IDEA

Innovations Deserving
Exploratory Analysis Programs

Highway IDEA Program

An In-Situ Shear Stiffness Test Facility for Asphalt Concrete Pavement

Final Report for Highway IDEA Project 87

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
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EXECUTIVE SUMMARY

While the past decade has seen many significant improvements in asphalt pavement technology, there remains much room for improvement, particularly in the use of shear properties to design, construct, monitor and predict the performance of asphalt concrete pavements. During the Strategic Highway Research Program (SHRP), shear properties of asphalt concrete were identified as being extremely important toward a pavement's ability to resist permanent deformation, however, prior to NCHRP IDEA Project #55, there was no available method or apparatus to measure the in-situ shear properties of asphalt pavements. In-situ tests possess certain advantages over their laboratory counterparts including significantly reduced testing time, more representative results (compared to laboratory prepared specimens), and reduced damage to the pavement structure (compared to coring).

The current NCHRP IDEA Project #87 is the second phase of NCHRP IDEA Project #55. Project #55 represented a Type 1 – Concept Exploration project, where the concept of measuring the shear properties of asphalt concrete layers as constructed was tested and verified. The project also saw the development of a new field test facility known as the In-Situ Shear Stiffness Test (InSiSST™) – a rugged, self contained facility that may be transported from site to site and perform rapid and repeatable tests with a single operator.

Based on the promising results of Project #55, this Type II – Product Application proposal has been developed to focus on the practical application of the InSiSST™ facility through product enhancement, additional field-testing and laboratory correlation. In the original IDEA proposal, it was expected that additional funding would be secured from the Ontario Ministry of Transportation to allow the construction of field test sections, QC/QA testing and periodic field-testing. Unfortunately, these funds did not materialize and a modified set of tasks was conducted as summarized below.

Task 1 – Review of Work Completed to Date

The InSiSST™ facility was designed and built at Carleton University for the purpose of evaluating the shear properties of asphalt concrete mixtures in the field. However, subsequent field-testing indicated that further enhancement was required:

1. The actual strain rate during field-testing might not be constant as assumed during the original investigation.
2. In some cases, the epoxy used to bond the steel plate to the pavement surface failed prior to the failure in the asphalt concrete mix. Furthermore, the epoxy required a 24–hour period before the test could be conducted.
3. Field testing using the InSiSST™ was carried out with no control over the actual pavement temperature.

Task 2 – Enhancements to the InSiSST™

After investigating alternative methods to directly measure strain rate, a Rotary Displacement Transducer (RDT) capable of providing 360° of unrestricted continuous rotation measurement was selected.

As an alternative load application technique, modified vane plates were constructed with vertical blades that can be inserted into grooves created in the pavement surface using a novel grinding system. The vanes provide a distinct area of contact between the blades and the asphalt concrete and eliminate the need for the epoxy. To investigate the effect of the plate size on the shear properties of the asphalt mix measured with the InSiSST™ facility, vane plates with diameters of 100, 125 and 150 mm (4, 5 and 6 in) were manufactured.

To control the pavement test temperature, an innovative heating system was developed consisting of four sheet heaters shaped to cover both the test plate and the surrounding pavement surface. Each sheet heater is equipped with a thermocouple to measure the temperature on the pavement surface.

Task 3 - Laboratory Shear and Uniaxial Compression Testing

Shear properties of asphalt mixes determined by applying torsion on cylindrical core samples were shown during NCHRP IDEA #55 to correlate well with pavement rutting susceptibility. As such, additional torsion testing was conducted for this investigation. The repetitive uniaxial compression (dynamic compression) test was also chosen as it can determine the susceptibility of a mix to permanent deformations related to shear flow as well as those associated with changes in the microstructure of asphalt concrete.

Task 4: Field Shear Testing at Carleton University and National Research Council sites

Field-testing was carried out to verify the proposed modifications, validate the laboratory results and investigate the effect of different variables on the measured shear properties. The testing program was undertaken in two different places - Carleton University campus and the National Research Council (NRC) of Canada. The first field-testing stage covered the study of the heaters' functionality as well as the asphalt concrete response to the heating process. In the second stage, the performance of the RDT was verified and the effect of plate size and temperature on the shear properties of asphalt mixes was investigated. During the third stage, the in-situ performance of the vane plates and the repeatability of the tests were assessed. Finally, in the last stage, the results obtained from InSiSST™ testing were evaluated.

Task 5: Analysis of Test Results and Task 6: Reporting of Findings

Due to the lack of cooperative funding, a considerably smaller testing program was conducted. A number of preliminary findings based on the reduced testing program are as follows:

1) The time required for heating appears to be sensitive to the asphalt mix type. The heating period tends to decrease as the strength of the asphalt mix increases.
2) The strain rate is sensitive to the mix properties and the pavement temperature. For the higher pavement temperature or relatively stronger asphalt mixes, the deviation from linearity is greater.
3) The shear properties of asphalt concrete mixes are sensitive to the pavement temperature. The higher the pavement temperature, the lower the shear strength and shear modulus.
4) There appears to be an exponential relationship between the in–situ shear properties of the asphalt mix and the pavement temperature – a finding supported by the results of IDEA Project #55.
5) At higher temperatures the in–situ shear strength and modulus of the mix appear to be independent of the test plate size – a promising result considering that permanent deformation occurs at higher pavement temperature.
6) There is a statistically significant relationship between the shear modulus values obtained from torsion tests using epoxy and the vane plate. Therefore, the vane plate can be a reliable substitute for epoxy.
7) The tests carried out using the InSiSST™ facility and the vane plates yielded acceptable repeatability.
8) For the pavements tested, the InSiSST™ facility and the vane plate results indicated that the facility is capable of differentiating between shear properties of different asphalt pavements with respect to the mix type and compaction method – a finding again supported by the results of IDEA Project #55.
9) There is a statistically significant relationship between the Shear Index obtained from the InSiSST™ testing with the vane plate and the shear modulus of cylindrical samples of the same mix, although the strength of the correlation is weaker than anticipated (R^2=0.68). It is surmised that the high variability of the laboratory test results is partially responsible.
10) Based on the preliminary laboratory testing the shear properties of asphalt concrete mix are correlated to the long–term performance of the material.

Next Steps

The considerable enhancements completed to the InSiSST™ facility during this investigation have mitigated the operational concerns observed during NCHRP IDEA Project #55. As such, the InSiSST™ may now be considered a production-ready prototype, although it is considered desirable to add dynamic testing capability. Initial discussion between Carleton University, EMPA and the TRB are underway to develop a strategic partnership to implement dynamic testing capability and conduct further testing.

Carleton University will also continue its efforts to find a suitable manufacturing company interested in final engineering development and manufacturing of the InSiSST™ for widespread availability to governments, pavement engineering companies and roadbuilding contractors.

IDEA PRODUCT

DESCRIPTION OF THE INSISST™

The current NCHRP IDEA Project #87 is the second phase of NCHRP IDEA Project #55. Project #55 represented a Type 1 – Concept Exploration project, where the concept of measuring the shear properties of asphalt concrete layers as constructed was tested and verified. That project also saw the development of a new field test facility known as the In-Situ Shear Stiffness Test (InSiSST™). Based on the promising results of Project #55, this Type II – Product Application project was awarded to focus on the practical application of the InSiSST™ facility through product enhancement, improved analytical modelling and additional field testing and laboratory correlation.

The InSiSST™ (Figure 1) was developed to provide a new method to measure the shear properties of asphalt concrete pavements in the field, without the need for specimen collection (i.e. coring or trenching) or complex laboratory analysis. This "on the road" approach for testing engineering properties such as shear strength and stiffness had never been successfully implemented prior to these investigations. The InSiSST™ is a rugged, self-contained facility that may be transported from site to site and perform rapid and repeatable tests with a single operator.

A comprehensive description of the original InSiSST™ facility may be found in Goodman (2000). Briefly, an electric motor and gearbox are utilized to apply a forced circumferential displacement to a steel plate bonded to the asphalt surface. The motor/gearbox combination is positioned vertically to save a significant amount of space compared to right-angled gearboxes. The motor/gearbox combination is mounted on a steel platform attached to two sets of electric worm-screw slides allowing positioning of the platform in both the longitudinal and transverse directions. The entire positioning system, whose movement is controlled by an electronic controller, is mounted to a two-level frame, which is attached to the trailer frame via four jacks. During transportation, the jacks are retracted to hold the frame above the ground to prevent damage. During testing, the frame is lowered until it sits on the pavement and the whole trailer lifts off the ground. Stability against the rotational force applied to the test plate is achieved through frictional force between a neoprene (rubber) pad epoxied to the bottom of the test frame and the pavement surface. The required weight is provided by the trailer, test frame and the test equipment. The main drive motor is controlled through a variable speed controller and the applied torque is recorded with a torque cell. A laptop computer provides control over the test procedure and data acquisition. Results are saved directly to the computer and other relevant information such as test site location, weather conditions, temperatures, etc. may also be directly entered into a database for future analysis. All of the individual components operate under the same power requirements as provided by the central generator.

The testing facility was originally designed to provide a constant strain rate loading. Consequently, the angular displacement was calculated using the motor speed and the gearbox reduction ratio. From the calculated displacement values and the torque values recorded during the test, the torque–twist curve was obtained. The mechanistic properties of the asphalt concrete mix were then evaluated according to the maximum displacement (strain at the time of failure), the average shear strength, average maximum shear stress at failure calculated based on secant shear modulus, or the shear stiffness of the mix (Bekheet 2002). Shear modulus, G was derived for the case of a forced angular displacement applied to the surface of a linear elastic half space (Reissner and Sagoci 1944).

As will be described in detail within the Investigation section of this report, a number of enhancements have been implemented to InSiSST™. These include the following:

1. The addition of a rotary displacement measurement system to more accurately record the rotation (i.e. strain) of the torque cell while testing,
2. The development of steel vane testing plates and an associated installation system to eliminate the requirement for adhering flat test plates to the pavement surface using epoxy,
3. Enhancement and integration of the data collection system, and
4. The provision of pavement temperature control through an innovative heating system.

These enhancements have overcome the limitations observed during NCHRP IDEA Project #55 such that the InSiSST™ has advanced to the stage where it may be easily transferred to a manufacturing company for final engineering, production and distribution.

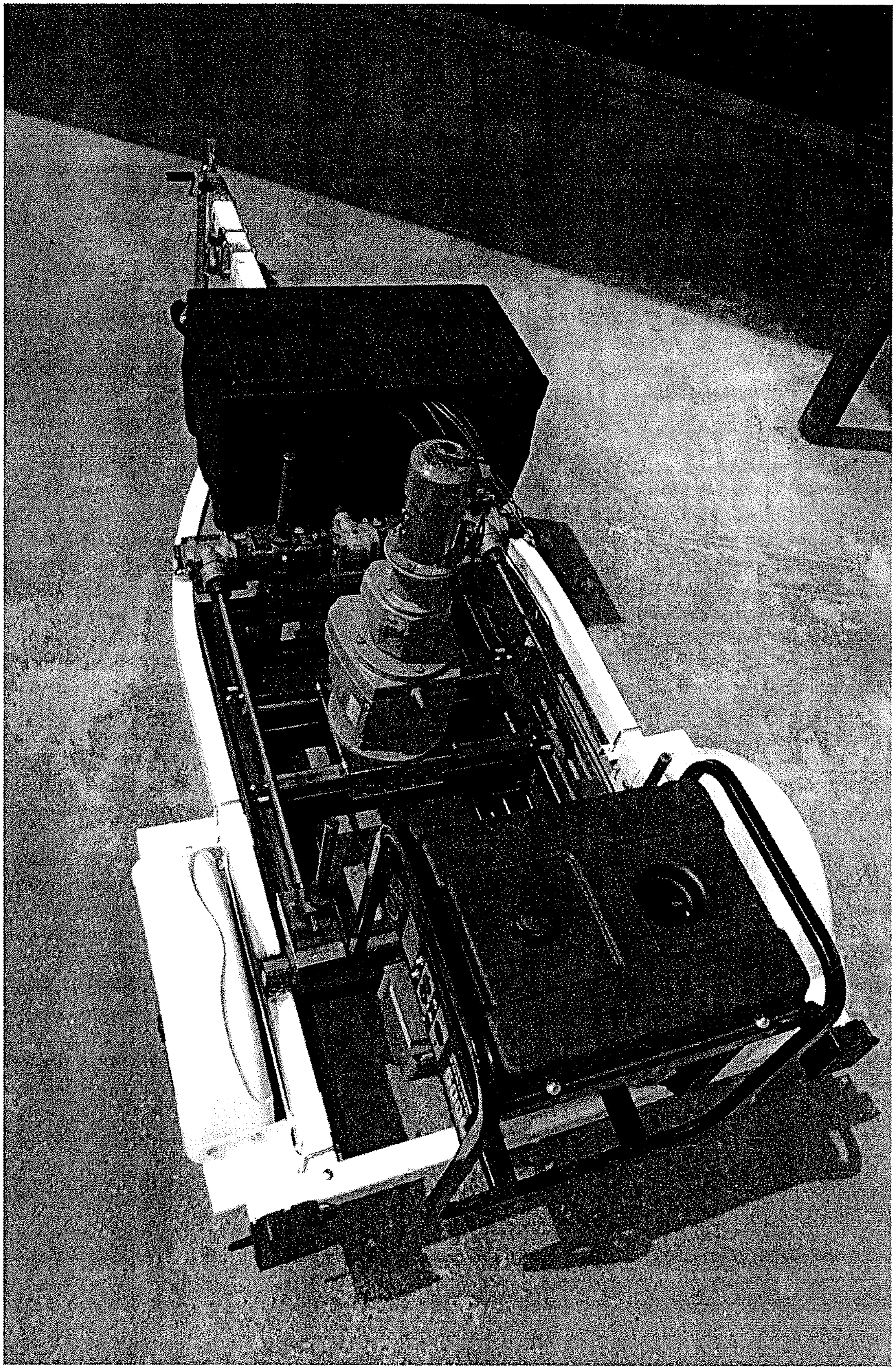


FIGURE 1 Top View of the In-Situ Shear Stiffness Test (InSiSST™) Facility

POTENTIAL IMPACT UPON TRANSPORTATION PRACTICE

The potential impact upon transportation practice has not changed since originally described in NCHRP IDEA Project #55, as repeated herein:

> The successful measurement of in-situ asphalt shear properties and widespread implementation of the InSiSST™ test facility will yield significant and immediate benefits to transportation practice. These benefits will be realized in three primary areas of pavement engineering. The first area is *design*. An in-situ shear strength/stiffness test in conjunction with laboratory testing would be a powerful combination for analyzing the performance potential of proposed mix designs. By evaluating performance potential at the mix design stage, millions of dollars may be saved each year by preventing the construction of road systems with substandard or under designed mixes. Also, the in-situ and laboratory test results could be used to produce "shift" or "master" curves relating in-situ shear properties to various factors such as loading rate, temperature and asphalt content among others.
>
> The second area is *quality control and quality assurance (QC/QA)*. Newly constructed asphalt pavements could be tested during, or immediately after construction to verify acceptable construction practices through the measurement and comparison of in-situ parameters with laboratory results or code requirements (yet to be developed).
>
> The third area is *long-term pavement performance (LTPP)*. Monitoring of the field shear properties of pavements with time would assist in predicting future pavement performance. This, in turn, would allow for more efficient allocation of limited rehabilitation funds and also help determine the effect of real world conditions, such as environmental factors, on pavement performance.
>
> Perhaps most importantly, InSiSST™ has the potential to further promote the use of fundamental engineering properties (i.e. mechanistic methods) – a move that was initiated by the Strategic Highway Research Program (SHRP) in the mid 1990's. The adoption of mechanistic methods will result in more cost effective pavements by providing more accurate mix design and performance analysis. At the time of this writing, a simple performance test (SPT) is under development for the Superpave asphalt mix design system under NCHRP Project 9-19. Although the final recommendation has not yet been made public, the SPT will likely be based upon a modified laboratory triaxial test, which will provide the complex modulus (E*) of an asphalt concrete specimen. Because the complex modulus and shear modulus are theoretically related, it is likely that a correlation between the SPT and the InSiSST™ can be developed. As noted previously, the combination of the SPT (in the laboratory) and the InSiSST™ (in the field) would provide a powerful combination toward improved mix designs, increased pavement life and reduced costs.

CONCEPT AND INNOVATION

BACKGROUND

While the past decade has seen many significant improvements in asphalt pavement technology, there remains much room for improvement, particularly in the use of shear properties to design, construct, monitor and predict the performance of asphalt concrete pavements. During the Strategic Highway Research Program (SHRP), shear properties of asphalt concrete were identified as being extremely important toward a pavement's ability to resist permanent deformation, also known as "rutting" (Célard 1977, US-SHRP 1994). Rutting presents two major problems to road systems and their respective governing agencies. First, commuter safety is jeopardized when wheelpath rutting becomes severe enough to influence automobile handling and braking. Ponding of rainwater further increases the potential for accidents through hydroplaning. Secondly, rehabilitation of rutted pavements costs taxpayers many millions of dollars per year, funds that could be better spent on new construction, rehabilitation, preservation or research.

Prior to NCHRP IDEA Project #55, *there was no available method or apparatus to measure the in-situ shear properties of asphalt pavements*. In-situ tests possess certain advantages over their laboratory counterparts including significantly reduced testing time, more representative results (compared to laboratory prepared specimens), and reduced damage to the pavement structure (compared to coring).

TESTING SHEAR PROPERTIES IN-SITU

Shear properties are very important for determining the rutting resistance of asphalt pavements. The combination of binder stiffness and adhesion, as well as the interlocking of aggregate particles, produces the majority of a pavement's shear strength and stiffness. In the laboratory, shear properties of asphalt concrete are usually measured from a cylindrical specimen prepared in the lab, or a core of asphalt taken from the field. There are various methods for measuring shear properties in the lab, including the triaxial test, Superpave Shear Tester (SST) and the torsion test.

However, shear testing in the field is considerably different. In-service pavements are flat, and quite thin in comparison with their length and width. Whereas a laboratory specimen has defined boundary conditions for stress and strain calculation, the in-service pavement surface does not. Therefore, the use of simple shear such as used with the SST was not applicable to field conditions. Other field test devices such as the Falling Weight Deflectometer (FWD) are able to provide in-situ layer stiffness, however, the test equipment is too costly to purchase and operate for most agencies, consultants and contractors.

INVESTIGATION

BRIEF REVIEW OF NCHRP IDEA PROJECT #87 GENESIS

The current NCHRP IDEA Project #87 is the second phase of NCHRP IDEA Project #55. Project #55 represented a Type 1 – Concept Exploration project, where the concept of measuring the shear properties of asphalt concrete layers as constructed was tested and verified. The project also saw the development of a new field test facility known as the In-Situ Shear Stiffness Test (InSiSST™) as described in the Product section of this report. Based on the promising results of Project #55, this Type II – Product Application proposal has been developed to focus on the practical application of the InSiSST™ facility through product enhancement, additional field testing and laboratory correlation.

Eight successive tasks were identified in the proposal as listed below.

Task 1: Review of Work Completed to Date
Task 2: Enhancements to the InSiSST™ Facility
Task 3: Construction of Six Field Test Sections
Task 4: QC/QA Field Testing and Laboratory Sampling
Task 5: Periodic Field Testing
Task 6: Laboratory Testing
Task 7: Analysis of Test Results
Task 8: Report Findings

In the original IDEA proposal, it was expected that additional funding would be secured from the Ontario Ministry of Transportation to allow the construction of field test sections, QC/QA testing and periodic field testing (Tasks 3-5). Unfortunately, these funds were not available due to budget restrictions and, as such, the following modified tasks were conducted to substantially address the original project objectives:

Task 1: Review of Work Completed to Date
Task 2: Enhancements to the InSiSST™ Facility
Task 3: Laboratory Shear and Uniaxial Compression Testing
Task 4: Field Shear Testing at Carleton University and National Research Council sites
Task 5: Analysis of Test Results
Task 6: Report Findings

This final report has been written to follow the modified project outline. To remain within the specified guidelines for this report, much of the included material has been summarized. A full account of the InSiSST™ enhancement and additional testing effort may be found in Rohani (2003).

TASK 1 – REVIEW OF WORK COMPLETED TO DATE

The InSiSST™ facility was designed and built at Carleton University for the purpose of evaluating the shear properties of asphalt concrete mixtures in the field. The first two generations of the test facility applied torque to the asphalt layer through forcing a steel plate bonded to the surface of the pavement surface to rotate about an axis normal to the surface. The testing facility has been equipped with a data acquisition system to record the instantaneous torque and the motor speed. The torque is measured directly using the torque cell. The angular displacement is calculated assuming constant strain loading is applied. However, field-testing showed a number of issues that may affect the accuracy of the InSiSST™ and indicated that further improvement was required. These issues are briefly listed below:

4. The actual strain rate during field-testing might not be constant, such that assuming a constant strain rate may affect the accuracy of the field–testing results. Subsequently, the actual angular displacement should be directly measured during testing and not calculated assuming constant strain rate.
5. In some cases, the epoxy used to bond the steel plate to the pavement surface failed prematurely prior to the failure in the asphalt concrete mix. Furthermore, the epoxy currently requires a 24–hour period before the test can be applied. In this case, field–testing is completed over two days - where the plates are glued to the surface on the first day and actual testing is carried out the following day. As such, further investigation to eliminate the use of epoxy is required to achieve a faster and more reliable field test.
6. Field testing using the InSiSST™ is carried out with no control over the actual pavement temperature during testing. The ability to control the actual temperature during testing will significantly enhance the ability of InSiSST™ to function under different weather conditions.

To address these issues, a series of enhancements to the InSiSST™ facility were devised and installed under Task 2.

TASK 2 – ENHANCEMENTS TO THE INSISST™ FACILITY

Rotary Displacement Measurement

Although the InSiSST™ facility was originally designed to provide a constant strain rate loading, observations during subsequent in-situ testing by Bekheet (2002) showed that the actual strain rate was not always constant and was dependent on the material properties as well as the pavement temperature. The higher the material resistance (or the lower the temperature), the slower the strain rate at the early stages of loading. Figure 2 illustrates this phenomenon by comparing the results of three asphalt mixes with different properties. For a weak material (Sample 1) the angular displacement variation with time is almost linear, while for typical and stronger mixes (Samples 2 and 3, respectively) the variation is nonlinear. However, it was found that the total rotation angle after the failure is similar to the total rotation angle under constant strain rate, as shown by the dashed line.

In addition, the analytical investigation showed that the shear stiffness of asphalt concrete mixes is less sensitive to the variation in the strain rate when the angular displacement is applied at, or close to, a constant strain rate. However, as the strain rate becomes nonlinear, the shear stiffness becomes more sensitive to the variation in the actual angular displacement. Therefore, it was realized that the actual angular displacement during in-situ testing has to be accurately evaluated to ensure accurate shear stiffness measurements, especially at lower temperatures, where the angular displacement at failure is relatively small.

In the current configuration, the maximum rate of angular displacement that can be applied is 0.222 revolutions per minute (rpm). This rate is quite fast and the failure happens in a short period of time (2-5 seconds as documented by Bekheet 2002). Therefore, manual measurement of the angular displacement with time was not feasible. To overcome this problem, Bekheet (2002) used a digital video camera to record the testing process. The recorded digital video was downloaded to a computer and viewed frame by frame, which allowed measurement of the angular displacement at time intervals as small as 0.033 sec. However, the data compilation from the recorded video was a fairly time consuming process and would not be a practical approach for a large-scale testing program. Therefore, it was necessary to use an electronic device that automatically measures the angular displacement.

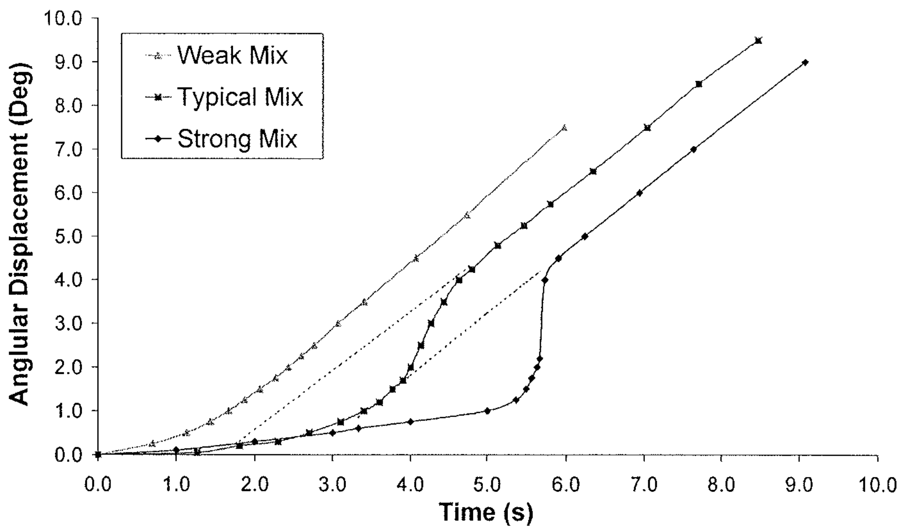


FIGURE 2 Variation of Displacement by Time (Bekheet 2002)

After investigating alternative methods, a Rotary Displacement Transducer (RDT) capable of providing 360° of unrestricted continuous rotation was selected. The RDT measures the displacement through a set of gears, one connected to the collar between the torque cell and the test-plate and the other connected to the RDT itself. The readings of the RDT are corrected for the ratio of the gears' diameters. The RDT is installed on a seat with three adjustable legs so that the two gears can be levelled (Figure 3). A large diameter gear was installed on the torque cell to help distance the RTD from the zone of influence imparted on the asphalt surface by the test plate. Bekheet (2002) determined through finite element modelling that the stress field was greatest at the edge of the test plate and dampened rapidly with distance to practically zero at a distance of one half the plate diameter. The legs of the RTD are approximately 75mm away from the edge of the test plate, and do not affect the resulting measurements.

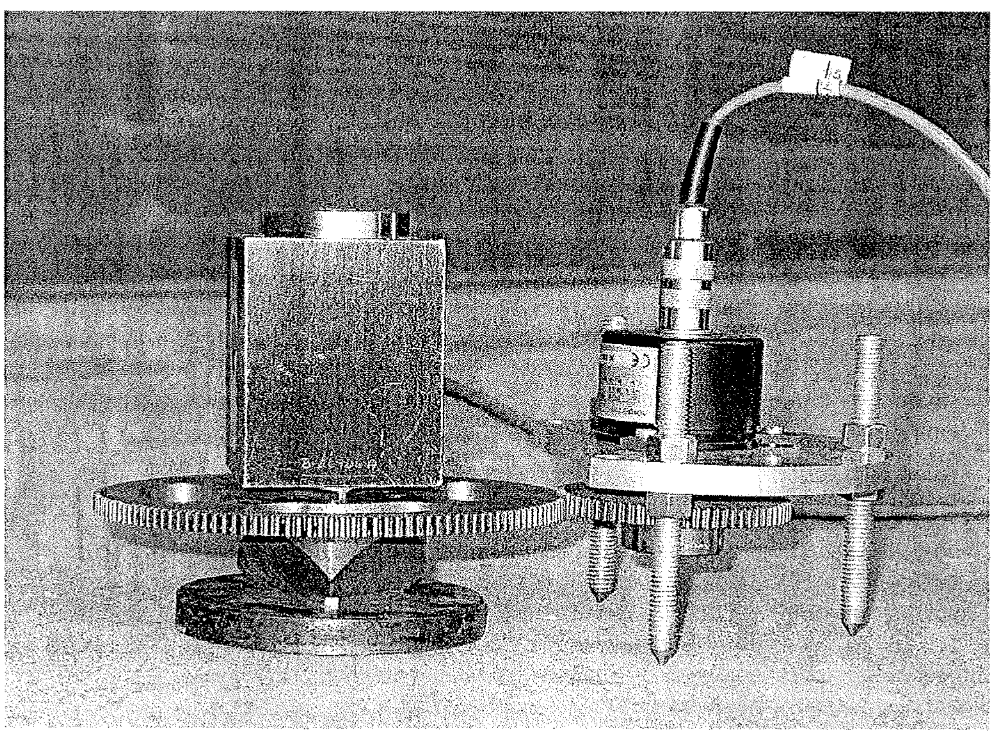


FIGURE 3 The RDT Connected to the Collar with a Set of Gears

Steel Vane Plates and Installation System

Steel Vane Plates

The epoxy used for InSiSST™ testing required a relatively long curing time - a period of eight to twenty four hours. This required the closure of the test site to traffic twice within a twenty four-hour period - once to epoxy the loading plates to the asphalt while the other for actual testing. Closing roads to traffic at any time period increases congestion and driver stress, as well as presenting significant safety risk to highway personnel. Although numerous adhesive systems were tested in the previous study a suitable replacement was not found (Goodman 2000).

To address this issue, a new approach was developed. This method is based on modified steel plates provided with vertical blades that can be inserted into the pavement surface. The steel blades provide enough area of contact between the blades and the asphalt concrete and eliminate the need for the epoxy. Two types of vane plates were designed and manufactured at Carleton University – cross vane plates (Figure 4a) and single vane plates (Figure 4b). The shape of the blades was chosen based on the shape of the failure surface observed from the previous tests i.e. the frustum of a cone. The height of 25 mm (1 in) was selected for blades based on the findings of Abd El Halim et al. (1997) who showed that the test would be successful if the height of the failed sample is greater than the nominal aggregate size of the mix.

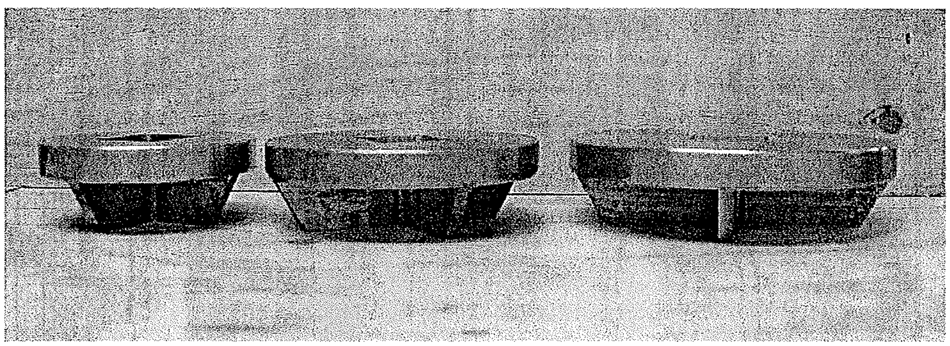


FIGURE 4a Cross Vane Plates (left to right are 100mm, 125 and 150mm in diameter)

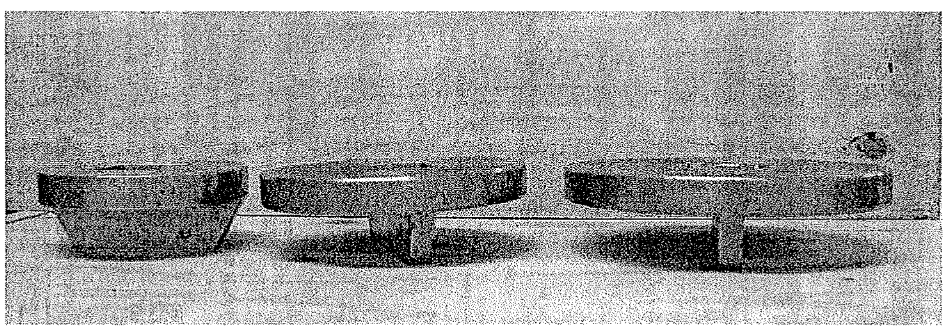


FIGURE 4b Single Vane Plates (left to right are 100mm, 125 and 150mm in diameter)

To investigate the effect of the plate size on the shear properties of the asphalt mix measured with the InSiSST™ facility, three vane plates with the diameter of 100, 125 and 150 mm (4, 5 and 6 in) were manufactured for each type.

Vane Installation System

To insert the vane plates, grooves with the same size and dimension as the blades must be formed on the pavement surface. The instrument used to make the grooves is a 5" angle grinder mounted to a system, which has been designed and manufactured at Carleton University to provide either a crossed or a single groove on the pavement. This device consists of two main parts, a stationary frame (Figure 5a) and a mobile unit (Figure 5b). The stationary part is an 840 x 840 mm (33" x 33") box-tube frame with parallel angle sections mounted on it in both directions.

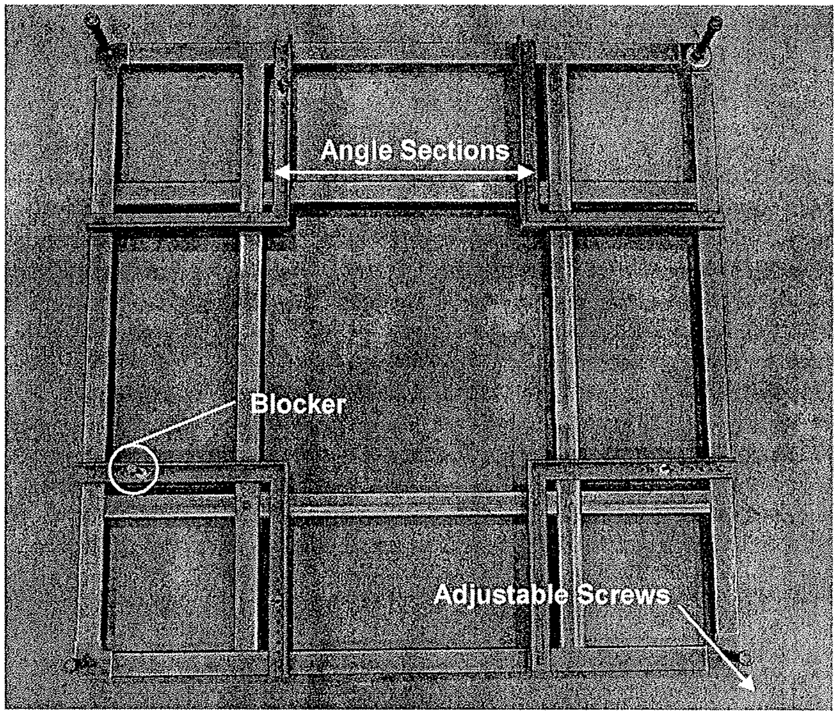


FIGURE 5a Stationary Frame

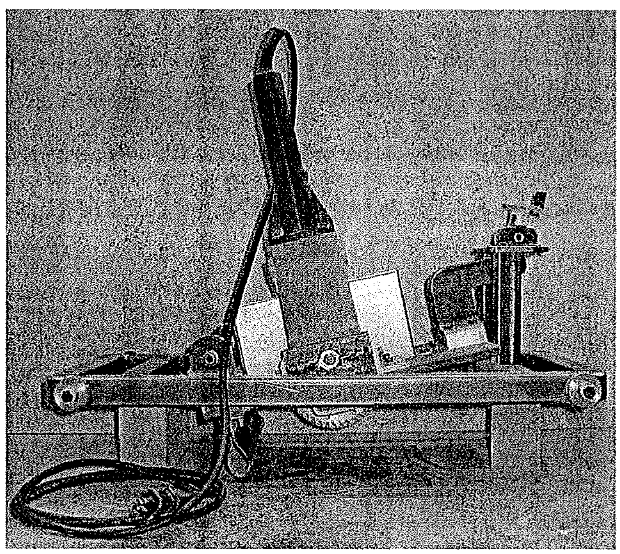


FIGURE 5b Cutting Tool and Mobile Unit

The angle sections act as a rail for the mobile unit and are squared to provide perpendicular grooves. The mobile unit holds the angle grinder and moves on the angle sections through 4 wheels. The angle grinder can also be moved manually in vertical direction using a handle provided for this purpose.

Introducing the vane as a new approach for attaching test plates to the pavement surface had a number of advantages. First, it eliminated the use of epoxy, which sometimes failed prematurely. The second and the most important advantage was the significant reduction of the total time required to complete field-testing. With this system, testing can be completed within 1 to 1.5 hours, instead of having to wait for the epoxy to harden for twenty-four hours. As such, only a single lane closure is required for testing, which greatly reduces the risk to test personnel.

In addition, for each plate size only one test plate is required. This test plate can be used for all the tests per testing day, eliminating the need for multiple test plates to be manufactured or the limitation in testing program due to the lack of test plates. Moreover, there would be no need for subsequent cleaning and roughening of the test plates. The last advantage is

that a more defined failure surface obtained from the tests with vane plates in comparison to those obtained using epoxy. In the latter case, the operator estimates the average dimensions of the failed surface and therefore, the results would be less accurate. However, in the case of the vane plate the failure surface follows the geometry of the blades with specific dimensions that leads to more accurate results.

Data Acquisition Enhancement

Although video taping the testing process provided the angular displacement variation versus time (Bekheet 2002), the problem was not completely solved because the torque and the angular displacement were measured separately and had to be cross-referenced. This might result in some inaccuracy when defining the exact starting point of the torque data as compared to the exact starting point of the angular displacement values.

The solution for this problem was the instantaneous measurement of both torque and rotary displacement through an enhanced data acquisition system called Personal Daq - a compact data acquisition device that makes use of the Universal Serial Bus (USB). Personal Daq can directly measure multiple channels of volts, thermocouples, pulse, frequency, and digital input/output (I/O). It provides measurement durations ranging from very slow (610 milliseconds) to very fast (12.5 milliseconds) that are equal to 1.6 and 80 samples per second respectively. The Personal Daq system can make thermocouple and volts measurements concurrently to facilitate measuring temperature during testing while the torque and displacement values are being measured through the torque cell and the RDT.

Pavement Temperature Control

Due to its viscoelastic nature, shear properties of asphalt concrete mixes are highly dependent on temperature. Bekheet (2002) studied the effect of the variation in the temperature on the properties of the asphalt concrete mixture and showed that this variation can have a significant effect on the in-situ measurement of the shear stiffness. Several sets of in-situ testing were completed at different temperatures. However, the previous study was limited to the prevailing temperature of the testing pavement.

Two alternatives were considered to control pavement temperature - an environmental chamber and flexible sheet heaters. Sheet heaters were preferred because of their lightweight, thin profile, low thermal mass and flexibility. They produce a very even, controllable heat, avoiding the temperature gradients associated with power resistors or radiant elements. They can also be constructed so that only the areas of interest are heated by varying the pattern of the resistive element within the heater.

Figure 6 shows the components of the heating system. Four sheet heaters (each 250 x 250 mm) were bonded to aluminum plates (good heat conductors) and were then shaped to cover both the test plate and the surrounding pavement surface. Two aluminum heat-transfer pieces were also manufactured for each plate size to fill the gap between the test plate and surrounding pavement and therefore eliminate the presence of air as a nonconductive material. Each sheet heater is equipped with a thermocouple mounted beneath the aluminum plate to measure the temperature on the pavement surface. These thermocouples are required for controlling the heater's temperature. Finally, the heaters were insulated using fibreglass altered to fit the shape of the aluminum plates and covered with aluminum foil.

A macro was developed in Microsoft Excel to control the heaters by turning them on and off periodically until a specified set-point is reached, as measured by a thermocouple located under the vane. Figure 7 demonstrates the temperature variation versus time at the surface and at 20mm depth. For the tests on the plates epoxied to the pavement, it was not possible to directly measure the temperature of the pavement (at a specific depth) so a formula was developed to estimate the pavement temperature, as will be described in Task 4.

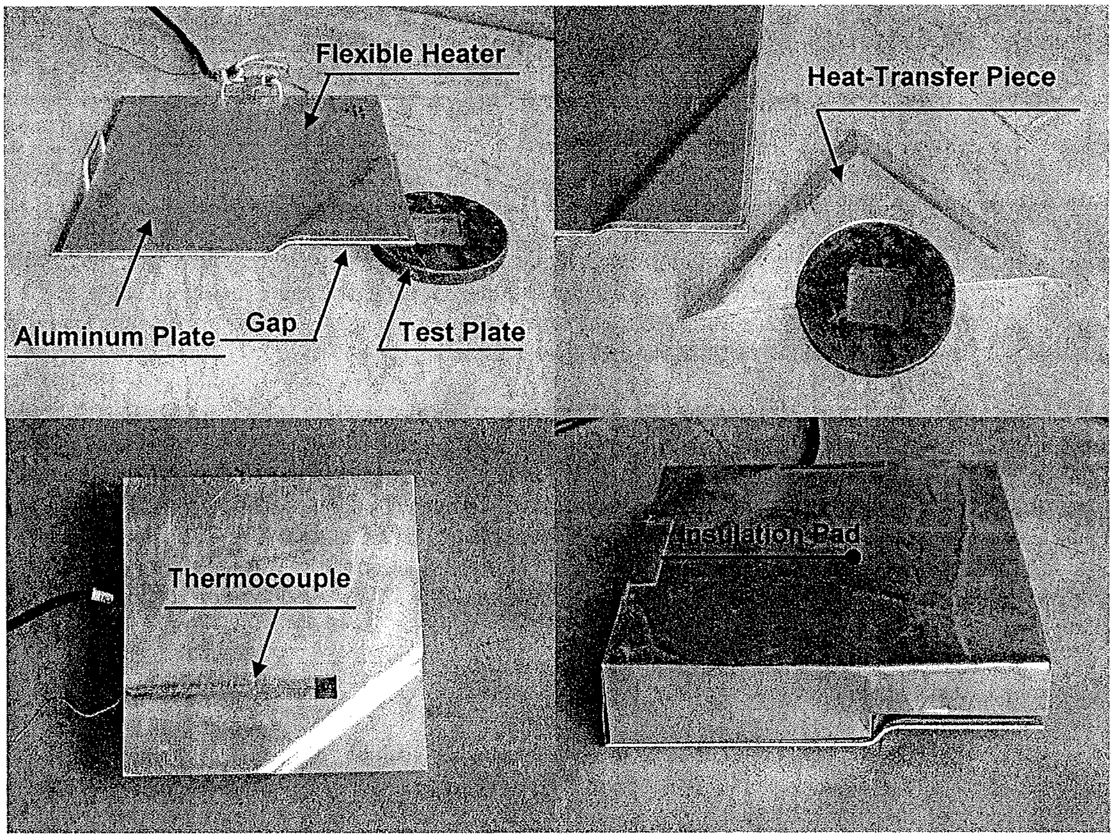


FIGURE 6 Heater Components

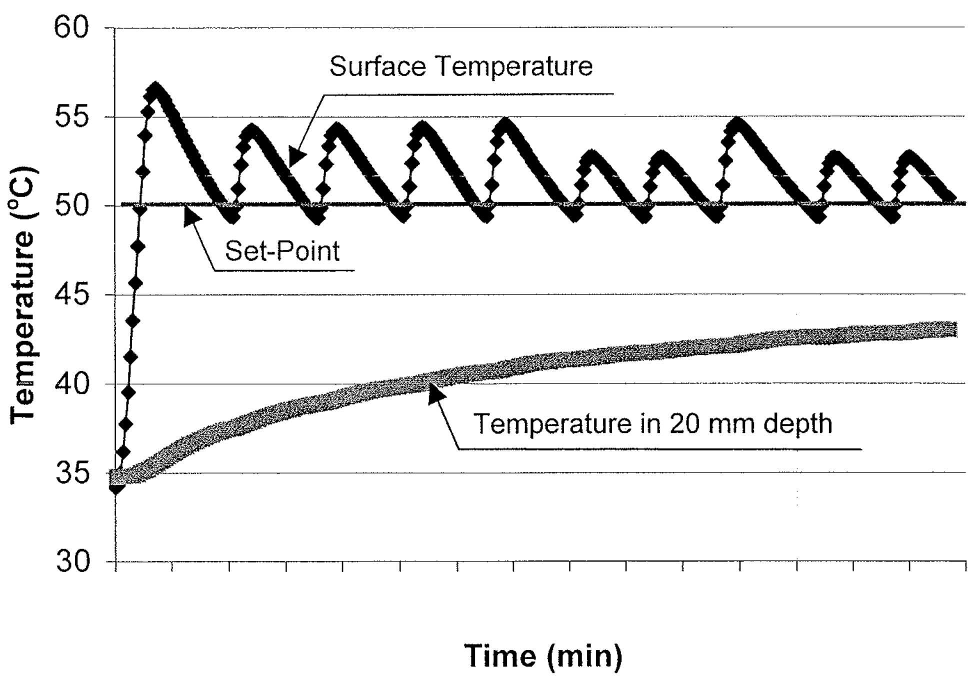


FIGURE 7 Temperature Variation versus Time (One Heater)

TASK 3: LABORATORY SHEAR AND UNIAXIAL COMPRESSION TESTING

Overview

The objectives of the laboratory testing were to verify the applicability of testing with the vane plates and to examine correlation between the shear properties of asphalt concrete mixes and their long-term performance. In this regard, two laboratory tests - pure torsion and repetitive uniaxial compression - were selected. Zahw (1995) measured the shear properties of asphalt mixes by applying torsion on cylindrical core samples. Further analysis on his results showed good correlation with the rutting susceptibility (Goodman 2000). This formed the basis for using the same laboratory device (torsion machine) in this research. The repetitive uniaxial compression (dynamic compression) test was also chosen because it can determine the susceptibility of a mix to permanent deformations related to shear flow as well as those associated with changes in the microstructure of asphalt concrete (Mohamed and Yue, 1994).

Tests were carried out on 150 x 100 mm cylindrical samples prepared in the laboratory by the National Research Council. The specimens were composed of two different asphalt concrete mixes. One mix type had coarser aggregate gradation and was expected to have higher shear strength and higher resistance to rutting. Accordingly, the two asphalt concrete mixes were classified as one weak (Type A) and the other strong (Type B). For each mix type, twelve samples were tested, nine samples using torsion machine and three samples using dynamic compression test machine. All tests were carried out at room temperature (25°C) so that the elastic properties of the material would be dominant.

Repetitive Uniaxial Compression Test

The repetitive uniaxial compression test was carried out to compare the resistance of the two mixes to permanent deformation under the vertical repeated load. In other words, this test was selected to classify the two available asphalt mixes with respect to their long-term performance. The cylindrical samples were placed between two horizontal plates and were loaded dynamically. A square wave loading function was selected based on the research work at Nottingham University (Brown and Brunton, 1984). The square wave consisted of a constant loading period of 0.2 sec followed by a rest period of 1.8 sec as shown in Figure 8. Maximum axial pressure of 690 kPa, representative of the tire pressure, was applied on the specimens. Therefore, the maximum load on the 150-mm samples was 1285 kg. During the rest period the load was reduced to a nominal 20 kg, almost 1.5 percent of the maximum value, to avoid separation of the loading head from the sample surface. The loading rate was also selected to be 0.5 Hz.

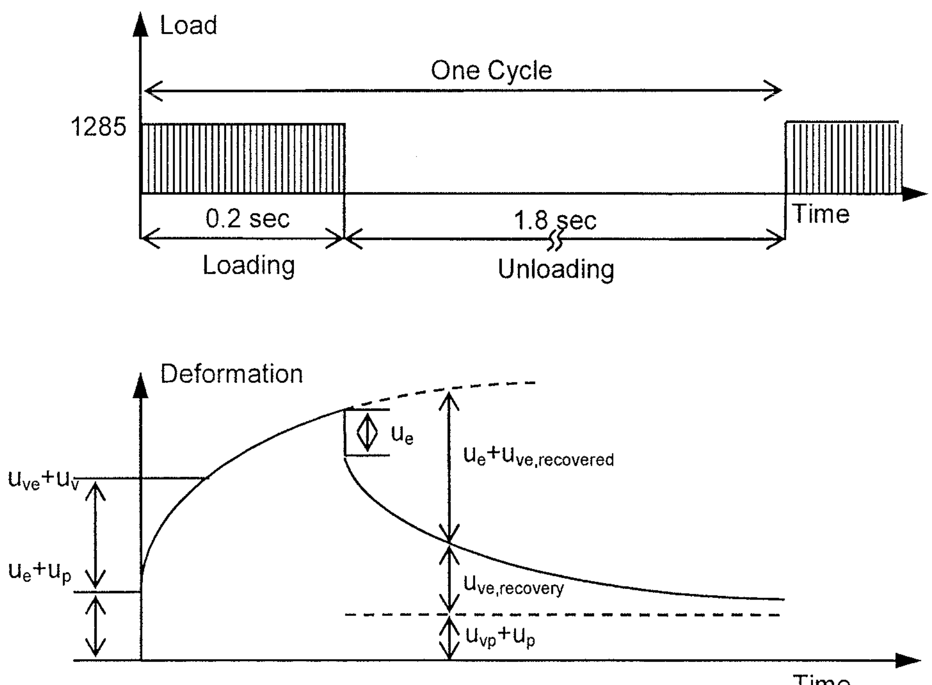
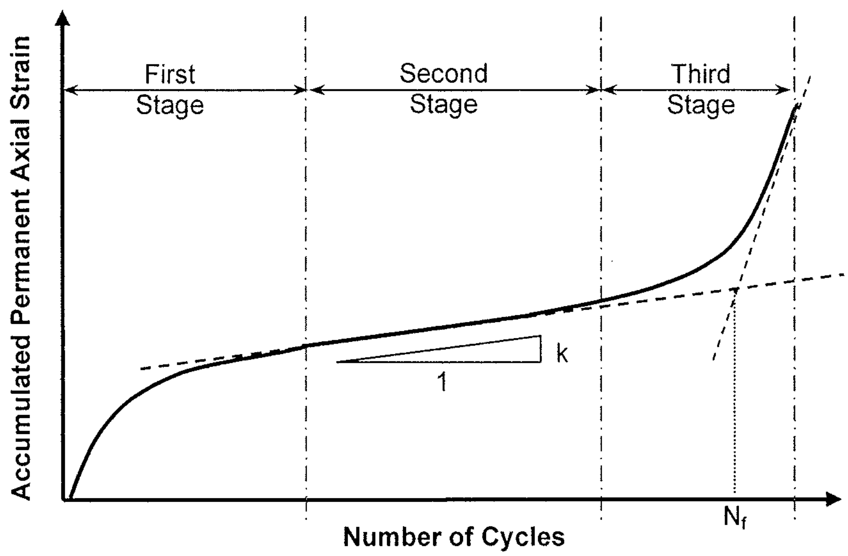


FIGURE 8 Deformation Components versus Time in One Loading Cycle

As stated by Lu and Wright (2000), the deformations in one cycle of the loading/unloading may consist of elastic, plastic, viscoelastic and viscoplastic components (Figure 8). These deformations can be decoupled according to whether they are time dependent and whether they are recoverable during the recovery period. The displacement reading in the end of each cycle (i.e. the total of plastic, viscoplastic and unrecovered viscoelastic deformations), was considered as the permanent deformation. The accumulated permanent strain was then plotted versus the corresponding number of load cycles. Plots of the permanent axial strain accumulated under cyclic loading exhibit an identifiable trend as shown in Figure 9. Mohamed and Yue (1993, 1994) described that the accumulated permanent axial strain undergoes three distinct stages with increasing number of cycles. These stages are referred to as primary, secondary and tertiary.



N_f = fatigue failure (number of cycles at which the specimen failed

FIGURE 9 Typical Relationship between Permanent Axial Strain and Number of Cycles

The primary stage includes an initial relatively large deformation due to surface irregularities and densification followed by a rapid decrease in the rate of deformation due to strain-hardening. During the secondary stage, the rate of accumulation of permanent deformation remains constant because the surface is already flattened and the strain-hardening is balanced by the recovery process. The permanent deformation during this stage is mainly caused by the shear flow. Finally, in the tertiary stage, the rate of deformation accelerates until complete failure takes place. This stage is usually associated with the formation of cracks, suggesting that fatigue could be the primary cause of failure.

Mohamed and Yue (1994) showed that the rate of deformation during the secondary stage is essentially a constant (k). Their results from testing two different mixes under different stress and temperature conditions clarified that this constant can be used to evaluate the rutting potential of different asphalt mixes. Consequently, the two asphalt mixes (used in this study) were compared according to the k values obtained from the uniaxial compression tests and were categorized with respect to their rutting resistance.

Torsion / Shear Test

One of the objectives of the torsion / shear test was to verify the applicability of the vane plates while the other objective was to examine the correlation between the shear properties of the mix and its long-term performance as measured from the dynamic compression test. Consequently, some of the cylindrical samples were tested following the conventional method and the rest were tested using the new vane plates. The results obtained from each method of testing were compared to investigate if the shear properties of the asphalt mix measured with the new method of testing was reliable. In this regard, the shear stiffness of each asphalt mix was determined using three sets of tests as is listed below:

i) Three specimens were tested with the circular disks glued on both sides (reference value).

ii) Three specimens were tested with one side glued to the disk and the other side connected to the cross-vane.

iii) Three specimens were tested with one side glued to the disk and the other side connected to the single-vane.

The apparatus used in the study was a Tinius Olsen torsion machine. During testing, a constant strain rate equal to three degrees per second was applied on the specimen and the torque value and angle of rotation are displayed on the dial gauge and the scale respectively. To obtain the initial shear stiffness of the mixes, the torque dial gauge was video taped. After downloading the data to a computer and recording the correspondent torque and time values manually, the torque-time as well as the torque-displacement curves were plotted. Assuming that the asphalt mix behaves elastically at lower temperatures and during the early stages of the test, the shear modulus can be calculated using Equation 1.

$$G = \frac{TL}{J\theta} \qquad \text{Equation 1}$$

where, T is the torque value, θ is the corresponding angle of twist and J is polar moment of inertia that for a circular section with diameter D, can be calculated using Equation 2.

$$J = \frac{\pi D^4}{32} \qquad \text{Equation 2}$$

These equations are valid for a cylinder with a total length of L. However, when using the vane plates the value of L is not clearly defined. Therefore, the decision was made to calculate the slope of the initial linear portion of the torque-displacement curve (called Shear Index) and consider it as a representative of shear stiffness of the asphalt mix when comparing different methods of testing.

TASK 4: FIELD SHEAR TESTING AT CARLETON UNIVERSITY AND NATIONAL RESEARCH COUNCIL

Overview

Field-testing was carried out to verify the proposed modifications, validate the laboratory results and investigate the effect of different variables on the measured shear properties. The testing program was undertaken in two different places namely Carleton campus and the National Research Council (NRC) of Canada. The first field-testing stage covered the study of the heaters' functionality as well as the asphalt concrete response to the heating process. In the second stage, the performance of the RDT was verified and the effect of plate size and temperature on the shear properties of asphalt mixes was investigated. During the third stage, the in-situ performance of the vane plates and the repeatability of the tests were assessed. Finally, in the last stage, the results obtained from InSiSST^{TM} testing were validated.

Test Sites

Carleton Campus

Two different asphalt concrete pavement sections were tested on Carleton University campus. The first section, Carleton–1, is a paved area used as an entrance to the Civil and Environmental Engineering Laboratory at Carleton University. The asphalt concrete mix is a standard Ontario HL3 85/100 mix, with an average in-situ compacted density of 2.30 g/cm3. Carleton–1 section has been in service since 1992 and the pavement surface has almost no visible surface distresses. It is not subjected to regular traffic, but is used to access the laboratory, for temporary parking and as a temporary storage area for different materials and equipment.

The second pavement section on campus, Carleton–2, is a test section that was constructed specifically for the testing and validation of the InSiSST^{TM} facility. This section is 3 m wide by 10 m long and was constructed using a standard Ontario HL3 85/100 mix, where the asphalt concrete layer thickness is 100 mm. The section was constructed in 2001 and was poorly compacted, with an average in-situ density of 2.06 g/cm3, to provide a relatively weak asphalt concrete mixture when compared to the Carleton-1 section (higher density and stiffer due to age).

National Research Council (NRC)

Four Sections were also tested at the National Research Council experimental road in Ottawa. The first two selected sections, NRC–1 and NRC–2, were constructed using a conventional HL4 mix designed according to the Ministry of Transportation of Ontario (MTO) specifications. The only difference between these two sections is that the NRC-1 section has 3% Sludge-Derived-Oil (SDO) as an anti-stripping additive. The regular HL4 mix and the SDO-modified mixes were laid and compacted side-by-side for a total road length of 25 metres following conventional construction procedures. The constructed layer was laid in one lift and the average compacted depth is 65 mm. Sections NRC-3 and NRC-4 were constructed using a standard Ontario HL3 85/100 mix. Section NRC-3 was compacted with the Asphalt Multi-Integrated Roller (AMIR) designed by Abd El Halim (1990) as a fundamentally new approach to asphalt compaction, while section NRC-4 was compacted using conventional steel roller. It should be noted that the first two sections were constructed in 1993 while the other two sections were constructed in 1990. All the sections are subjected to light traffic, i.e. the local traffic in the National Research Council area, with minimal truck traffic.

Testing Program

Stage 1: Heaters and Pavement Temperature

The heaters were designed to facilitate heating the testing area up to any required temperature. In the beginning, it was essential to understand the response of asphalt mix to the applied heat. A test plate was located on the pavement, and then both the heaters and the heat-transfer pieces were installed in place. To assess the heat transfer rate at different depths, five different holes were drilled to 10, 15, 20, 25, and 30 mm were provided. A thermocouple was placed in each hole, and the opening was filled with silica sand to create good temperature conductivity. The heaters were then turned on and controlled using the developed macro in Microsoft Excel. A number of tests were completed on the Carleton-1 and Carleton-2 sites with various set-points and time periods, such as 15, 30, 45 and 60 min. A regression model (R^2=0.937) was developed to relate the required temperature to the chosen variables (Equation 3).

$$\begin{aligned}\text{Depth Temperature} = {} & 14.68 + 0.083*\text{Set Point} + 0.345*\text{Surface Temperature} \\ & + 1.004*\text{Depth} + 0.158*\text{time} - 2.337*\text{Asphalt} \qquad \text{Equation 3}\end{aligned}$$

Where all temperatures are in degrees Celsius, time is in minutes, Depth is in centimetres and Asphalt was equal to 0 for Carleton-1 (correct mix density and aged mix) and equal to 1 for Carleton-2 (low density and newer mix). The results tend to indicate that heat transfer is depended upon the mix properties (density and perhaps age) such that the Asphalt coefficient would not be accurately known for all mixes observed in the field without additional testing. However, the equation is simply a tool for estimating the time (or set point) required to achieve even temperature within the testing zone. Even if the Asphalt coefficient is set to one for all mixes, the equation will slightly overestimate the time required to achieve the desired temperature -- a conservative approach to ensure even temperature distribution.

Stage 2: RDT and the Effect of Different Variables

In this stage of the study, a number of tests were carried out to verify the angular displacement measurements using the RDT. In addition, the effect of plate size and temperature on the measured shear properties was studied. Three test plate sizes (100, 125, and 150 mm) were selected for testing. In total, 23 tests were completed that included five tests using 100-mm plates and nine tests for each of the other two plate sizes. Some of the tests were implemented at the prevailing temperature, while for the rest of the tests the temperature of pavement was controlled using the heaters. Desired temperatures between 40°C to 50°C were selected with regard to the existing pavement temperature. As the vane plates were not manufactured at the time of testing, the surface plate method was used to attach the test plates to the pavement and the Reissner–Sagoci equations were used to calculate the shear strength and modulus of the asphalt concrete mix.

Stage 3: Vane Plate and Repeatability

Once the vane plates were manufactured, they were tested with the InSiSST™ facility to verify their applicability in the field. The 125-mm plate was selected for the tests because, at this stage of the study, the cutting tool was only capable of

providing grooves appropriate for this plate size. Sections Carleton–1 and Carleton–2 were used for testing. Twelve tests were completed using cross-vane plates, five on section Carleton–1 and seven on Carleton–2. Only one test was carried out using the single-vane plates because of time constraints.

Stage 4: Validating the InSiSST™ Test Results

The last stage of the testing program was scheduled to validate the results obtained from the InSiSST™ facility using the vane plates. As mentioned earlier, the shear modulus of the tested pavement was calculated for the case where the angular displacement was applied to a steel plate bonded to the surface of the pavement. Reissner and Sagoci (1944) showed that the application of such forced displacement to the surface of a half space would result in pure shear stresses. However, when the displacement is applied through the embedded vanes, other stresses would be also distributed in the material. Therefore, the Reissner and Sagoci equation cannot be used to calculate the shear modulus of the asphalt concrete mix. Since there is no closed form solution to address the relationship between the shear modulus of the material and the buried laterally applied load (similar to the case of the vane plates), it was decided to correlate the new InSiSST™ results to the shear modulus obtained from applying pure torsion on cylindrical samples. The following three methods of testing were selected:

i) A cross-cut was provided on the asphalt pavement surface using the cutting tool and the cross-vane plate was inserted into the grooves. The torque was applied on the plate using the InSiSST™ facility and the torque-displacement relationship was obtained.

ii) The asphalt concrete layer was partially cored to a specific height that was less than the total thickness of the layer. Then the test plates were glued to the surface of the pavement. The torque was applied to the surface of the asphalt concrete while the tested sample was a cylinder, rather than a half space (Figure 10a).

iii) A cross-cut was provided on the pavement surface and the asphalt concrete layer was also partially cored. The vane plate was then placed in the grooves of the cylindrical sample, whose end was fixed to the pavement (Figure 10b).

The tests were completed at NRC experimental road sections i.e., NRC–1 to NRC–4 and for each testing method, six tests were carried out per section, two close to the edge, two on the middle of the lane and two close to the centreline of the road. Therefore, the total number of tests on each section was eighteen and considering the four selected sections, the total of 72 tests were completed. Since the available blade size for the coring machine was 100 mm (4"), the same size vane plate was chosen for testing and the study was limited to the cross-vane plates. The pavement was heated up to 45°C prior to testing and all the tests were performed with the maximum loading rate or motor speed.

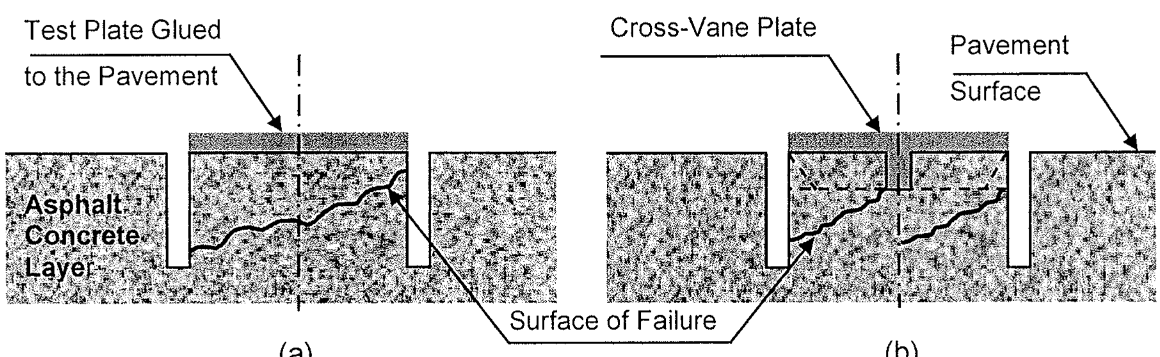


FIGURE 10(a) Partial Coring and Epoxy, (b) Partial Coring and Cross-Cut

TASK 5: ANALYSIS OF TEST RESULTS

Overview

The test results were first analyzed to study the effect of different variables, namely temperature and plate size, on the strain rate and the measured shear properties of the mix. Since the tests were also carried out on the plates glued to the pavement surface, the Reisner-Sagoci equations were used to calculate the shear modulus and shear strength of the asphalt mix. Considering that the Reissner–Sagoci equations were derived for an elastic material, the initial shear modulus was calculated because in the early stages of the test the torque values are smaller and therefore the asphalt mix behaves more elastically. The summary of the test results and the shear properties are reflected in Table 1.

Table 1 Shear Properties and Temperature Values (Section Carleton–1)

Diameter (mm)	**Temperature** (°C)	**Max Torque** (N.m)	**Max Displacement** (Radians)	**Shear Strength** (MPa)	**Initial Shear Modulus** (Mpa)
100	33	579.2	0.02276	1.57	49.34
100	33	710.4	0.02684	1.81	48.94
100	33	751.8	0.02346	1.98	61.53
100	37	461.3	0.01990	1.32	43.97
100	55	173.2	0.02553	0.46	17.58
125	33	1053.2	0.02880	1.39	56.61
125	35	1089.4	0.01834	1.51	107.03
125	37	831.7	0.02063	1.12	90.24
125	37	1026.8	0.02442	1.42	86.58
125	39	653.8	—	0.93	—
125	45	611.5	0.02409	0.88	56.52
125	47	515.6	0.02382	0.79	23.19
125	50	382.9	0.02416	0.52	36.17
125	53	389.6	0.01850	0.52	48.18
150	36	1100.5	0.01626	0.95	102.69
150	37	1012.0	0.02388	0.83	65.06
150	42	1101.2	—	0.90	—
150	44	732.2	0.02438	0.65	59.08
150	47	771.5	0.02927	0.62	45.87
150	48	735.8	0.02409	0.62	63.04
150	48	689.2	0.01827	0.60	75.63
150	51	587.6	—	0.43	—
150	51	685.8	—	0.55	—

As shown, the maximum angle of rotation (and therefore the shear moduli) are missing for some of the tests. This was due to temporary problems associated with the wiring system of the InSiSST™ facility that resulted in losing the angular displacement readings from the RDT in a few cases. However, the torque values measured by the torque cell were available for those tests and the shear strength of the material was calculated and used in the analysis.

Strain Rate

The study by Bekheet (2002) revealed that the actual strain rate obtained from the InSiSST™ testing is significantly different from the assumed constant strain rate; therefore, the RDT was added to the facility to address this issue. The actual angular displacement rate measured using the RDT confirmed this statement, however, the results of the tests carried out on section Carleton–1 clarified that the actual rotary displacement at failure is significantly less than the angle of rotation at failure calculated based on the constant rate of variation assumption, especially for larger plates.

Bekheet (2002) also concluded that the larger the plate used during testing the smaller the actual angular displacement at failure. However, the results of the tests obtained from the RDT showed that there is no significant difference between the angles of twist at failure when using different test plate sizes. Figure 11 demonstrates the variation of the strain rate with plate size at a constant pavement temperature of 37°C. As shown, the failure rotation angles are 0.0199, 0.0213 and 0.0239 radians for 100–, 125– and 150–mm plates respectively.

The results of the tests with the vane plates were also analyzed with respect to the strain rate. Figures 12 and 13 show the rotary displacement variation versus time for the tests on sections Carleton–1 and Carleton–2, as representatives of typical and weaker asphalt mixes with regard to compaction and age, respectively. The displacement–time curves in these figures indicate that the strain rate is non-linear for both asphalt mixes up to the point of failure, as presented by dashed lines. However, the deviation from linearity is higher for the typical mix compared to the weaker mix, taking into consideration that the pavement temperature is even higher for the former asphalt mix.

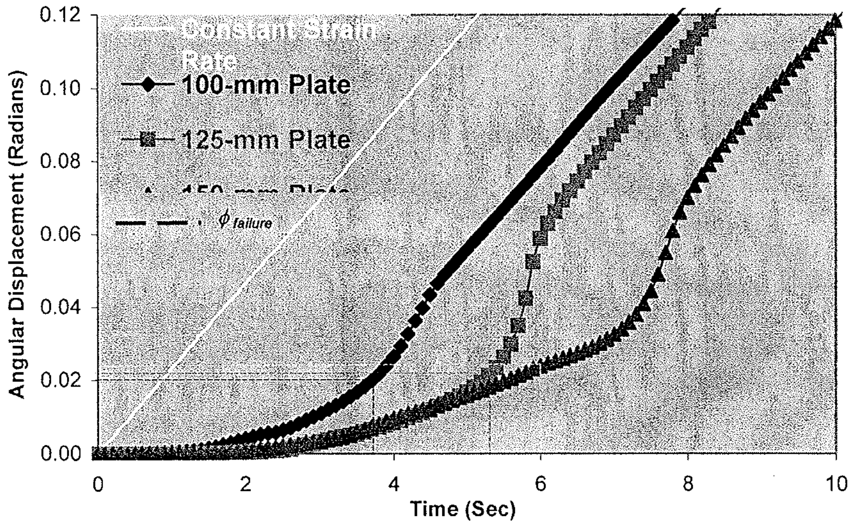


FIGURE 11 Variation of Strain Rate with Plate Size (at 37°C)

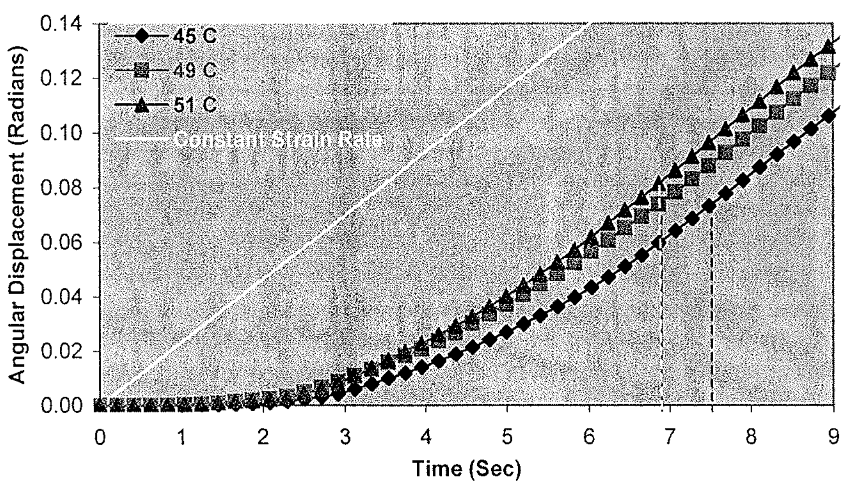


FIGURE 12 Angular Displacement Variation with Time for Carleton-1 Mix

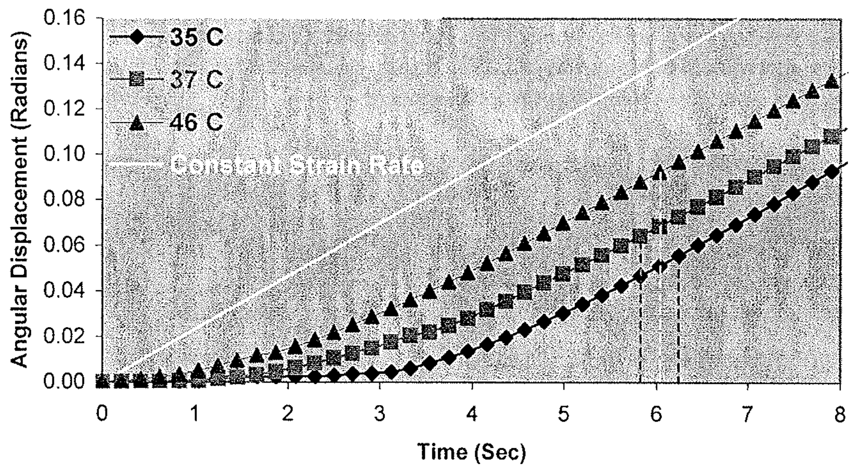


FIGURE 13 Angular Displacement Variation with Time for Carleton-2 Mix

Temperature

The effect of pavement temperature on the measured in–situ shear modulus of asphalt mixes was investigated previously. Bekheet (2002) correlated the shear modulus (G) of asphalt mix to the temperature (T) using an exponential model with a general form of Equation 4, where A and B are constants. The variation of the shear properties of asphalt concrete mixes with temperature are further analysed in this study using the results obtained from the RDT.

$$G=Ae^{-BT} \qquad \text{Equation 4}$$

The results of the tests completed on section Carleton–1 (Table 1) were analyzed following the same general model. Both the shear moduli and the shear strength values were correlated to the asphalt pavement temperature at the time of testing. The results related to each plate size were analyzed separately and are reflected in Figures 14 and 15. The graphs show that as the temperature decreases the maximum shear stress and the shear modulus increase.

As shown, the coefficients of determination (R^2) for all the cases were high, ranging from 0.772 to 0.979. However, it should be mentioned that obtaining high R^2 values can be due to the fact that the sample size was not large enough for robust modelling. As a result, the model is presented only to introduce the general trend. A large–scale experimental program is required to develop temperature master curves for the in–situ shear stiffness of asphalt concrete mixes, however, establishing such an experimental program is beyond the scope of this investigation.

Plate Size

The variation of in–situ shear properties of asphalt mix with temperature was studied for the tests with different plate sizes separately. These results, as shown in Figures 14 and 15, were then compared to account for the effect of the plate size on the measured shear strength and shear modulus. First, The Analysis of Variance (ANOVA) was carried out to examine the effect of plate size on the measured shear strength of asphalt mix. The null hypothesis was that there is no difference between the mean values of the shear strength (maximum shear stress) for different plate sizes. The results showed that there was a statistically significant difference, at the 95% confidence level, between the mean shear stresses obtained from the tests using different test plate sizes and that for a particular mix, the larger the plate size, the lower the shear strength. This result is expected since the effect of the aggregate size would be more influential when the plate size is smaller. Clearly, more shear stress would be required to fail one aggregate than failing the bond between two aggregates. Furthermore, the results shown in the same figure indicate that the difference between stress values obtained from different test plate sizes increases as the pavement temperature decreases.

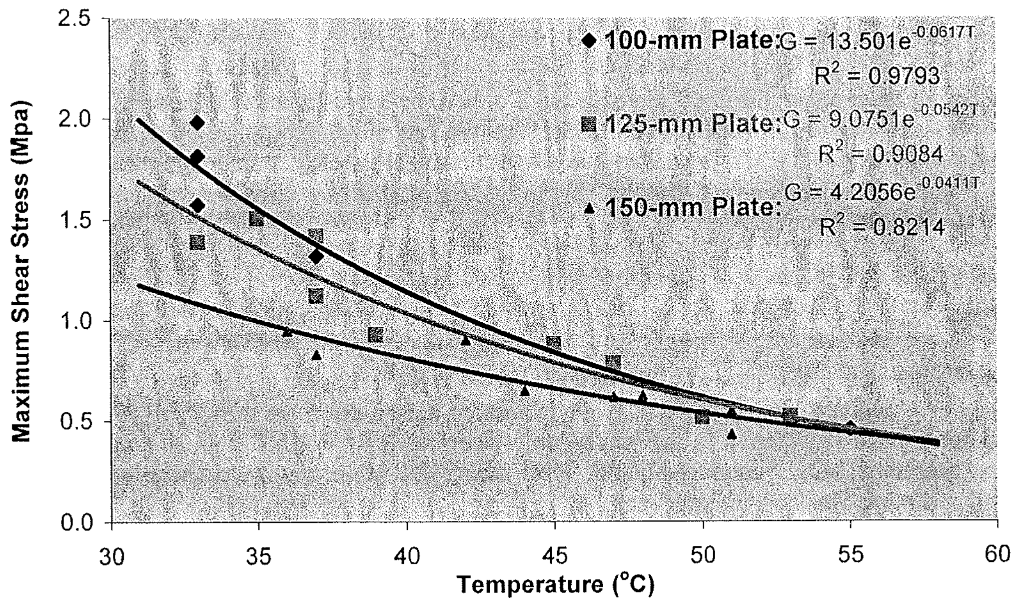


FIGURE 14 Maximum Shear Stress Variation with Temperature for Different Plate Sizes

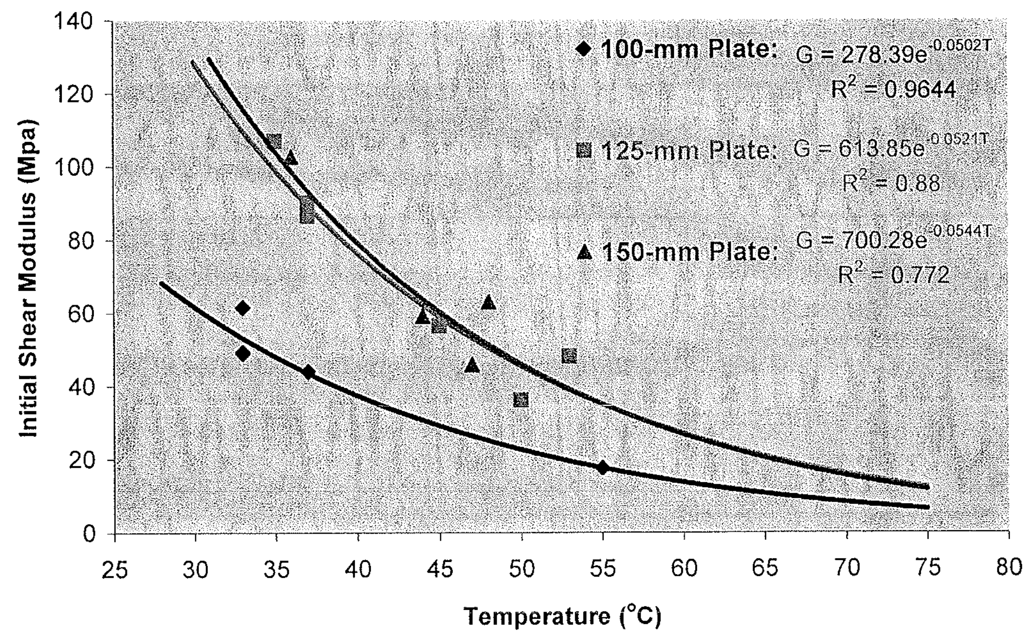


FIGURE 15 Initial Shear Modulus Variation with Temperature for Different Plate Sizes

Interestingly, at higher temperatures (i.e. higher than 50°C), the in–situ shear strength of the mix appeared to be independent of plate size which supports the explanation given regarding the effect of plate size on measured shear property under normal temperature conditions. Clearly, when the mix is subject to higher temperatures the viscosity of the asphalt cement is greatly reduced and thus the effect of the plate size appears to have no significant influence.

The second shear property, whose variation with temperature and plate size was studied, is the initial shear modulus. Bekheet (2002) investigated the effect of test plate size on the measured shear moduli that were calculated using the angular displacement values obtained from the constant strain rate assumption. However, the discussion on the actual strain rate, presented earlier, showed that the measured shear modulus will be different if the actual displacement values are used in the calculations. Figure 15 displays the variation on initial shear modulus with temperature and test plate size.

The graphs show that in contrary to the shear strength, the shear modulus increased as the test plate diameter increased when testing in lower temperatures.

Similar to the maximum shear stress, the shear modulus tends to become constant under higher temperatures. Interestingly, the curves related to 125– and 150–mm plate sizes indicate that the test plate diameter might not have any effect on the measured shear modulus if it is greater than a certain value. However, it should be noted again that the trend lines presented in Figure 15 are based on the database that is not large enough for modelling; therefore, an extended field testing is required to clarify this conclusion.

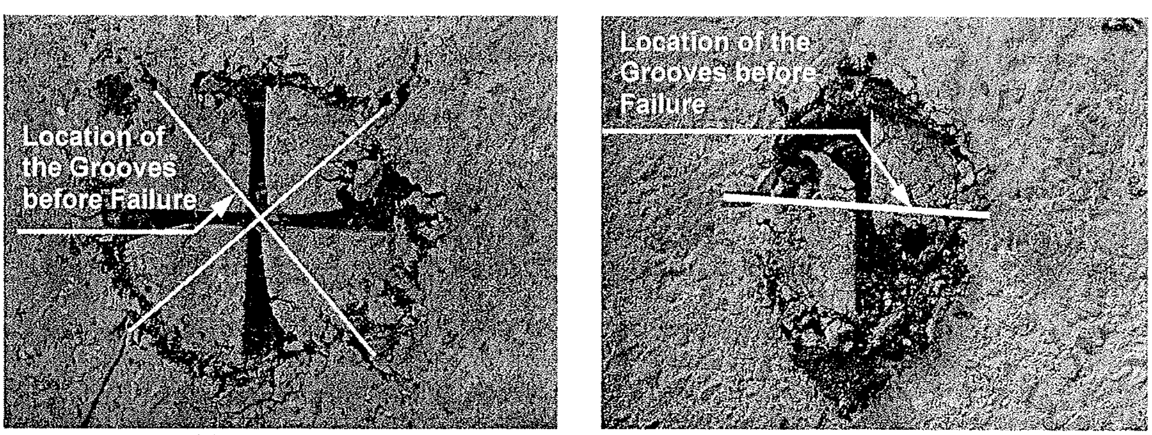
Vane Plates

The applicability of using vane plates instead of flat plates epoxied to the pavement surface was examined both in the laboratory followed by in-situ testing . The results of the laboratory testing effort are shown in Table 2. The initial slope of the torque-displacement curve, referred to as Shear Index, was calculated for all tests and it was observed that the mix with a more coarse gradation (Mix B) displayed higher Shear Index. As shown, the mean Shear Index for the vane plate tests are very similar to those obtained with the epoxy.

The vane plates were then tested in-situ at the Carleton-2 site. The resulting Shear Index values were again observed to be similar to the epoxied plates. As such, either of the vane plate types (single vane or cross) may be used to determine Shear Index. Figure 16 displays the failure mechanisms resulting from the cross and single vane plates.

Table 2 Summary of the Torsion Test Results

Test Method	Sample No.	Density (g/cm^3)	Slope (Nm)	Average Shear Index (Nm)	Sample No.	Density (g/cm^3)	Slope (Nm)	Average Shear Index (Nm)
One side single- vane	A1-1	2.487	0.40		B1-1	2.251	0.61	
	A1-2	2.485	0.44		B1-2	2.258	0.44	
	A1-3	2.477	0.51	0.45	B1-3	2.262	0.70	0.58
One side cross-vane	A2-1	2.518	0.49		B2-1	2.254	0.58	
	A2-2	2.498	0.40		B2-2	2.303	0.50	
	A2-3	2.483	0.57	0.49	B2-3	2.182	0.63	0.57
Two sides epoxied	A3-1	2.515	—		B3-1	2.248	0.52	
	A3-2	2.459	—		B3-2	2.293	0.56	
	A3-3	2.494	0.57	0.57	B3-3	2.135	0.50	0.53



(a) (b)

FIGURE 16 Failure View of the Tests with (a) Cross–Vane and (b) Single–Vane Plates

Shear Property Measurements

Shear Strength

The InSiSST™ testing with the cross–vane plate resulted in a failed section that is a quartet and each portion represents one quarter of a frustum of a cone. The failure surface obtained from testing on the epoxied plates was also assumed to be a frustum of a cone, however, the dimensions of the frustum were somewhat dependent on the judgement of the operator. As such, the calculations based on these dimensions would result in the values that were less accurate. Conversely, when testing with the vane plate the geometry of the failure surface is clearly defined as it is the same as the vane dimensions and this will lead to more accurate results.

The shear strength or shear resistance of asphalt pavement was calculated at the time of failure from the maximum torque. Although the stresses distributed in the pavement under the load would not be pure shear stresses (as was the case for tests on epoxied plates), the stresses on the failure surface are pure shear. Figure 17 demonstrates the shear stress distribution on the failure surface.

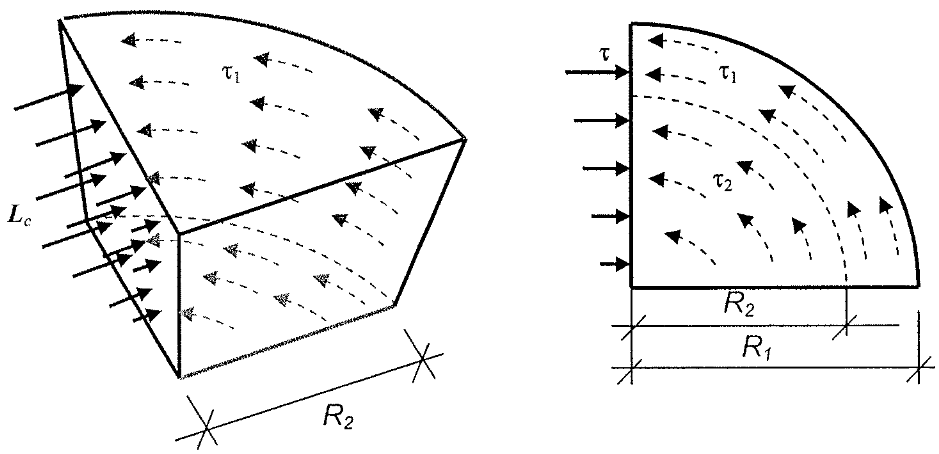


FIGURE 17 Stress Distribution on the Failed Section in Case of the Vane Plate

At the early stages of loading and at lower temperatures the asphalt mix would behave elastically therefore, the maximum stress at each moment can be calculated assuming that the stress is uniformly distributed on the side and that the relation given by Equation 5 is valid for the stresses on the bottom surface. The average shear stress would then be calculated using Equation 6.

$$\tau_{(r)} = \tau_1 \left(\frac{r}{R_2}\right) \qquad \text{Equation 5}$$

$$\tau = \frac{T}{\pi\left(\frac{1}{2}R_2^{\,3} + \frac{2}{3}h\frac{R_1^{\,3} - R_2^{\,3}}{R_1 - R_2}\right)} \qquad \text{Equation 6}$$

where T is torque, τ is shear stress.

At higher temperatures and at the time of failure the asphalt mix would behave non–elastic; therefore, assuming that the failure is fully plastic the shear strength can be calculated using Equation 7.

$$\tau = \frac{3T}{2\pi(R_2^3 + h\frac{R_1^3 - R_2^3}{R_1 - R_2})}$$ Equation 7

For the tests on sections Carleton–1 and Carleton–2 the shear strength was calculated using 7 and the results are reflected in Table 3. Comparing the results of section Carleton–1 to those obtained earlier when using epoxy, as presented in Table 2, one can conclude that the shear strength values are similar. The variation of shear strength with temperature for the tests on section Carleton–2 is shown in Figure 18. The same general model as presented earlier was fitted to the data and a high coefficient of determination was obtained indicating that a good correlation exists between the shear strength and temperature. Moreover, this analysis shows that the same trend as was observed for the tests with the epoxy is observed for the tests with the vane plate.

Table 3 Shear Properties of the Asphalt Mix on Sections Carleton–1 and 2

Section	Test No.	Temperature (°C)	Shear Stress (Mpa)
Carleton-1	1	45	0.95
	2	51	0.96
	3	49	0.85
Carleton–2	1	33	0.36
	2	31	0.39
	3	37	0.31
	4	36	0.28
	5	35	0.32
	6	35	0.34
	7	46	0.17

The results of the tests at NRC were also analyzed with respect to the shear strength of the material. The shear strength values were calculated according to the fully plastic assumption (as before) and the results are reflected in Figure 19. The figure depicts that the results obtained from the InSiSST™ testing with the vane plate were able to differentiate between the pavements constructed with different asphalt mixes and compacted with different compaction methods.

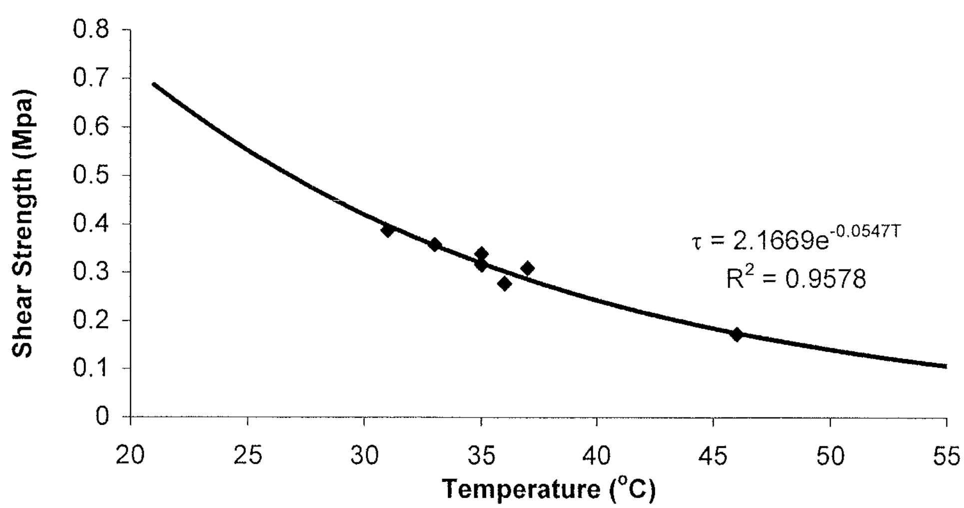


FIGURE 18 Shear Strength Variation with Temperature (Section Carleton–2)

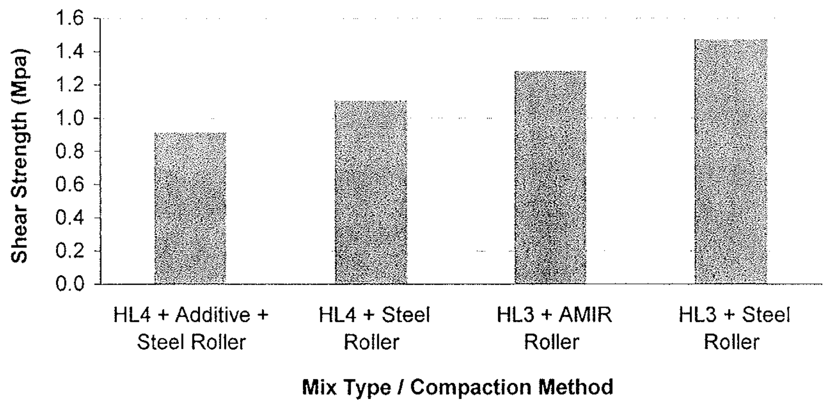


FIGURE 19 The Effect of Asphalt Mix Type or Compaction Method on the Shear Strength

Shear Modulus

The tests were carried out on the experimental road at NRC with two different methods of testing. The first method included the tests on the pavement surface with the vane plate (called Surface–Vane tests) while for the second method the pavement was partially cored and the test plate was bonded to the surface (called Cored–Epoxy tests). Since there was a problem associated with the torsion tests in the laboratory, a third set of tests was added to the schedule to verify the result obtained from the laboratory tests. In the third method, the pavement was partially cored however, the vane plate was used instead of the epoxy and therefore, the tests with this method were called Cored–Vane tests. For both of the partially cored methods, Equation 1 was used to calculate the shear modulus and the total length of the core was taken as the length the cylindrical sample. The results of the tests obtained from the three methods are tabulated in Table 4.

ANOVA was carried out for each test method to investigate if the mix type and compaction method affect the shear modulus / Index values. The results showed that there was a statistically significant difference at the 95% confidence level, between the mean shear moduli obtained from the tests on different sections. It was again verified that the InSiSST™ facility was able to differentiate between the pavements constructed with different asphalt mix and compaction methods, whether it was used with the vane plate or the epoxy.

Table 4 Shear Modulus / Index for the Tests at NRC

	Shear Modulus (Mpa)				Shear Index (Nm)	
	Cored–Epoxy		Cored–Vane		Surface–Vane	
Section	**Mean**	**COV**	**Mean**	**COV**	**Mean**	**COV**
NRC–1	8.10	0.26	7.00	0.33	4886.45	0.12
NRC–2	13.61	0.26	11.79	0.29	7840.90	0.15
NRC–3	17.52	0.26	10.71	0.32	9311.87	0.24
NRC–4	24.52	0.19	12.50	0.29	10934.49	0.14

The main objective of the testing program at NRC was to correlate the shear index obtained from the surface–vane tests to the shear modulus of the material that is a fundamental shear property. In this regard, a regression model was developed as shown in Figure 20 where the scatter plot showing the relationship between the surface–vane shear index values and the cored–epoxy shear modulus values is presented. A coefficient of determination (0.688) was obtained and the coefficients were statistically significant at the 95% confidence level. Although the relationship was somewhat weaker than anticipated, it is surmised that the high variability of the laboratory test results is at least partially responsible.

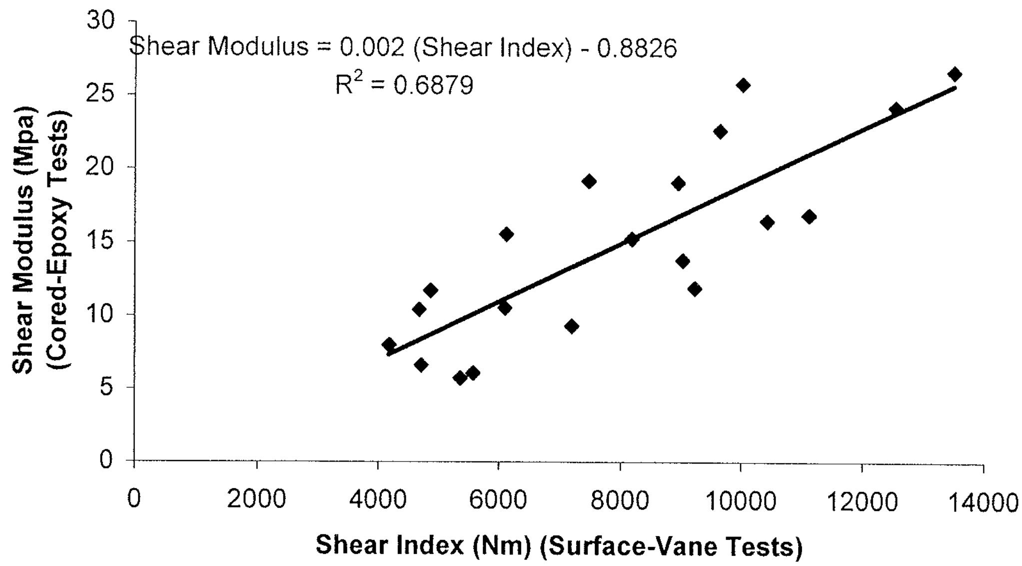


FIGURE 20 Relationship between the Shear Index (Surface–Vane tests) and Shear Modulus (Cored–Epoxy tests)

Shear Properties and the Long-Term Performance

The summary of the results from the dynamic compression tests as well as the physical mix properties are tabulated in Table 5. The results were in conformance with the results of the torsion/shear tests in that the mix with coarser aggregate (asphalt mix type B) had higher resistance to permanent deformation. All the samples made of asphalt mix type B had lower k values meaning that for a particular load cycle mix B sample would deflect less than mix A. Moreover, the results indicated that the stronger mix failed at higher load cycles showing that it was also stronger with respect to resistance to fatigue. An example of the results for each mix type is presented in Figure 21, which shows that the weaker mix had higher k value and failed at a lower number of load cycles in comparison with the stronger mix with lower k value and higher number of load cycles at failure.

Table 5 Summary of the Uniaxial Compression Tests

Asphalt Type	Sample No.	Density g/cm^3	Air Voids %	Slope (k) (E-06)	Cycle No. N_f
A	A-1	2.46	0.73	24.18	108242
	A-2	2.51	0.44	19.57	121176
	A-3	2.45	1.10	26.70	97445
	Average	**2.47**		**23.48**	**108954**
B	B-1	2.30	2.95	12.79	167501
	B-2	2.30	2.96	8.65	328384
	B-3	2.31	2.96	7.35	352245
	Average	**2.30**		**9.60**	**282710**

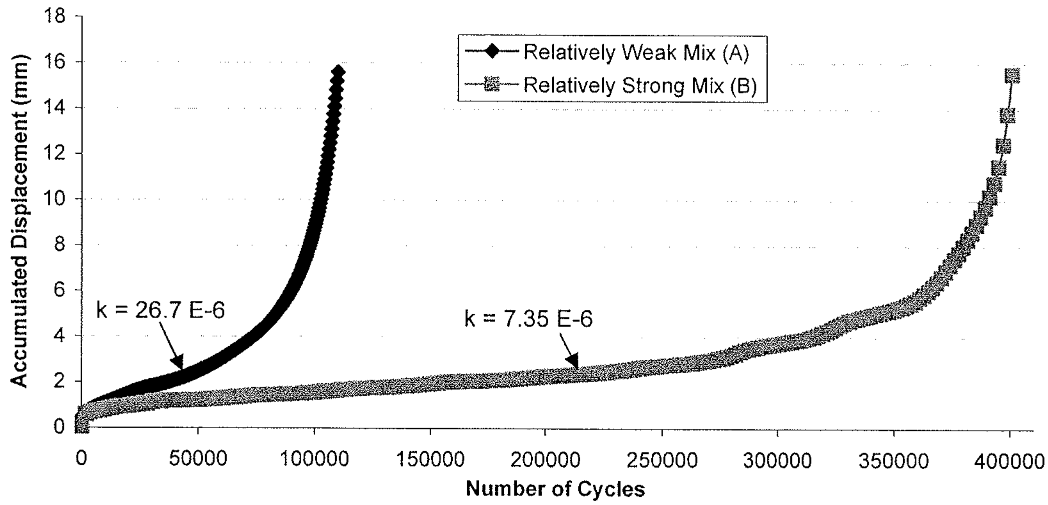


FIGURE 21 Comparison between Weak and Strong Mix according to Dynamic Compression Test

Test Repeatability

With reference to Table 3 (Carleton test site results) and Table 4 (NRC test site results), the coefficient of variability (COV) between replicate tests for the surface vane test ranges between 10 to 15% - considered reasonable given the relative heterogeneity of asphalt pavement. The only exception was NRC-3, where the COV observed was 24%. This test section was compacted with the AMIR roller, although consistent density was not achieved due to a temporary breakdown of the prototype AMIR. Furthermore, the COV for in-situ test results was considerably lower than the laboratory test results supporting the findings of Goodman (2000) who indicated that the specimen preparation process (involving destructive coring in the field) damages the specimens to the point that variable results are observed.

PLANS FOR IMPLEMENTATION

The considerable enhancements completed to the InSiSST™ facility during this investigation have mitigated the operational concerns observed during NCHRP IDEA Project #55. As such, the InSiSST™ may now be considered a production-ready prototype, although further discussion with industry experts has suggested that dynamic testing capability would be desirable. Dynamic testing would allow the testing of fatigue related properties of the mix as well as ultimate strength and/or modulus. A strategic partnership between Carleton University, the Swiss EMPA agency and TRB may ….

Carleton University will also continue its efforts to find a suitable manufacturing company interested in final engineering development and manufacturing of the InSiSST™ for widespread availability to governments, pavement engineering companies and roadbuilding contractors.

CONCLUSIONS

As already stated, the amount of laboratory and field testing conducted under this investigation was considerably reduced from the anticipated level due to lack of cooperative funding from the Ontario Ministry of Transportation. As such, the findings provided below must be considered preliminary, although many provide additional support to findings obtained during IDEA Project #55.

The findings of the testing program can be summarized as follows:

Temperature Response of Asphalt Mix:

1) The heating system was capable of rapidly heating the pavement to a desired test temperature.

2) In general, with reference to a particular set–point and desired temperature, the higher the existing temperature, the shorter the required heating time.
3) The time required for heating was sensitive to the asphalt mix type. The heating period appears to decrease as the density and/or age of the asphalt mix increases.

Strain Rate:

4) The maximum rotation angle was not dependant on the plate size and pavement temperature. However, both the test plate size and the temperature influenced the time of testing. The larger the test plate diameter or the lower the asphalt concrete temperature, the longer it took to reach the failure point.
5) The strain rate was sensitive to the mix properties and the pavement temperature. For the higher pavement temperature or stronger asphalt mixes the deviation from linearity is greater.

Temperature:

6) The shear properties of asphalt concrete mixes were sensitive to the pavement temperature. The higher the pavement temperature, the lower the shear strength and shear modulus.
7) There was an exponential relationship between the in–situ shear properties of the asphalt mix and the pavement temperature.

Plate Size:

8) At higher temperatures the in–situ shear strength and modulus of the mix were independent of the test plate size – a promising finding considering that permanent deformation usually occurs at elevated temperature.
9) For the test plates with greater diameters, the initial shear modulus of the asphalt mix was not dependent on the plate size. No difference was seen in the measured shear modulus values obtained from testing with 125-mm and 150-mm test plates.

Vane Plates and the Shear Properties:

10) There was a statistically significant relationship between the shear modulus values obtained from torsion tests using epoxy and the vane plate. This finding suggests that the vane plate can be a reliable substitute for epoxy.
11) The tests carried out using the InSiSST™ facility and the vane plates provided acceptable repeatability and were considerably more repeatable that the laboratory tests.
12) The tests with the InSiSST™ facility and the vane plate indicated that the facility is capable of differentiating between shear properties of different asphalt pavements with respect to the mix type and compaction method.
13) The variation of shear strength with temperature followed the same trend (exponential relationship) as was observed for the tests when using epoxy.
14) There was a statistically significant relationship between the Shear Index obtained from the InSiSST™ testing with the vane plate and the shear modulus of cylindrical samples of the same mix, although a weaker relationship was observed than anticipated. The high variability of the laboratory test results is likely responsible to some extent.

Shear Properties and the Long-Term Performance:

15) Based on the preliminary laboratory testing the shear properties of asphalt concrete mix are correlated to the long–term performance of the material.

Overall, the improvements applied to the InSiSST™ have improved its functionality and accuracy. Most significantly, the utilization of shear vanes as opposed to the former surface-plate method has reduced the required testing time from 24 hours to less than 2 hours per site, as well as provided a more distinct failure surface for analytical modelling – particularly shear strength. The reduction in testing time will not only increase efficiency and reduce cost, but will greatly reduce the risk of injury to testing personnel by requiring only a single lane closure per site. Finally, despite a reduced field testing regime than originally anticipated (due to reduced financial resources), it is clear that InSiSST™ is capable of differentiating between different asphalt mixes and even compaction methods.

INVESTIGATOR PROFILE

Dr. Abd El Halim is the Director of the Centre of Geosynthetics, Research, Information and Development (C-GRID) at Carleton University. He has been recognized internationally for his work on the AMIR asphalt concrete compactor and research innovation in the field of asphalt pavements and field measurement. Professor Abd El Halim has published over 125 technical papers and has supervised many research works and projects in the asphalt pavement and materials fields. He has lectured and consulted in many countries and is an active member of many professional bodies and associations such as TRB, ASCE, CSCE, CTAA, ISAP among others.

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