axis is shown in Figure 4 by the dashed line. More details of the data analysis can be found elsewhere (*6*).

The torque-angular displacement relationship is used to calculate the shear stiffness of the AC mix. Reissner and Sagoci (*7*) and Sneddon (*8*) showed that for an elastic, homogeneous and isotropic material, and using the cylindrical co-ordinates (r, q, z), the only non-vanishing stresses are the shear stresses t_{zq} and t_{rq}. The relation between the applied torque (T), the angular displacement (F), the shear stiffness (G), and the radius of the loaded area (a) could be derived by integrating t_{zq} over the area of the loaded area, resulting in Equation [1].

[1] $$T = \frac{16}{3} G \ddot{O} a^{3}$$

The mathematical model by Reissner and Sagoci is valid for a linear, elastic, isotropic and homogeneous material. The AC pavement material is a heterogeneous material formed by mixing a viscous binder (asphalt binder) with an elastic-perfectly plastic material (aggregate). The behaviour of the AC material may vary from being linear elastic, to being a viscoelastoplastic material depending on the temperature and loading rate. However, this equation is used to calculate the shear modulus of the pavement material, or as better known in the pavement literature, the shear stiffness to imply that this value is not constant and is dependent upon test conditions such as the pavement temperature. The initial elastic shear stiffness is calculated using the relationship between the torque and the angular displacement at the early loading stages, after correcting the initial section of the curve, as described earlier (*9*).

It should be noted that in some cases, a bond failure might occur prematurely in the interface between the steel plate and the epoxy, rather than in the AC mix. This might happen due to the contamination of the steel surface, or due to improper epoxy application. However, field verification has shown that torsional resistance and angular displacement prior to the bond failure are due to the shear resistance of the AC mix and not to a movement in the epoxy material (*9*). Subsequently, the initial shear stiffness of the AC mix can be calculated using the data collected prior to the failure.

SHAKE UP TESTING

Shake up testing for the InSiSST facility was carried out in Bancroft and Toronto, Ontario, in addition to Carleton University campus. Testing in Bancroft and Toronto was carried out as pilot testing to assess the capabilities of the InSiSST, while testing on Carleton University campus was with the objective of fine tuning the InSiSST facility and to examine the effects of different testing conditions on the results.

BANCROFT, ONTARIO

Testing in Bancroft, Ontario was planned as pilot testing to evaluate the capabilities of the InSiSST as field-testing equipment. Testing was completed on two adjacent sections of highway 62, where one section was on the Northbound (NB) lane, while the other was on the Southbound (SB) lane. Seven samples were tested on each section and all tests were completed using 100-mm diameter steel plates. The top AC surface layer was a standard HL3 mix.

Table 1 shows the field-testing results for both sections tested at Bancroft. As can be noted, average shear stiffness of the AC mix for the NB section was slightly higher than the SB lane. However, the results were fairly consistent with a coefficient of variation of 2.3% and 1.8% for the NB and SB lanes, respectively. To test the statistical significance of the difference between the means of the two data sets, a two-tail t-test was carried out at a 95% confidence level, assuming samples with equal variances. The t-test is used to test the hypothesis that the two data sets under consideration have equal means. The acceptance of the hypothesis indicates that there is no statistical significance between the two data sets, while the rejection of the hypothesis indicates that the two data sets are significantly different.

The results of the t-test are shown in Table 2, and as can be noted the means of the two sections were found to be significantly different. The difference in the results of the two sections can be attributed to the difference in temperature and to the actual accumulated traffic loading, since the SB section was much wider than the regular lane as parallel parking was allowed at that section. The width of the SB section resulted in some difficulties locating the actual wheel paths, where the mix properties are expected to have changed due to accumulated traffic. However, the consistency in the results for each of the two pavement sections suggests that the InSiSST facility successfully evaluated the shear stiffness of AC mix.

TORONTO, ONTARIO

Testing in Toronto was carried out on a paved yard on the Ministry of Transportation premises. The section tested was an old pavement section used as an entrance and manoeuvring area in front of the garages. The AC mix was again a standard HL3 mixture. However, the pavement surface was severely deteriorated, with multiple cracking and the AC surface mixture was stiff due to ageing.

On this pavement section, only four samples were tested as a demonstration. Table 3 shows the test results for each of the samples tested. The first sample was on a soft patch and it failed in the pavement at a low resistance and relatively high strain, indicating high ductility. However, the other three samples were on the stiff, aged pavement and a bond failure happened in all three samples. However, as can be noted from the results, the aged pavement had a much higher shear stiffness that the soft patch, which was expected.

CARLETON UNIVERSITY CAMPUS

A large number of shake up tests were carried out on Carleton University campus using the InSiSST facility. Testing was performed in late July, August, late November 2000, September 2001, and August 2002. Testing was carried out to assess the capability of the InSiSST facility to evaluate the shear stiffness of the AC mixtures and investigate the variation of the shear stiffness of the AC mixes with temperature. An asphalt concrete pavement section at the entrance of the Civil and Environmental Laboratory at Carleton University was used for these tests. It is a flexible pavement sections and has been in-service since 1992 and the pavement surface is intact with almost no visible surface distresses, other than some ravelled areas. The pavement sections is not subjected to regular traffic, but has been used for loading to and from the laboratory, temporary parking and as a temporary storage area for different materials and equipment. The AC mixture on the surface of the pavement, which is the tested layer, is aged and rather stiff.

A number of test sets were carried out at different temperatures. However, given the nature of field-testing, there was no control on the actual temperature during testing. The number of tests per set varied between three to seven samples. The variation in the sample size was due to several reasons including the change in the weather conditions, or errors in the data acquisition system. Table 4 shows the results of the different field-testing sets carried out on this pavement section.

The temperature shown in the table is the average temperature recorded for the samples within the test set. The actual temperature was different between samples due to the change in the air temperature over the period testing and the localized differences due to falling shade from nearby buildings. However, within each set, the variation of temperature was within ± 2^{o}C. Figure 5 shows the calculated initial shear stiffness versus the average temperature at which the tests were performed, for this particular AC mix. Although only six data points are available, a preliminary model for the relationship between the shear stiffness of the AC mix and temperature was developed based on the limited data. The exponential function, shown in Figure 5 was used for the regression analysis with a coefficient of determination (R^2) of 66%, which shows a relatively good correlation, given the high variability expected from the AC mix.

TESTING AT THE SPS-9A 870900 SITE

Field-testing using the InSiSST was carried out at Petawawa on six adjacent pavement sections at the LTPP SPS-9A 870900 test site. Testing at Petawawa was carried out with the objective of evaluating the shear stiffness of different in-service AC mixtures subjected to identical traffic and environmental conditions. Furthermore, the historic performance of these sections is available through the National Information Management System (NIMS), which will allow for the evaluation of the rutting performance of these sections in against the shear stiffness of the surface mixture.

The SPS-9A study is a Specific Pavement Study (SPS) for the evaluation of the SuperPave mix design. A typical SPS-9 site consists of three structurally identical flexible pavement sections (core sections), with each section having a different AC surface mixture. The first section has a surface mixture typical to the local agency specifications, while the second section has a SuperPave surface mixture that is suitable for the environmental conditions of the site location. The third section is typically designed using another SuperPave mix with an expected inferior performance than the second section. In addition, the site may include extra supplemental sections with surface mixture of particular interest to the local agency.

The SPS-9A test site 870900 was constructed in April 1997 and is composed of six adjacent test sections; three core sections in addition to three supplementation sections. Table 5 shows the mixture specifications of each of the six sections located at the 870900-site, while Table 6 shows the as-built mixture properties of these sections as evaluated through the quality control inspections during construction. It is worth noting however, that all of the sections are a part of a controlled experiment and were constructed using high quality materials.

FIELD TESTING AND RESULTS

Seven samples were tested at each section. Five of these samples were located in the lane centreline, while the extra two samples located either in the wheel paths or on the shoulder of the road. The pavement material in the lane centre line is the least trafficked pavement across the lane and should provide the nearest approximation to the pavement properties just after construction. The results reported in this paper are only for those in the lane centreline. Testing was carried out in the summer of the year 2000 and the air temperature during the testing period ranged between 27^{o}C and 32^{o}C and the pavement temperature ranged between 33^{o}C and 39^{o}C.

The rutting data for the sections at the SPS-9A 870900 site were collected in the year 1997 (immediately after construction), in 2000 (3 years after construction), and in 2001 (4 years after construction). The data was acquired from NIMS, the DataPave database and from the Ministry of Transportation Ontario (MTO) records. Due to the fact that three rutting data points are known for each sections and the existence of some rutting immediately after construction, that cannot be attributed to the pavement performance, the rutting rate in mm/years was used as a rutting performance (*6*, *10*). The rutting rate is the average annual rutting over the four years between 1997 and 2001. Table 7 shows the shear stiffness results and the rutting rate for the different pavement sections at the SPS-9A test site. As can be noted from the results, the mean shear stiffness for the different sections were fairly close, but the standard deviation was also rather small, indicating high consistency within the results of each test section. To check the statistical significance of the results, ANOVA analysis at a confidence level of 95% was carried out. Table 8 shows the ANOVA results for the shear stiffness data from the different sections, and as can be noted, the analysis shows that at least one of the sections had significantly different shear stiffness than the other sections.

To further investigate the sections that were statistically significant, a multiple t-test was carried out for the results of each pair of sections. Table 9A shows the multiple t-test analysis results, while Table 9B shows the acceptance/rejection results based on the t-test. The bolder lines in Table 9B show the sections that are not significantly different.

As can be noted from the results section 870901, which is designed using the Marshall mix design approach and the penetration graded binder, had significantly higher shear stiffness than the other section, with the exception of 870903. Section 870961 had significantly lower shear stiffness than the other sections, with the exception of section 870902. It was also noted that both sections 870961 and 870902, which showed the least shear stiffness, were designed using the SuperPave mix design approach and a performance graded binder.

The field testing results were reformatted to show the results against the different mix designs and binder grading. For the six sections located at the SPS-9A test site, two sections were designed using the Marshall mix design, while 4 were designed using the SuperPave mix design. Also one section had a penetration graded binder, while the other five sections had a performance graded section, with three having polymer additives. Since the shear stiffness, and subsequently rutting, is more affected by higher temperatures, only the higher temperature was considered to classify the sections, such that binders PG 58-34 and PG 58-40 are both considered PG 58.

Figure 6 and Figure 7 show the average shear stiffness of the AC mixture and average rutting rate calculated for the different mix design and binder grading combinations in the SPS-9A site, respectively. As can be noted from the figures, the section with AC mixture designed by the Marshall mix design using the penetration graded binder showed the highest shear stiffness and lowest rutting rate, while the sections with the non-modified performance graded binder designed using the SuperPave mix design showed the lowest shear stiffness and the highest rutting rate.

CONCLUDING REMARKS

In this paper, a new field test facility for measuring shear stiffness of compacted asphalt concrete surface layers is presented. The In-Situ Shear Stiffness Test (InSiSST™) was developed at Carleton University and provides a much-needed tool to evaluate the in-situ shear stiffness of asphalt concrete surface mixtures in an accurate, efficient and timely manner. Shake up testing was carried out in Bancroft, Toronto, and on Carleton University Campus in Ottawa, Ontario to examine the newly developed facility. Field-testing was completed on the LTPP SPS-9A 870900 test site near Petawawa, Ontario.

The shake up testing performed at Bancroft, Ontario and on Carleton University campus showed that the InSiSST™ facility is capable of identifying the shear stiffness of the different asphalt concrete mixes and evaluating the variation in the shear properties among the different mixes. Furthermore, a preliminary relationship between the shear stiffness and the temperature was developed using the data collected from field tests on Carleton University campus.

Field tests at the SPS-9A 870900 at Petawawa Ontario showed the potential of the InSiSST facility as an accurate and efficient field-testing tool. At this test site, six test sections with identical pavement structures, but with different surface asphalt concrete surface mixtures were tested. The AC surface mixtures for the sections at this site were designed using different combinations of mix design approaches and asphalt binder grading.

The results from the 870900 site test section showed that the test section designed using the traditional Marshal mix design approach and using the penetration graded asphalt binder had higher in-situ shear stiffness and lower rutting rate than the sections designed using the SuperPave mix design approach and the performance graded asphalt binder. However, given the limited amount of data, further testing to verify these results is warranted.

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Table 1: Field Testing Results for Field Testing on HWY 62 at Bancroft Ontario

Section	Average Temperature (^{o}C)		Count of Samples	Mean (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
	Air	Pavement				
NB	20	28	7	13.97	2.33	2.3
SB	24	33	7	11.83	1.79	1.8

Table 2: t-Test Results for Field Testing HWY 62 at Bancroft Ontario

	NB	SB
Mean (MPa)	13.97	11.83
Variance	5.43	3.21
Observations	7	7
Pooled Variance	4.32	
Hypothesized Mean Difference	0	
Degrees of Freedom	12	
t-Stat	1.93	
P(T<=t) two-tail	0.0782	
t Critical two-tail	2.18	

Table 3: Field Testing Results at MTO Yard - Toronto, Ontario

Test Sample	Shear Stiffness (MPa)	Comments
S_01	4.90	Pavement failure - Soft patch
S_02	35.32	Bond Failure - Stiff, aged AC mixture
S_03	31.63	Bond Failure - Stiff, aged AC mixture
S_04	22.00	Bond Failure - Stiff, aged AC mixture

Table 4: Results of In-Situ Testing on the Pavement Section at Carleton University

Test Set	Date	Sample size	Pavement Temperature (^{o}C)	Shear Stiffness		
				Mean (MPa)	**St. Dev.**	**CoV (%)**
1	Jul 31, 2000	7	28	19.46	1.98	10.2
2	Aug 4, 2000	5	35	14.43	3.92	27.2
3	Aug 25, 2000	4	31	17.18	5.00	29.1
4	Nov 25, 2000	3	5	50.89	7.02	13.8
5	Sep 15, 2001	4	22	41.05	7.68	18.7
6	Aug 1, 2002	4	44	19.00	2.49	13.1

Table 5: LTPP SPS-9A 870900 Test Site Sections' Mixture Specification

Test Section	Surface Thickness	Mix Design	Binder specifications
870901	72 mm	HL3 Marshall design	85/100 penetration graded AC
870902	59 mm	SuperPave 12.5-mm mix	PG 58-40 (Polymer Modified)
870903	67 mm	SuperPave 12.5-mm mix	PG 58-34
870960	67 mm	SuperPave 12.5-mm mix	PG 58-28 (Polymer Modified)
870961	64 mm	SuperPave 12.5-mm mix	PG 58-40
870962	69 mm	HL3 Marshall design	PG 58-40 (Polymer Modified)

Table 6: As-Built Properties of AC Surface Mixture for the 870900 Sections

Test Section	BRD*	MRD**	Compaction (% of MRD)	Air Voids	% AC	% Passing 4.75- mm
870901	2343	2461	91.0-93.0	4.8	5.11	53.3
870902	2375	2499	90.5-91.8	4.0	4.00	34.9
870903	2379	2491	90.0-92.0	4.5	4.18	36.3
870960	2373	2490	91.0-95.0	4.7	4.16	35.3
870961	2378	2487	91.0-93.0	4.4	4.19	35.6
870962	2360	2452	91.0-95.0	3.8	5.20	52.2

* Bulk Relative Density (kg/m^3)

** Maximum Relative Density (kg/m^3)

Table 7: Field Testing Results for the SPS-9A 870900 Sections

Section	Pavement Temp. (^oC)	Rutting Rate (mm/yr)	Shear Stiffness (MPa)			
			Count	Mean	St.Dev.	CoV (%)
870901	33	0.074	5	16.66	1.28	7.71
870902	35	0.471	5	13.90	1.72	12.35
870903	36	0.523	5	15.93	1.99	12.49
870960	39	0.501	5	14.00	1.53	10.91
870961	37	1.235	5	12.13	0.73	6.02
870962	38	0.278	5	14.78	0.99	6.70

Table 8: ANOVA Results for the Shear Stiffness

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	64.95	5	12.99	6.28	0.0007	2.62
Within Groups	49.61	24	2.07			
Total	114.56	29				

Table 9A: Multiple t-test Results for the Shear Stiffness

	870901	870903	870962	870960	870902	870961
870901	1	0.51017	0.032282	0.017586	0.020566	0.00013
870903		1	0.282163	0.123632	0.122387	0.003902
870962			1	0.363622	0.347756	0.001316
870960				1	0.924869	0.038721
870902					1	0.066702
870961						1

Table 9B: Hypothesis Acceptance/Rejection based on Multiple t-Test

	870901	870903	870962	870960	870902	870961
870901	1	Accept	**Reject**	**Reject**	**Reject**	**Reject**
870903		1	Accept	Accept	Accept	**Reject**
870962			1	Accept	Accept	**Reject**
870960				1	Accept	**Reject**
870902					1	Accept
870961						1

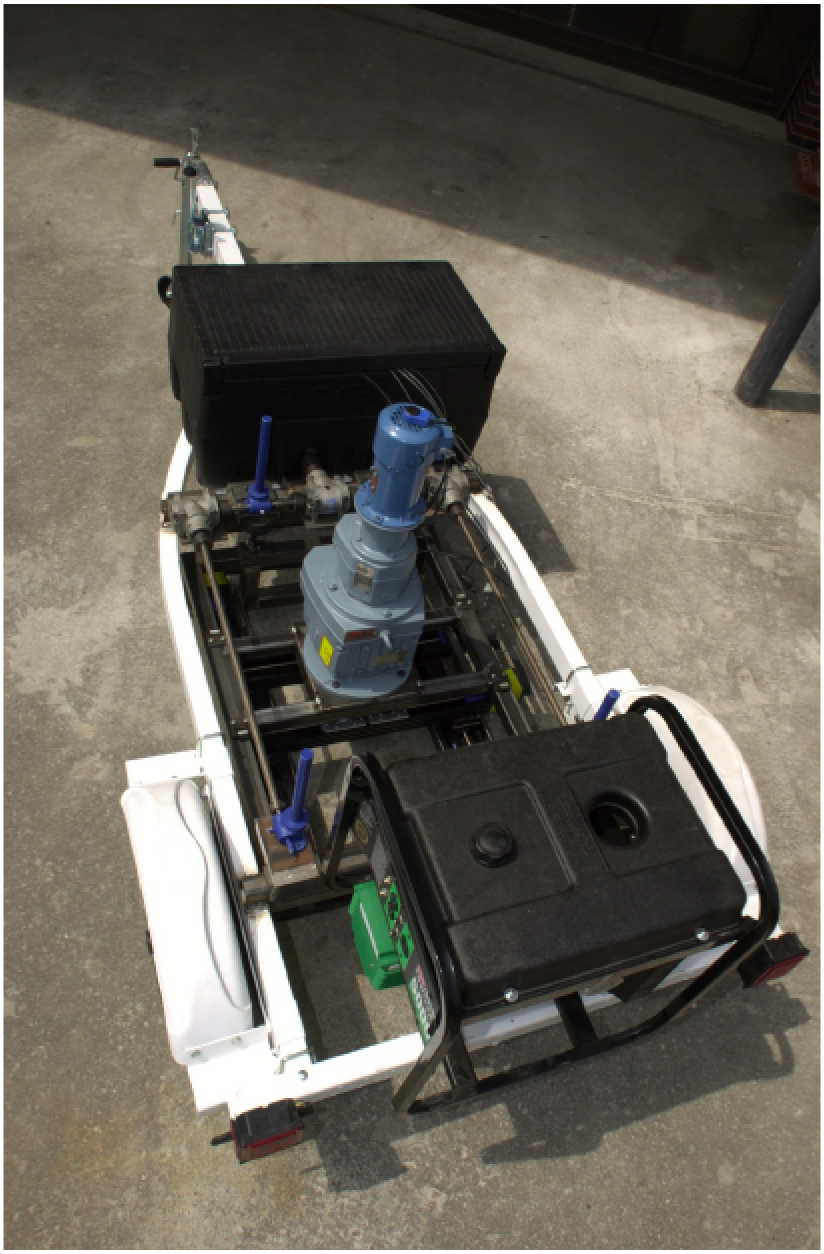

Figure 1: Top View of the In-Situ Shear Stiffness Test (InSiSST™) Facility

Figure 2: Applying torque to the pavement surface

Figure 3: Sample after the Completion of Field Testing

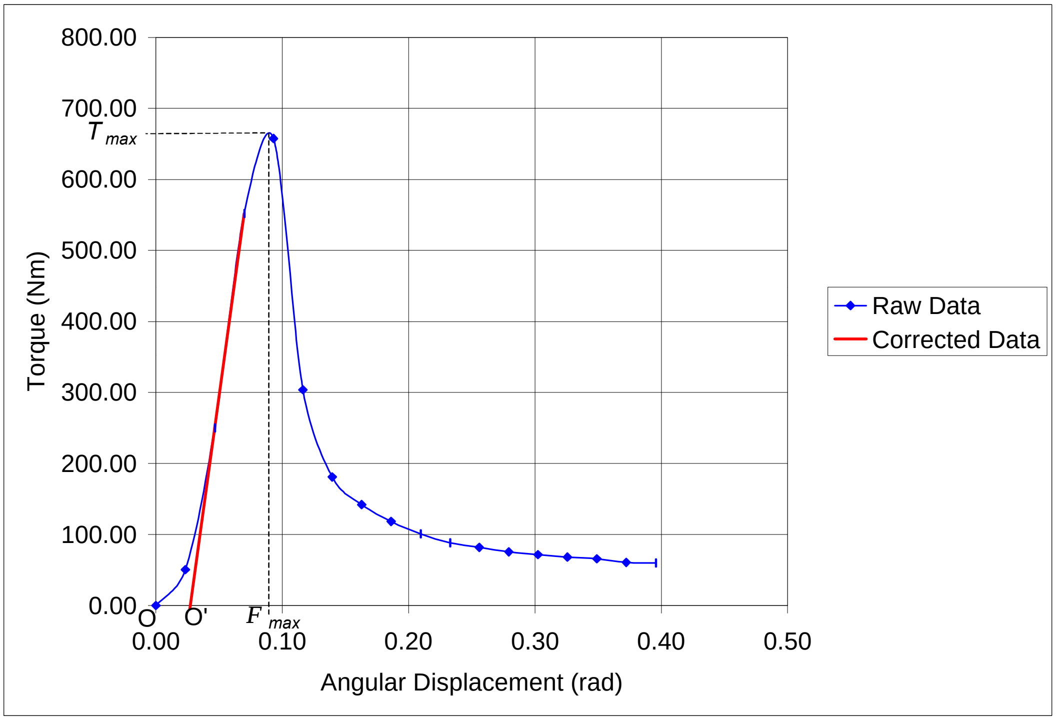

Figure 4: Typical Relationship between the Torque and the Angular Displacement

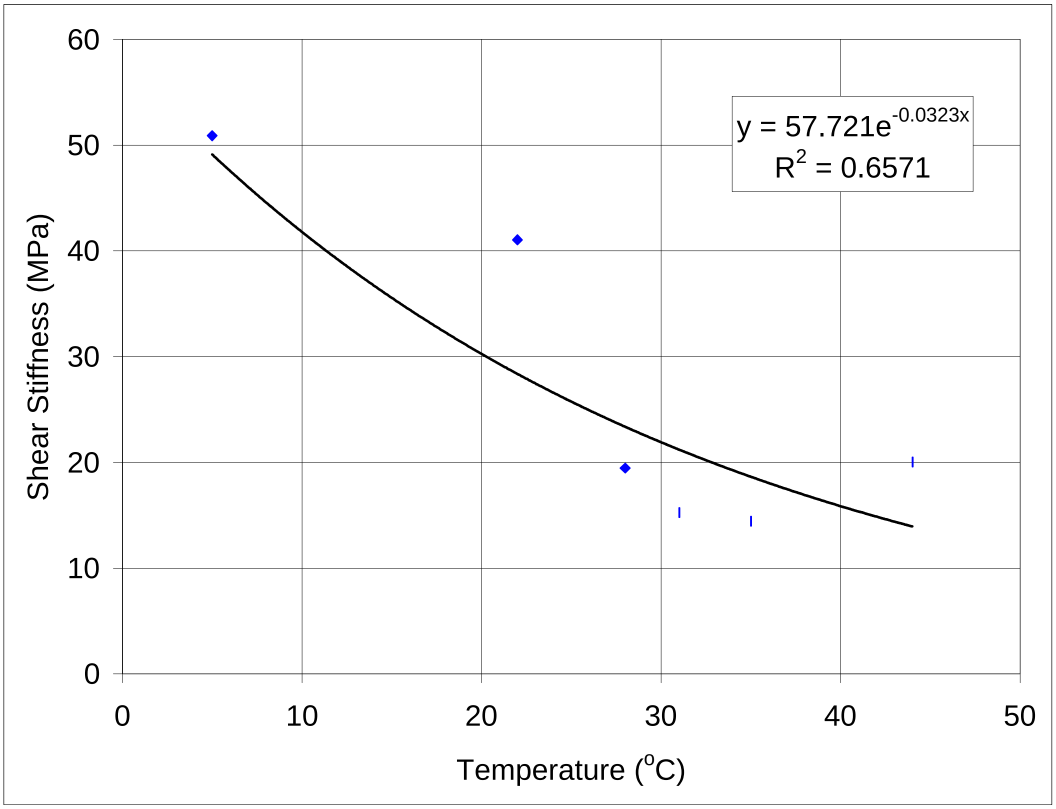

Figure 5: Variation of Shear Stiffness with Temperature

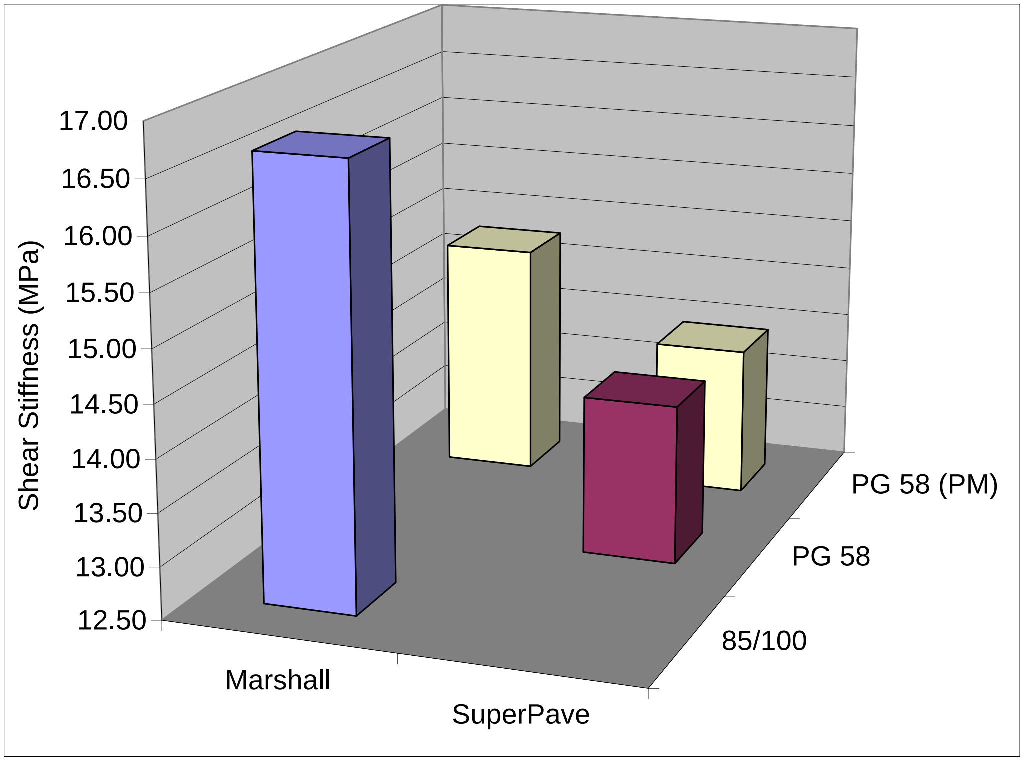

Figure 6: AC Shear Stiffness by Mix Design and Binder Grading

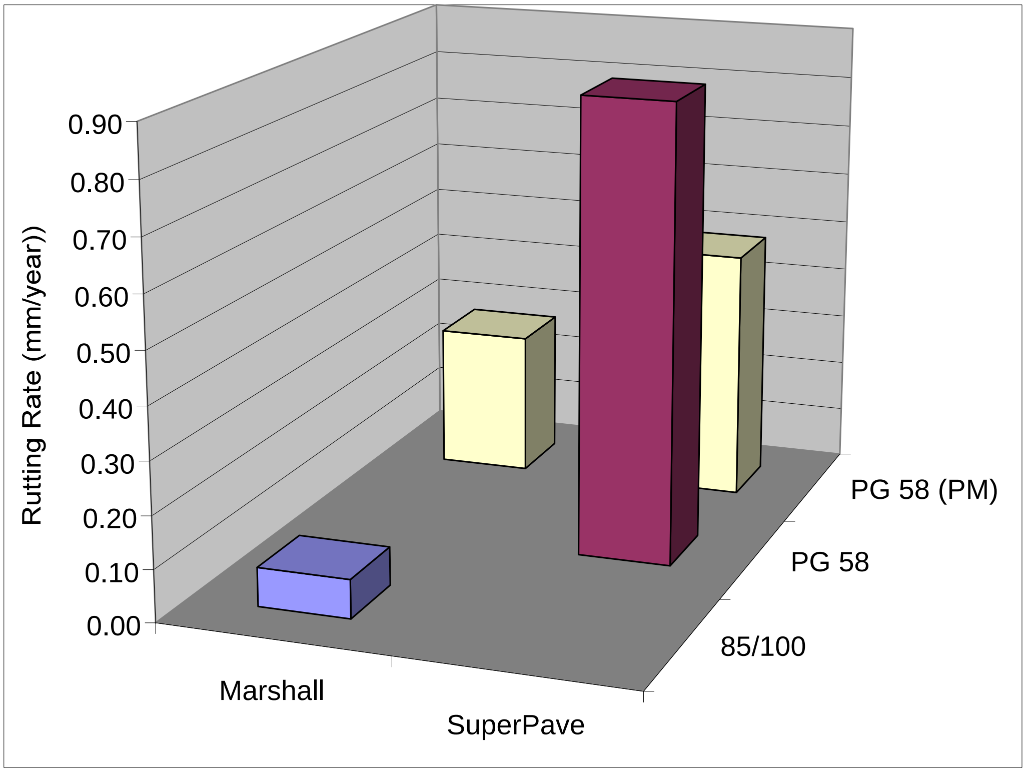

Figure 7: Rutting Rate by Mix Design and Binder Grading