Investigation of In-Situ Shear Properties of Asphalt Concrete

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements of the degree of

Doctor of Philosophy

in Civil Engineering

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ABSTRACT

The main objective of this thesis is to investigate the behaviour of asphalt concrete mixes under the effect of a forced angular displacement on its surface, as prescribed by a new testing facility. The facility was developed at Carleton University to evaluate the in-situ shear properties of the asphalt concrete mixes. A theoretical, numerical and experimental research program was planned and executed to achieve the research objectives.

The theoretical investigation included studying the Reissner Sagoci problem of applying a forced angular displacement to the surface of a half space, while the analytical phase was completed using a three dimensional, viscoelastic Finite Element Model (FEM) to study the effect of the different variables, such as the strain rate, on the shear stiffness evaluated during in-situ testing. The experimental investigation included in-situ testing on Carleton University campus and at an LTPP test site near Petawawa, Ontario, in addition to laboratory testing of core samples recovered from these sections. The testing program was planned to evaluate the characterization of the in-situ asphalt concrete mixes using the newly developed facility, versus the laboratory characterization using the resilient modulus testing and torsion testing. Furthermore, the effect of the actual strain rate on the in-situ testing results was investigated.

The research showed that the viscoelastic material properties and the actual strain rate during testing affect the field measurements. The thesis provided a number of significant enhancements to the developed InSiSST facility in terms of the data interpretation and analysis, with the most significant contribution of introducing a framework relating the in-situ shear stiffness of the asphalt concrete mixes to rutting in the asphalt concrete pavements.

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CHAPTER 1

1 INTRODUCTION

1.1 Background

Shear stiffness of asphalt concrete mixes has been traditionally measured in the laboratories under controlled testing conditions. Until recently, there has been no reliable testing procedure to isolate and/or measure the in-situ shear properties of the asphalt concrete mixes. The first documented attempt to evaluate these properties was by Abd El Nabi at Carleton University (Abd El Nabi 1995). He developed a prototype of an in-situ testing facility, which was called the Carleton In-Situ Shear Tester (CISST). In using this facility, a steel plate is fastened to the pavement surface and forced to rotate through a torsional moment. As a result, a circular area of the asphalt concrete surface is forced to rotate around an axis normal to the surface, resulting in pure shear stresses in the asphalt concrete mix. The shear strength of the asphalt concrete mix was then related to the resulting torque and angular displacement.

The data collected during in-situ testing was limited to the maximum torque and an approximate angle at failure, measured manually. The shear strength of the asphalt concrete mix was subsequently evaluated and used to compare between different mixes. The CISST was an innovative testing facility. However, it had a limited capacity and was difficult to move and manoeuvre. Furthermore, it was only capable of capturing the maximum torque at failure.

In 2001, Goodman used the same principles of the CISST and developed a more advanced version of this facility called the In-Situ Shear Stiffness Test (InSiSST) facility (Goodman 2001). Figure 1.1 shows a top view of the InSiSST facility. The InSiSST had higher capacity than the CISST and had the advantage of the presence of a data acquisition system, capable of recording the torque and the instantaneous motor speed with time, during in-situ testing.

Figure 1.1: Top View of the In-Situ Shear Stiffness Test (InSiSST) Facility

The InSiSST is currently under development and an investigation of the behaviour of the asphalt concrete material under the loading conditions prescribed by the testing facility is required. Furthermore, an experimental investigation into the relationship between the evaluated material properties and the pavement performance is required to develop the InSiSST into a reliable testing facility for asphalt concrete mixes evaluation.

Previous studies have shown that the shear resistance of asphalt concrete mixes is a fundamental property in determining the ability of the mix to resist lateral deformation (Abd El Halim et al 1995). In a laboratory investigation, Abd El Halim has shown that improving the shear strength of the asphalt concrete mix can substantially reduce the longitudinal depression in the wheel-tracks of asphalt pavements, commonly known as rutting (Abd El Halim et al 1997). The SuperPave mix design method has also acknowledged the importance of the shear resistance of asphalt mixes as a fundamental property in resisting deformation of the asphalt concrete mixes. (Harrigan et al 1994, and SHRP 1994).

Rutting is one of the widely observed surface distresses in asphalt concrete pavements, especially in hot-weather areas (Emery1990). It can cause ride discomfort in addition to a safety hazard for highway users. Water can accumulate in rutted sections resulting in a potential of hydroplaning. The hydroplaning phenomenon is the build up of a thin layer of water between the pavement and the tires, causing a reduction in the traction between the tires and the road surface. This phenomenon can result in a loss of steering control, which in turn jeopardises commuters' safety especially during lane changes (Yoder and Witczak 1975). Economically, rehabilitation of rutted roads cannot be done by localized treatment and generally requires overlaying the entire pavement section, thus costing taxpayers millions of dollars yearly. Consequently, the development of a testing facility that can evaluate the shear properties of the asphalt concrete mixes, and subsequently the rutting

potential of the pavement surface will have significant economic benefits in addition to improving the safety on the highways.

1.2 Demand for In-Situ Testing of Asphalt Concrete

Many improvements to the practices of asphalt concrete layers construction were introduced during the last decade. These improvements involved all aspects of asphalt concrete mixing and construction technologies including the mix design, layer construction, Quality Control (QC), and Quality Acceptance (QA). Most of these improvements were mainly aiming at producing asphalt concrete layers that provide better performance at a lower life cycle cost.

Asphalt mix design methods shifted from the traditional Marshall mix design method to the performance based SuperPave mix design method to relate the design aspects of the asphalt mix to its field performance. Construction of highways also shifted from the traditional system where the design and specifications are completed by the agencies to the implementation of the End-Results specifications for acceptance or rejection of a completed asphalt concrete layers. The traditional method provided a prescriptive method to complete the highway construction, which when followed by the contractor; the agency was obligated to accept the project regardless of its quality (Northwood et al 1996).

The introduction of the End-Results specifications made the contractor responsible for the quality of the material and construction methods. This resulted in reducing of the likelihood of lesser quality materials being incorporated in the work, and in improving the overall quality of construction (Mah et al 1997). The implementation of End-Results specifications requires the contractor to be responsible for controlling the materials and construction of the asphalt concrete, while the agency determines the acceptability of the finished work. Ontario started using the End-Results specifications for hot mix asphalt concrete as an acceptability criterion for finished work in 1991. At the early stages of utilizing

the End-Results specifications as basis for QC/QA, only the asphalt binder content and the aggregate gradation of the asphalt concrete mix were evaluated. Requirements for the degree of compaction of the asphalt concrete layer, air voids in the asphalt concrete mix, and smoothness of the resulting surfaces were later introduced.

The main disadvantage of the current QC/QA practices is using empirical material indices as a measurement of the asphalt concrete mix quality and not including any mechanistic material properties that can be related to the actual performance of the asphalt concrete mixes. Furthermore, the QC/QA requirements are mainly based on laboratory testing results. Laboratory testing has the advantage of being fully controlled in terms of the testing conditions and sample conditioning. However, testing asphalt concrete mixes in the laboratory may fall short of fully representing the actual field conditions due to the difference in boundary conditions between the field and the laboratory samples conditions and the potential disturbance of the recovered field samples during coring and transportation.

Another disadvantage for using Laboratory testing for QC/QA purposes is the long time required for the testing completion. The QC/QA results are usually known after the construction has been completed and, in some cases, after the highway has been opened to traffic. If the results showed that the asphalt concrete mix was of an inferior quality, the contractor is either financially penalized, or required to remove-and-replace the already constructed layer.

Consequently, the pavement industry is in need of a QC/QA tool that can evaluate the quality of the newly constructed asphalt concrete layers in an efficient, accurate, and reliable manner. There is a need for a QC/QA testing procedure that can be used immediately after construction, allowing for timely decisions for acceptance or rejection of the constructed asphalt concrete layers. The development of an in-situ testing facility that can measure a

mechanistic material property, predicting the expected long-term performance of the pavement can be the answer for such demand. Furthermore, it can.

1.3 The In-Situ Shear Stiffness Testing (InSiSST) Facility

The InSiSST facility is used to evaluate the shear properties of the asphalt concrete surface mix by forcing a circular area of the asphalt concrete surface to rotate about an axis normal to the pavement surface. A torque is applied to a circular plate bonded to the pavement surface to introduce the required forced angular displacement, resulting in pure shear stresses within the asphalt concrete mix. The torsional resistance is measured and related to the applied forced angular displacement to evaluate the shear properties of asphalt concrete mix.

On failure of the pavement, a volume of the asphalt concrete layer is separated from the surface. The failed sample generally has a rough surface due to the interlocking of the aggregate particles. The failure surface can be approximated to a spherical segment or an inverted frustum of a cone. The height of the failed sample is usually small compared to the diameter of the loading plate. Abd El Halim et al (1997) showed that the test is successful as long as the height of the failed sample is greater than the nominal aggregate size of the mix. Figure 1.2 shows a failed sample for one of the in-situ tests.

The InSiSST facility employs an innovative approach that has not been used before for in-situ testing of asphalt concrete mixes to evaluate the asphalt concrete mix shear properties. It provides the opportunity of measuring a fundamental material property of the asphalt concrete in the field immediately after construction. However, to develop the InSiSST facility as a useful tool for in-situ testing, an in-depth investigation of the behaviour of asphalt concrete mix under the loading conditions prescribed by the InSiSST is needed. Furthermore, an experimental investigation is required to study the effect of different variables on the in-situ

Figure 1.2: Failed Sample from an In-Situ Testing

measurements of the InSiSST and to investigate the relationship between the measured asphalt concrete mix properties and the long-term performance of the pavement surface.

1.4 Problem Definition

The need for an in-situ field-testing facility that can be used as a tool for QC/QA is evident. The InSiSST facility has a potential of becoming an effective tool for QA/QC of asphalt concrete mixes. Preliminary results by Abd El Nabi (1995) and Goodman (2001) showed that the concept behind the InSiSST has the potential of being used to quantify the in-situ shear properties of the asphalt concrete mixes. However, the actual material properties and theoretical background behind the application of the testing facility has not been investigated. The testing facility is still in the preliminary stages of development and the effect of different testing conditions has not been investigated. Furthermore, the possible relationship between

the in-situ shear properties of the asphalt concrete mixes, as determined using the InSiSST facility, and the long-term performance of the asphalt concrete pavements has not been investigated.

1.5 Objectives

The main objectives of this thesis are

- To investigate the behaviour of the asphalt concrete material under the effect of the loading conditions prescribed by the InSiSST facility during in-situ testing.
- To quantify the material parameters evaluated using the InSiSST and investigate the effect of in-situ testing conditions on these parameters.
- To determine the relationship between the asphalt concrete material parameters evaluated using the InSiSST and the long-term performance of the asphalt concrete pavements as defined by the permanent deformation in the wheel path (rutting).

More specifically, the objectives of the thesis include the investigation of the relationship between the torque and the angular displacement in terms of a fundamental material property of the asphalt concrete mix, and to investigate the effects of testing conditions, such as the temperature and strain rate, on the calculated material parameters.

1.6 Scope

The scope of the thesis includes theoretical and numerical investigation of the behaviour of the asphalt concrete surface mixes under the effect of the loading conditions prescribed using the InSiSST facility. The scope also includes an experimental program for field and laboratory testing of asphalt concrete mixes from different pavement sections to address the thesis objectives. More specifically, the thesis includes the following tasks:

- Theoretical investigation and numerical analysis, using the Finite Element Method, of the behaviour of asphalt concrete mix under the effect of a forced angular displacement on the surface of the pavement. The material modelling is limited to a viscoelastic model and the plastic behaviour near failure was not considered in the analysis.
- An experimental program including field and laboratory testing to investigate the effects of the testing conditions on the measured material properties. The testing conditions investigated in this thesis include the diameter of the steel plate used during in-situ testing, the pavement temperature, and the actual strain rate used during testing. Field-testing for this investigation was carried out on two pavement sections; a relatively weak, uncompacted pavement sections and a relatively stronger old pavement section, on Carleton University Campus.
- An experimental program including field and laboratory testing to investigate the relationship between rutting of asphalt concrete pavements and shear properties of the asphalt concrete mixes. This investigation is carried out using test sections located in a Long Term Pavement Performance (LTPP) test site, where six asphalt concrete sections with different asphalt concrete surface mixes are regularly monitored and yearly rutting data is available.

1.7 Thesis Organisation

In Chapter 2, a comprehensive literature review for evaluation of the shear properties of the asphalt concrete mixes and the relationship between the shear properties of the asphalt concrete mixes and rutting of asphalt pavement is presented. An account of mechanical models previously used in the literature to model the asphalt concrete mix for numerical investigation is also presented in this chapter. Chapter 3 describes the InSiSST facility, data

collection, data interpretation, and material parameters calculated based on the in-situ measurements.

In Chapter 4, a review of the materials behaviour under the effect of a forced angular displacement on the surface of a half space and the theoretical investigation for modelling the in-situ testing is presented, while Chapter 5 describes the development finite Element model and numerical investigation. Chapter 6 describes the field and laboratory testing programs, and the analysis and results are presented in Chapter 7. Finally the conclusions and the recommendation for future work are presented in chapter 8.

CHAPTER 2

2 LITERATURE REVIEW

The main objectives of this thesis include studying the behaviour of the asphalt concrete mixes under the effect of a torsional moment applied to its surface and investigating the relationship between the shear properties of the asphalt concrete surface mixes and rutting in flexible pavements. Subsequently, a comprehensive literature survey of the rutting phenomenon in the asphalt concrete pavements and the shear properties of the asphalt concrete mixes is presented. The objective of this survey is to establish the research background behind the relationship between shear properties of asphalt concrete and rutting in asphalt pavements.

As part of the scope of the thesis, the Finite Element Method (FEM) is used to investigate the effect of the testing conditions on the in-situ measurements using the InSiSST. In this analysis, the asphalt concrete mix is modelled as a linear viscoelastic material. In this chapter, the different approaches to model the asphalt concrete mixes for numerical investigation is also presented, with the objective of examining the most suitable material model to be in the FEM.

2.1 Rutting in Flexible Pavements

Permanent deformation in the wheel path of flexible pavements, generally known as rutting, is one of the main types of observed surface distresses in asphalt concrete surfaces. It has been historically one of the primary criteria of structural performance in many pavement design methods (AASHTO 1960). Rutting is a two-fold problem for pavement engineers as it

presents both a safety concern and an economic issue. Rutting presents a safety concern as water might accumulate in the depressed longitudinal wheel paths resulting in a potential of hydroplaning. The hydroplaning phenomenon is the build up of a thin layer of water between the pavement surface and the tires, resulting in reduced traction and a subsequent loss of steering control (Yoder and Witczak 1975). In severely rutted highway sections, rutting may pose a safety hazard during lane changes. Economically, rehabilitation of rutted roads cannot be done by localized treatment and generally requires overlaying the entire pavement section, thus costing taxpayers millions of dollars yearly.

2.1.1 Rutting Mechanism

Rutting develops in asphalt concrete surfaces through two major mechanisms; densification and shear plastic deformation. Densification of the asphalt concrete mix is the secondary compaction in the top layers due to traffic. Shear plastic deformation is the deformation of the pavement layers laterally. As a result of traffic loading, a depression is developed in the wheel paths forcing the pavement material to heave up on the sides. Rutting caused by material densification in the wheel path is usually minor and contributes to a small portion of the rut depth (Huber 1999). A study commissioned for the Organisation of Economic Co-operation for Development in 1988 showed that rutting develops within the asphalt concrete layers when the stresses induced by the traffic loading are sufficient to cause shear displacement within the material (OECD 1988).

Eisenmann et al showed that if a pavement section is well compacted during construction, further densification during rutting is unlikely (Eisenmann and Hilmer 1987). Trenching studies at the AASHO Road Test, as well as at other full-scale test tracks, have indicated that shear deformation, rather than densification, is the primary rutting mechanism in asphalt concrete surface mixtures when reasonably stiff supporting layers are present

(Epps et al 1998). Simpson showed that in asphalt concrete layers, permanent deformation is limited to the upper 100 mm of the surface layer and the rut depth is proportional to the number of load applications (Simpson 1999).

Figure 2.1 shows a typical flexible pavement structural section. As mentioned earlier, rutting happens mainly in the top asphalt concrete layer, when reasonably stiff supporting base and subbase layers are present. Classic pavement design procedures are based on reducing the vertical stress on top of the subgrade and the tensile stress at the bottom of the lowest asphalt concrete layer. In general, increasing the layer thickness and/or the material stiffness can reduce stresses and strains. As a result, pavement structures are composed of layers possessing successively higher stiffness approaching the surface.

In 1987, a study was commissioned by the City of Lethbridge, Alberta to investigate premature rutting in asphalt concrete pavements within its arterial street system. The study addressed causes of the rutting and means of mitigating future rutting (Dawley et al 1990).

Figure 2.1: Typical Pavement Structural Section

The study concluded that three types of rutting could develop in asphalt concrete pavements:

- Wear rutting, which is due to progressive loss of coated aggregate particles from the pavement surface. This type of rutting is caused by combined environmental and traffic influences.
- Structural rutting, which is due to the permanent vertical deformation of the pavement structure under repeated traffic loads. Structural rutting is a reflection of permanent deformation within the subgrade
- Instability rutting, which is due to lateral displacement of asphalt concrete material. This type of rutting is manifested in the form of a depression in the wheel paths, accompanied by an upheaval on the sides. Instability rutting occurs when the structural properties of the compacted pavement are inadequate to resist the stresses imposed upon the pavement, particularly by frequent repetitions of high axle loads.

The distress surveys and field observations showed that a substantial portion of the rutting resulted from mixture instability, but some of the rutting could have been due to structural inadequacy. To differentiate between structural inadequacy and mixture instability rutting, trenches were excavated at 11 sites. The trenches revealed that all of the rutting was confined to the asphalt concrete surface layer, i.e. instability rutting. The alignment of the aggregate particles on the vertically sawed faces of the pavement demonstrated that shear failure had occurred within the asphalt concrete layer.

The previous discussion shows that rutting developed in asphalt concrete pavements occurs in the top asphalt concrete layers as long as the pavement structure was designed and constructed according to proper engineering procedures, and the materials used in the construction are of fairly high quality. Furthermore, rutting is more attributed to lateral shear flow, rather than asphalt concrete material densification, which has a minimal contribution to the total rutting in asphalt concrete pavement sections.

2.1.2 Factors Affecting Instability Rutting Asphalt Concrete Pavements

Asphalt concrete instability rutting is affected by many factors. These factors can be grouped in four main categories, as follows

- Asphalt concrete mix volumetrics
- Traffic characteristic
- Construction
- Environmental factors

Rutting resistance of asphalt concrete mixes was found to be affected by many factors related to the asphalt concrete mixture volumetrics. Higher asphalt content and air voids below a certain level were found to increase the rutting susceptibility of asphalt concrete mixes (Archilla and Madanat 2001). The percentage of air voids is one of the main factors affecting rutting. Higher air voids results in excessive initial rutting due to densification, while very low air void results in an increase in the voids filled with asphalt concrete and subsequently, higher rutting susceptibility. Aggregate gradation and aggregate structure were also found to affect the rutting performance of the mix. Goode and Lufsey (1962) suggested that the farther away the gradation of a given mix is from the maximum density line, the more susceptible it is to rutting.

Traffic characteristics, such as tire pressure, axle loading and axle configuration, were found to significantly affect rutting in flexible pavements (Archilla and Madanat 2000). Higher axle-loads and higher tire pressures result in more rutting to the pavement surface. However, rutting produced by two different wheel configurations for a given load, could be different due to the different stress distribution in the upper portion of the pavement layers. Furthermore, tire pressure can significantly vary depending on the temperature difference between the tires and the road surface, and pavement surface irregularities (OECD 1988).

As mentioned earlier, high air voids would result in excessive initial rutting. Consequently, proper compaction during construction could affect the rutting performance of a pavement structure. The environmental factors are one of the very important factors that affect rutting. Seasonal variation and alternate cycling of freezing and thawing would result in a reduced strength of the subgrade soil, which may cause structural rutting. Excessive moisture may cause stripping and general weakness to the surface material. Furthermore, rutting is more reported in hot weather area (Emery 1990). At higher temperatures, the viscous behaviour of asphalt concrete is more prevalent, resulting in a reduced shear resistance and higher rutting susceptibility (OECD 1988).

2.1.3 Evaluation of Rutting Susceptibility of Asphalt Concrete Mixes

Rutting susceptibility of asphalt concrete mixes has been traditionally measured in laboratories. The objective of laboratory testing is to simulate, as closely as possible, the in-situ conditions of the mixes. These conditions include the temperature, moisture, and stress-state. Three main types of laboratory tests are used to characterize the permanent deformation response of asphalt pavement materials. The uniaxial and triaxial stress tests, the diametrical tests and the wheel track tests (SHRP 1991).

Uniaxial and Triaxial Tests

The uniaxial and triaxial tests include testing confined and unconfined cylindrical asphalt concrete samples under creep, repeated or dynamic loading. During the creep test the asphalt sample is subjected to a relatively low static axial load and the deformation is measured over time. Shell researchers used the creep test to predict rutting (Hills 1973). Due to the fact that the loading time in the field is very small compared to the creep test loading time, Van De Loo (1974) recommended that the creep test should be done at relatively low stress level, within the linear range of the material. Results of the creep test were found to be

independent of the sample size proportions, provided that the ends of the asphalt concrete specimen are parallel and smooth (SHRP 1994).

The repeated load uniaxial tests are used to determine a wide variety of the asphalt concrete mix parameters including the resilient modulus and Poisson's ratio. These parameters are usually calculated as a function of the load repetitions (SHRP 1991). In these tests, the sample is subjected to a repeated axial stress pulses, either compression or tension. The rest period between pulses range between almost zero to several seconds. It was found however, that the shape of the stress pulse and the duration could greatly influence the measurements. Subsequently, these pulses should simulate the traffic loading as closely as possible (Barksdale 1971).

Dynamic uniaxial tests are more sophisticated and are used to measure dynamic properties of the asphalt mix. The sample is subjected to a constant lateral pressure, while the vertical pressure is varied sinusoidally over a range of frequencies. Dynamic tests are used to evaluate material parameters such as the dynamic modulus, which is the ratio between the peak stress and the peak strain, and the phase angle, which is the part of the cycle by which the strain lags the stress (SHRP 1994).

In general, the uniaxial tests could provide a good indication of the rutting susceptibility of asphalt concrete mixes. The results of the laboratory tests in some cases did not correlate with the results from the field. However, the dynamic modulus is currently gaining more and more acceptance in the pavement researcher community as an indicator of the pavement performance.

Diametrical Tests

The diametrical compression test, also called the indirect tensile test or the Brazilian test, was developed in the 1940's. This test is widely used to determine the material parameters of asphalt concrete and Portland cement concrete. In this test, a cylindrical

specimen is subjected to a compressive load along a diametrical plane, resulting in a nearly uniform tensile stress over a significant portion of the loaded plane (Thaulaw 1957). The diametrical testing was deemed inappropriate for permanent deformation characterization because the stress state in the specimen is non-uniform and depends on the shape of the specimen (SHRP 1991). Furthermore, the shear stresses, which significantly contribute to the permanent deformation, are highly non-uniform (Khosla and Omer 1985). The diametrical compression test is still widely used to determine material properties such as the resilient modulus and the indirect tensile strength (ITS). However, researchers had little success in correlating these material properties to the rutting performance in the field.

Wheel Track Testers

Wheel track testers do not measure the mechanical properties of the asphalt concrete mix. The specimen is subjected to a repeated load and the rutting performance is then related to the number of load repetitions prior to failure. The French rut tester, Hamburg rut tester, and Georgia loaded wheel tester are the most famous types of rut testers. Using the French rut tester, rutting susceptibility is evaluated by applying a repetitive loading using a pneumatic type on an asphalt concrete slab sample. Developers of the of the French tester believe that no statistical correlation of rutting in the rut tester and rutting on the road can be achieved because the rut tester simulates the most severe rutting conditions, while most traffic would be carried in less severe conditions. However, the French tester was found to be successful in differentiating between mixes and ranking them (Huber 1999).

Hamburg road tester is used to measure moisture damage resistance, utilizing the same load application mechanism for submerged specimens. Rutting susceptibility could be evaluated using this device, albeit the failure in the specimens is usually due to stripping. In the Georgia loaded wheel tester, the load application rate is much faster, at 45 times per second.

All wheel track testers have the disadvantage of being empirical methods. The results obtained from wheel testers cannot be generalized to different asphalt concrete mixes and is limited to the specific mixes for which the test was performed.

2.1.4 Modelling Rutting in Asphalt Concrete Mixes

As mentioned earlier, rutting susceptibility of asphalt concrete mixes is evaluated using either an empirical testing procedure, where the field conditions are simulated and the rutting performance is observed, or a mechanistic procedure, where a fundamental material property is evaluated and related to the rutting performance of the mix (Huber 1999). The difference between the two approaches is that the mechanistic testing evaluates an engineering property of the asphalt concrete mix, such as the dynamic modulus or the shear stiffness that can be directly related to performance or modelled to predict performance. Empirical tests, such as rut testers, Marshal stability test, and Hveem stability test are usually designed to simulate the road conditions in the laboratory. In all cases, laboratory testing is performed to evaluate a material parameter that is used to evaluate rutting.

The mechanistic-empirical approach is gaining a lot of support among the pavement researchers. In this approach, a performance-based test is performed to measure a mechanical property of the asphalt concrete mix. The measured mechanical property is either modelled in an empirical equation to calculate the rutting depth, or correlated to field rutting through regression analysis. Some of these models incorporate mechanical properties measured in the laboratory and volumetric characteristics of the mixes to develop the empirical models.

Morris and Haas (1972) used the elastic characteristic of the asphalt concrete mix to calculate the rutting depth in pavements. They used the elastic theory to calculate the total vertical strain in the pavement and suggested that the rutting depth can be calculated using

the accumulated plastic strains above the elastic limit. Van De Loo (1974) used the axial creep and the elastic multi-layer theory to predict rutting. Meyer and Haas (1977) developed a mechanistic-empirical model to relate the permanent axial deformation to the stress-state in the pavement, temperature, number of load repetitions, and air voids in the mix. Hills et al (1974) and later Van De Loo (1987) used a model based on the results of unconfined creep test that relates the rutting depth to the stiffness of the bitumen mix. This model assumes that the rutting solely depends on the viscous and non-elastic component of the asphalt binder stiffness. Monismith and Taybali (1988) used a model that was based on the viscoelastic properties of the mix and accounted for temperature to predict rutting. Harvey et al (1994) used the accumulated axial deformation during the dynamic creep test at elevated temperature to evaluate rutting. Barksdale (1994) used the same test but by applying a shear load instead of an axial load.

Zahw (1995), and later Goodman (2000), proposed statistical models that used the mechanical properties including the tensile strength, shear strength, tensile modulus and shear stiffness together with the material properties, such as the kinematic viscosity of the binder, compaction effort and the stress applied during the creep test to develop an empirical model for predicting rutting. They showed that an increase in the shear strength and the shear stiffness of an asphalt concrete mix would increase its resistance to rutting. However, they found that the correlation of the shear stiffness is higher than the correlation with the shear strength.

As can be noted from the previous discussion, many researchers have tried to correlate the rutting performance to different kind of material properties, with varying success. However, the main drawback in these trials is that they were mainly laboratory performed testing. The laboratory testing has the disadvantage of using samples, which are either

manufactured in the laboratory or cored from the field, but always have different boundary condition than the in-situ material.

2.2 Shear properties of Asphalt Concrete Mixes

The mechanical properties of the asphalt concrete mixes have been traditionally carried out through evaluating the compressive strength or the tensile strength of the mix. The compressive strength mostly relates to the aggregate skeleton, while the tensile strength mostly reflect the strength of the binder. Recently, shear properties started to gain wider acceptance among the pavement researchers. The shear properties can better represent the strength of the asphalt concrete mix as a mixture of aggregate materials and binder. Shearing forces, or stresses, have to overcome both the interlocking of aggregate structure, in addition to overcoming the cohesive forces of the binder. Moreover, as the rutting is observed as a shear flow, it is reasonable to expect the shear properties of the asphalt concrete mixes to better describe its rutting susceptibility.

Asphalt concrete is a mixture of a random configuration of an aggregate structure, and a non-linear and non-elastic asphalt binder material. The asphalt concrete mix resists shearing forces induced by traffic loads mostly by the binder cohesion strength. However, if the applied loads surpass this strength, the shearing resistance would be mainly attributed to the friction between the aggregate particles in the asphalt concrete matrix. Previous studies have shown that the asphalt concrete mixes have general characteristics under shear loading (Sousa et al 1991). These characteristics include dilation, dependency of the results on temperature and rate of loading, and the presence of permanent deformation (Tayebali et al 1991). Dilation, which is the increase of volume by shear loading, is usually attributed to the unlocking of the aggregate particles under the shearing forces leading to an increase in

volume. This phenomenon supports the assertion that the shearing forces have to overcome the aggregate interlocking in the mix.

Dependency of the results on the temperature and on the rate of loading has been a long observed phenomenon of pavement material due to the viscous nature of the asphalt concrete mixes (Sousa et al 1993). At lower temperatures and higher strain rates, the behaviour of the asphalt concrete mixes is closer to the behaviour of linear elastic materials, while at higher temperature and lower strain rates, the pavement behaviour can be similar to viscoelastoplastic materials. Although this applies to all types of stress-states, being shear or otherwise, these effects can significantly affect the pavement characterization under such conditions (Foster 1995).

2.3 Evaluation of the Shear Properties of Asphalt Concrete

As early as the 1940's, Smith (1949) used the triaxial shear test to evaluate the shear properties of the asphalt concrete mixes. He used six different mixes and evaluated the cohesion and the angle of internal friction, as two fundamental material properties. These quantities were developed using Mohr's circle. Monismith and Vallergera (1956) used the same testing procedure to develop the same material properties, however their results, for the cohesion, were significantly different from the results obtained by Smith.

Sousa (1986) used torsional oscillations on hollow cylindrical asphalt concrete samples to evaluate the strength of the pavements. However, the results obtained were not as encouraging when evaluated against the complexity of the sample preparation and the testing procedures. Alavi (1994) used the same hollow asphalt concrete specimens but by applying dynamic shear loading and again the correlation with the field results were not high. Zahw (1995) used torsion to measure the shear strength of cylindrical core samples. His

results, as further analysed by Goodman (2000), showed good correlation with the rutting susceptibility of the tested asphalt concrete mixes through creep testing.

The Superior Performing Asphalt Pavements (SuperPave) shear tester was introduced by the Strategic Highway Research Program (SHRP) to evaluate the shear properties of the asphalt concrete mixes (SHRP 1994). This testing facility is planned to be utilized in level-3 pavement design, which has not been implemented yet. The SuperPave shear tester can provide two type of testing; Repeated Shear at Constant Height (RSCH) and Frequency Sweep at Constant Height (FSCH). The RSCH was not originally included in the SuperPave mix analysis, but is now widely used to estimate relative rutting performance (Sousa 1995). In this test a haversine shear load is applied to a cylindrical specimen, maintaining the height of the specimen. The rutting is then related to the accumulated permanent shear strain, or the number of loading cycles to achieve a fixed strain. The FSCH is the only SuperPave mix analysis that uses dynamic loading (Wang et al 2001). In this test, a very small, repeated, controlled shear strain is applied to the specimen through a shear actuator. The complex shear modulus and the phase angle are evaluated from this test, which can then be related to the pavement performance.

The previous discussion shows how complex the determination of the shear properties of the asphalt concrete mixes can be. However, all these trials are mainly based on laboratory testing. Although, laboratory testing has the advantage of providing full control over the testing conditions, it might not reflect the actual properties of the asphalt concrete mixes in the field. Differences of the results between field and laboratory testing can be attributed to many factors including the difference in the boundary conditions, sample preparation methods or disturbance of the samples during transportation to the laboratory.

An innovative approach was adopted by the researchers at Carleton University to evaluate the shear properties of the asphalt concrete mixes, both in the laboratory and in the

field. Zahw (1995) used a laboratory-testing device to measure the shear properties of pavement samples by applying a torsional moment. The idea of applying a torsional moment was extended to the field by introducing the CISST (Abd El Nabi 1995) and the InSiSST (Goodman 2001). In using either facility, a torsional moment is applied to the surface of the pavement, which would result in pure shear stresses. The CISST, and the InSiSST, are the first documented attempt to evaluate the in-situ shear properties of the asphalt concrete mixes using direct field measurements in the pavement literature.

2.4 Analytical Modelling of Asphalt Concrete Mixes

Asphalt Concrete is a complicated engineering material as its mechanical properties vary by time and temperature. Subsequently, mathematical modelling of the behaviour of the asphalt concrete mixture is rather complicated task (Le Tallec 1990). The properties of the asphalt concrete mixture range from being linear elastic to viscoelastoplastic behaviour. The asphalt concrete mix may exhibit viscous properties and/or non-elastic properties depending on the loading and environmental conditions. Consequently, most of the material models used in the literature to model the asphalt concrete mixture were approximate and the choice of a specific material model mainly depended on the particular problem being investigated and the objective of the research. A review of different formulations of the pavement material is presented in the following sections.

2.4.1 Linear Elastic Modelling

Asphalt concrete mixes have been traditionally approximated as a linear elastic material. Most design procedures for the pavement use elastic properties, such as Young's Modulus, to characterize the asphalt concrete mix and determine required thickness of surface layers (AASHTO 1993). Moreover, many pavement management systems use the elastic properties

of the pavement layers to determine their structural capacity. Young's Modulus can be backcalculated from the results of the Falling Weight Deflectometer (FWD) test. Albeit the linear elastic approximation might not be an exact representation of the pavement material, it is still widely acceptable by many designers and highway and aviation agencies (Haas 1993).

The linear elastic approach for modelling the asphalt concrete mix might be acceptable for design and pavement management application purposes. The stress levels considered in the analysis are usually much less than the stresses that cause failure of the pavement. The accuracy required for such purposes is generally low and the effect of ignoring other material properties would not affect the overall outcome of the analysis (Huang 1993). Consequently, most of the design codes are based on the multi-layer elastic theory, where the pavement layers, including the base and subbase layers, are assumed to be linear elastic materials defined by only two parameters, such as the elastic modulus and Poisson's ratio.

2.4.2 Elastoplastic Modelling

The elastoplastic modelling of asphalt concrete mixes assumes the material to have a linear elastic behaviour at the early stages of the loading and a maximum yield or failure strength. A number of elastoplastic material models were used in the literature to model the asphalt concrete mixes, such as the Tresca model, the Von-Mises model or the Drucker-Prager model. Tresca yield criterion assumes that the material yields when the stress-state at a point reaches the maximum shear value. The von Mises criterion states that failure occurs when the energy of distortion reaches the same energy for yield/failure in uniaxial tension, which is more suited for homogeneous materials, such as metals. The Drucker-Prager model is more suited for the heterogeneous material, such as the soils, where the yield criterion is a function of the cohesion and the internal friction of the material.

Ganzon et al (1993) used the octahedral shear stress, which is based on the Von-Mises yield criterion, to evaluate pavement strength. He showed that the Von-Mises yield criterion gave an acceptable correlation with the results of his experimental program. Boon-Hwee et al (1992), Tan et al (1994) and Fwa et al (1997) modelled the pavement material as an elastoplastic material, and assumed it would follow a Drucker-Prager yield criterion. They assumed that the properties of the pavement could be explained using the two parameters for this model, namely, the angle of internal friction and the cohesion. Tan (1994) showed that the angle of internal friction was entirely a function of the internal friction of the aggregate and the interlocking between the particles. Furthermore, they showed that the cohesion of the mix vary with temperature, which indicates that it is a function of the properties of the bituminous material. The results of their models gave high correlation to the experimental data collected from the Marshall stability test.

In general, modelling the asphalt concrete mix as an elastoplastic material may provide more accuracy to the material modelling. However, the disadvantage of such models is that they ignore the viscous properties of the pavement material, especially if these tests were done at higher temperature or at slower rates of loading.

2.4.3 Viscoelastic Modelling

The change of the viscous properties of asphalt pavement materials due to temperature is well known and well documented. The most effective contributor to the viscosity of the asphalt mix is the asphalt cement. Foster (1985) reported that the viscosity of a typical paving grade of asphalt cement would be in the order of 2500-poise at 140°F and 6,000,000-poise at 77°F. However, there is no general theoretical method for determining the viscosity of the asphalt mixtures. Typically, the viscoelastic properties of the asphalt mixes are determined in

terms of creep compliance, which is defined as the reciprocal of the instantaneous elastic modulus (Huang 1993).

Hopman suggested that as the creep is assumed to be a shear flow phenomenon, subsequently, it would be reasonable to fit the results of the creep test to determine the rheological behaviour for the asphalt mix (Hopman et al 1992). Collap introduced a model to determine the asphalt mix viscosity as a function viscosity of the bitumen and the percentage of voids in mixed aggregates (Collap et al 1995). Helwany suggested a shear relaxation modulus that decays exponentially by time (Helwany et al 1998). These models were correlated with experimental data from laboratory testing with varying degrees of success.

The viscoelastic material modelling, although ignores the plastic deformations in the asphalt concrete mix during loading, could be a good approximation to the material behaviour, especially at lower stress levels, where the plastic deformations had not been developed yet.

2.4.4 Viscoelastoplastic Modelling

Viscoelastoplastic modelling of the asphalt concrete mixes is not the usual approach in the literature to model pavement materials due to its complexity. However, many researchers suggest that it is the most realistic approach to model the asphalt concrete mixes. This type of modelling is usually used only in modelling problems that involve permanent deformations of pavement layer such as rutting and asphalt concrete compaction.

Shell researchers (1978) have developed a pavement design system in which rutting potential of the asphalt concrete is characterized by a simple creep test (Hilster et al 1977). This led to the establishment of an empirical link between the rheological properties of the asphalt concrete mix and its viscoelastoplastic behaviour. Drescher et al (1993) suggested that only conducting creep and recovery tests with different loading times could identify the

recoverable and irrecoverable components of the deformations. Recently, Lu and Wright (1998; 2000) used a viscoelastoplastic model, where the visco-plastic theory was incorporated in the viscoelastic modelling, to model the temperature effects on the elastic, viscoelastic and viscoplastic strains in the pavement material. Furthermore, they investigated the empirical formulations of the temperature relationships with viscoelastoplastic properties of the pavements.

2.4.5 Selection of a Material Model

The selection of a material model is always dependent on the objective of the research work and the nature of the modelled problem. As shown earlier, different material models ranging from linear elastic to viscoelastoplastic models were used to model the behaviour of the asphalt concrete mixes with different degrees of success. There is no final consensus among researchers on the most suitable material model for the asphalt concrete mix. However, the selection of the model depends on the prevailing conditions of the problem and the acceptable level of approximation for that particular problem.

2.5 Summary

In this chapter two main topics were discussed. The first was the rutting phenomenon in flexible pavements and its relationship with the shear properties of the asphalt concrete surface mix. The second topic was the mechanical modelling of the asphalt concrete mix for numerical investigation.

As shown through the work of different researchers, rutting has been a widely observed surface distress in the asphalt concrete pavement. It was shown that it correlates well with the shear properties of the asphalt concrete surface mix. However, the shear properties were only measured in the laboratory, where the different boundary conditions and

the possible disturbance in the samples during transportation may affect the accuracy of the results. Subsequently, the development of an in-situ testing facility, where the shear properties of the asphalt concrete mixes can be directly evaluated will be a significant contribution to the asphalt concrete pavement industry.

The mechanical models used to represent the asphalt concrete mixes in the numerical investigation ranged from the linear elastic models to the viscoelastoplastic models. The selection of a particular model for a particular problem mainly depends on the conditions of the investigation problem. Since the viscous properties of the asphalt concrete mixes can be observed at normal service conditions and warm temperatures, a model that accounts for the viscous properties of the mix should be considered. Subsequently, modelling the asphalt concrete mix as a viscoelastic material might be suitable for the scope of this thesis. This will be further discussed in Chapter 4.

CHAPTER 3

3 FIELD TESTING DATA INTERPRETATION

In testing the asphalt concrete surface, the In-Situ Shear Stiffness Testing (InSiSST) facility is used to apply a forced angular displacement to a steel plate bonded to the surface of the pavement. Reissner and Sagoci (1944) have shown that the application of such forced displacement to the surface of a half space would result in pure shear stresses. Since the pavement surface compared to the size of the loading plate, can be considered to extend infinitely, the Reissner-Sagoci approach could be utilized to model InSiSST loading pattern. The shear stresses can be related to other material properties, such as the shear stiffness of the asphalt concrete mix.

The InSiSST facility is currently being developed to test the in-situ shear properties of asphalt concrete mixes. However, the concept behind its development can be easily extended to other materials such as Portland cement concrete and granular layers. An overview of the InSiSST facility and the data acquisition system is presented in this Chapter.

The InSiSST facility, shown in Figure 1.1 in Chapter 1, is a trailer-mounted testing equipment, which was developed at Carleton University (Goodman 2001). In using the InSiSST, a forced angular displacement is applied to a steel plate bonded to the surface of the pavement. The steel plate is connected to a torque cell to measure the pavement resisting torque. The torque cell is connected to a gearbox and a driving motor. The stability of the facility is provided by the weight of a steel frame that when lowered to the ground the wheels of the trailer lift off the ground. The whole weight of the testing facility is thus carried by the frame, which has rubber pads on its lower surface allowing enough frictional forces to

resist the movement of the whole set-up during testing. Figure 3.1 shows the test setup with the steel plate bonded to the surface of the pavement.

3.1 Data Acquisition System

The InSiSST facility is provided with a data acquisition system to record the resisting torque and the motor speed at a time step that can be as small as 50-millisecond. The resisting torque is measured directly using the torque cell at the top of the steel plate. However, the current configuration of the facility does not allow for the direct measurement of the angular displacement, which could be calculated using the motor speed, assuming constant strain rate loading conditions. Figure 3.2 shows a typical output from the torque cell of the InSiSST, where the torque is measured over time.

Figure 3.1: In-Situ testing Setup using the InSiSST

Figure 3.2: Typical Output from the InSiSST facility

Prior to each test, the torque cell is calibrated by inducing an instantaneous imaginary high torque reading. The torque readings from the torque cell are then converted to torque units. For the particular configuration of the InSiSST, Equation [3.1] is used to convert the torque cell output to torque units.

$$[3.1] \quad T = 593.3 \frac{R_t - R_{min}}{R_{max} - R_{min}}$$

where T is the torque in pound-foot, R_t is the reading at time t , R_{min} is the minimum reading at calibration and R_{max} is the maximum reading at calibration. The InSiSST is provided with a motor controller and a gearbox. The motor controller controls the speed of the motor and can display the instantaneous motor speed. The output speed can range between 0 to 1800 rpm. The gearbox reduces the speed by a fixed ratio and for the particular gearbox used in the InSiSST, the reduction ratio is 8101:1. The testing facility was originally designed to provide a

constant strain rate loading. In such case, the angular displacement varies linearly with time. Consequently, the angular displacement in radians for each time step can be calculated using the motor speed and the gearbox reduction ratio as shown in Equation [3.2].

$$[3.2] \quad A_t = A_{t-\Delta t} + 2\pi \frac{S}{60R} \Delta t$$

where A_t is the angular displacement at time t in radians, Δt is the time step for data acquisition, S is the motor speed in rpm and R is the gearbox reduction ratio. It should be noted however, that field experiments, described in Chapter 7, showed that the actual rate of angular displacement might not be constant, depending on the material properties at the time of testing in relationship with the capacity of the testing facility. This would be discussed in the following sections.

3.2 Torque Measurements and Data Interpretation

The data acquisition system in the InSiSST is designed to measure the resisting asphalt concrete torque with time. Figure 3.2 shows a typical output curve resulting from the InSiSST for the torque measured over the duration of testing. The following sections describe the output curve and the field observations on the strain rate effect on the testing results.

3.2.1 Torque-Time Curve Description

The first part of the curve is characterized by very small torsional resistance, which is not expected from the asphalt concrete mix at this stage of loading. This part of the curve does not represent the resistance of the asphalt concrete, but rather represents the time required for the motor to pick up its speed, in addition to the small movement in the rubber pad used to stabilize the steel frame and increase the friction between the frame and the pavement surface. Although the movement across the thickness of the rubber pad would be continuous

as the loading progresses, the greater part of this movement would be at the beginning of the loading.

Following the initial stage of mechanical movements, an almost linear increase in the resisting torque with time is observed. At this stage of loading, the motor has reached its target speed and the gearbox has maintained its inertia. The only resistance at that point is the resistance of the pavement material. It was noted in almost all the tests done using the InSiSST, that this linear section was present.

As the pavement reaches its maximum resistance at time t_2 , the increase in the torsional resistance with time ceases to be linear, and the resistance of the asphalt concrete mix decreases sharply with the load increase until reaching a constant residual torque value at time t_3 . The final section of the curve after time t_3 is almost a horizontal section where failure has already occurred and the asphalt concrete sample has already separated from the pavement surface. The measured torque then is due to friction between the separated pavement material and the remaining in-place material. It should be noted that at lower temperatures, where the pavement had higher stiffness, and using a bigger plate size, the torque needed to fail the pavement was sometime higher than the capacity of the testing facility in its current configuration.

3.2.2 Torque-Time Curve Correction

As mentioned earlier, the initial part of the curve is characterized by very small torque values, which is attributed to initial movement of the rubber pads, rather than the actual asphalt concrete resistance. As shown in Figure 3.2, the time values are corrected by extending the linear segment of the curve, or common tangent at the inflection point at time t_1 , 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 time values for the measured torque data was correcting by subtracting the

time different between time O and time O'. The modified vertical axis is shown in the figure by the dashed line. The corrected curve consists of the torque values as evaluated on the tangent, shown in the figure as a dashed line, until time t_1 . The torque values measured after time t_1 are considered the actual torque values and the resulting corrected curve is used in the later stages of the analysis.

3.2.3 Observed Effect of asphalt concrete Strength on the Torque-Time Curve

The InSiSST facility was designed to apply constant strain rate loading, where the angular displacement would increase linearly with time, such that at any point of time, the angle of twist can be calculated using Equation [3.2], and directly related to the measured torsional resistance. Figure 3.3 shows the Torque-Time curve resulting when testing a relatively strong asphalt concrete mixture versus a relatively weak asphalt concrete mix.

As can be noted, the difference between the time t_2 (the maximum torque) and the time t_3 (the residual torque) decreases, as the pavement apparent strength increases. The term "pavement strength" in this case is used as a relative description rather than actual evaluation of the asphalt concrete mixture properties. This observation lead to more in-depth investigation of the actual strain rate applied during testing. Field measurements, done at later stages of the research, confirmed that the relationship between the actual angular displacement on the pavement surface and time can vary significantly depending on the loading conditions and the material strength at the time of loading with respect to the capacity of the testing facility. However, the total angle of twist at time t_3 is the same as the total angle calculated using Equation [3.2] at the corresponding time step. Figure 3.4 shows the results of recorded displacement with time for three different asphalt concrete samples of varying strength.

Figure 3.3: Torsional Resistance Variation with Pavement Strength

Figure 3.4: Variation of Displacement by Time

As can be noted from Figure 3.4, the first sample was rather weak and the angular displacement was almost linear with time. The second sample was stronger, and the measured angular displacement was not linear with time, as the asphalt concrete mix showed higher resistance to deformation. However, as shown by the dashed line, the inertial forces in the gearbox caused the total angle to be similar to the total angle under constant strain rate loading conditions. The point of time when the straight line in the Time-Angular displacement relationship start corresponds to the time t_3 in the Torque-Time curve.

The third sample had the same behaviour of the second sample. However, it was stronger and subsequently, the strain rate in this case was less than the strain rate in the second sample. It should be noted that in all the samples, the displacement at the beginning of the curve was due to the movement in the rubber pad and not actual deformation in the asphalt concrete surface.

Figure 3.5: Relationship between Torque and Angular Displacement

3.2.4 Relationship between Torque and Angular Displacement

The torque recorded through the torque cell and the angular displacement are related through the time steps to define the relationship between the torque and angular displacement during the load application through the InSiSST. An example of the Torque-Angle relationship for an asphalt concrete mix is shown in Figure 3.5. The figure shows that in the relationship between the angular displacement and the resulting torsional resistance of the pavement is not always linear, which is probably due to the viscoelastic effects of the asphalt concrete mixture and the relatively slow rate of loading.

3.3 Calculated Material Properties

One of the main objectives of this thesis is to investigate the behaviour of the asphalt concrete under the effect of a forced angular displacement and to investigate a possible relationship between the measured properties and the pavement performance. The InSiSST facility provides such prescribed displacement. However, in its current configuration, only the torque measurements are recorded, while the angular displacement is either calculated or measured independently. The resulting relationship between the torque and the angular displacement, as shown in Figure 3.5, can be used to evaluate mechanistic and semi-empirical material properties that can be then related to the pavement performance. These properties are presented in the following subsections. It should be noted that if the angular displacement was not recorded, the displacement was assumed to be applied at a constant rate and calculated using Equation [3.2].

3.3.1 Shear Stiffness (G)

Reissner and Sagoci (1944) and Sneddon (1946) investigated the effect of applying a forced angular displacement to the surface of a linear elastic half space. Since then, this problem

has been known in the literature under the name of the *Reissner-Sagoci Problem*. The Reissner Sagoci Problem would be further investigated in more detail in Chapter 4. However, Reissner and Sagoci concluded that for a loading area of radius a , the relationship between torque T , angular displacement ϕ and shear modulus G for such material can be expressed using Equation [3.3].

$$[3.3] \quad G = \frac{3}{16} \frac{T}{\phi a^3}$$

This relationship can be used to define the shear modulus, or shear stiffness as better known in the pavement literature, of the asphalt concrete mixture. However, due the nature of asphalt concrete mix, the relationship between the torque and the angular displacement might not be linear. Consequently, both an initial shear stiffness and a secant shear stiffness could be evaluated as mechanistic material properties.

The initial shear stiffness (G_i) defines the shear stiffness at the early stages of loading, which would give more information about the elastic properties of the material at low stress levels. However, the initial shear stiffness would require accurate measurement of the angular displacement, which might not be always possible using the InSiSST in its current configuration. The secant shear stiffness (G_s) is calculated based on the torque and the angular displacement at failure. As mentioned earlier, the angular displacement at failure can be calculated using Equation [3.2] with an acceptable level of accuracy.

The ratio between the initial shear stiffness and the secant shear stiffness (G_s/G_i) defines the non-linearity of the asphalt concrete mix. A ratio of unity indicates a perfectly linear material, and as this ratio decreases, the non-linearity of the mix increases. It should be noted that when the strain rate is assumed to be constant, this ratio is generally very high, such that using any of the shear stiffness measurements should be sufficient.

3.3.2 Average Shear Strength (τ_{av})

Abd El Nabi (1995) suggested an approximate method to calculate average shear strength over the failure surface. He approximated the failure surface to a frustum of a cone as shown in Figure 3.6. He then used Equation [3.4] to calculate the average shear stress at failure over the surface area of the cone frustum, and considered this to be the shear strength of the asphalt concrete mix.

$$[3.4] \quad \tau_{av} = \frac{3T_{max}}{2\pi \left[\left(\frac{r_f^3 - r_o^3}{r_f - r_o} h_f \right) + r_o^3 \right]}$$

where T_{max} is the maximum torque, τ_{av} is the average shear stress at failure, r_o is the radius of failure at the surface, and r_f is radius of failure at depth h_f .

Figure 3.6: Actual Failure Surface and Approximated Frustum of Cone Surface

The shear strength calculated using the previous equation relates the shear properties of the pavement directly to the torque regardless of the exact measurement of the angular displacement. However, it has the disadvantage of being approximate, as the failure surface is generally very rough and as a result, the measurement of the dimensions of the assumed frustum of a cone is rather subjective.

3.3.3 Maximum Strain (Φ_{max})

The maximum strain at failure can be defined as the accumulated angle of deformation from the start of the test until failure. This angle corresponds to the time t_2 in the Torque-Time relationship. In general, the failure of a sample could be defined in terms of the maximum strain as a failure criterion. Consequently, the angular displacement at failure in radians could be used as a semi-empirical property to evaluate the properties of the asphalt concrete mix. A ductile material would have a large angular displacement at failure and would be more susceptible to rutting.

3.3.4 Average Maximum Shear Stress at Failure (τ_{max})

An average value of the maximum shear stress at failure can be calculated as the product of the shear stiffness and the maximum strain as shown in Equation [3.5]

$$[3.5] \quad \tau_{max} = G \Phi_{max}$$

The maximum shear stress value represents a uniform shear stress distributed over the total area of failure of the pavement sample, assuming the linear relationship between the torsion and angular displacement is valid until failure. The shear stress calculated using Equation [3.5] depends on the shear stiffness used for the calculations. If the initial shear stiffness were used, then the resulting stress would be a hypothetical elastic stress. However, if the secant modulus was used, then the shear stress calculated would be very approximate

as it is calculated using the elastic theory assumption, while near failure, the non-linear plastic properties of the asphalt concrete mix are more prevalent.

3.4 Variables Affecting the InSiSST Facility Results

The InSiSST facility was first tested on Carleton University campus. Pilot testing was carried out on a paved section on campus. During pilot testing, several observations were noted. These observations will be addressed either analytically or experimentally to determine their effects on the results from the field tests.

3.4.1 Effect of Plate Size

The diameter of the steel plate was found to have an effect on the results of the InSiSST facility. Most of the preliminary testing was carried out using a 100-mm diameter steel plate, and the angular displacement was not measured. However, on using the same testing speed on the same asphalt concrete mix using a larger steel plate, the resulting curve was different. Figure 3.7 shows an example of a curve resulting from a test done using a 150-mm diameter steel plate. As can be seen from the curve, it starts in the same manner as the 100-mm plate, but at a certain point, the slope of the straight curve changes, resulting in a bilinear graph. The same shape was observed for 125-mm steel plates.

One hypothesis for the effect of the plate diameter is the fact that as the plate diameter increases the depth of the influence of the forced displacement increases. The properties of the unexposed material is expected to be different from the surface due to a number of reasons including the differential temperature gradient and the ageing of the surface, which might result in stiffer surface crust. Consequently, it is estimated that the resistance at the first stages of loading is the result of the stiffer surface crust and as this crust fails, the resistance will be due to the softer deeper layers.

Figure 3.7: Typical Output for a Test using a 150-mm Diameter Steel Plate

The other assumption, which is probably the more reasonable assumption, is related to the capacity of the testing facility. The maximum torque that can be measured by the InSiSST is about 1300-Nm. It is expected that a larger plate would require a bigger torque to fail the sample, and since the testing facility cannot provide a higher torque, the sample would fail after sometime of sustained torque as a result of creep, rather than an elastoplastic shear failure. However, in all cases, the initial shear stiffness can still be calculated using Equation [3.3].

To address the effect of plate size on the results of the InSiSST, a series of tests are done on a section Carleton-2 using different steel plate diameters. Using different plate sizes would provide data to examine the effect of plate size and using a newly constructed section, provides a homogeneous pavement profile without the ageing effect. Furthermore, the angle would be accurately measured in some samples to define the actual relationship between the

torque and angular displacement for different plate sizes and to examine the effect of the plate size on the calculated parameters.

3.4.2 Failure between the Epoxy and the Steel Plate

The steel plates are bonded to the surface of the pavement using epoxy. In some cases, the sample failed between the steel plate and the epoxy, before the test was completed. Possible explanations for such failure include improper resin and hardener mixing, very smooth or contaminated plate surface, or locally stiff pavement with very high stiffness and very low ductility.

Several types of epoxies were examined to select the best type that would be used with the InSiSST facility. The criteria for the epoxy selection included the setting time, epoxy film thickness and the temperature operating range. An excess of 8 different types of commercially available epoxies were examined. These epoxies included epoxy gels, fast setting epoxies and 24-hour epoxies. Field observations showed that epoxy gels did not provide the expected performance as they formed a thick layer between the steel plate and the pavement surface that distorted during testing, in addition the epoxy gels failed to provide enough strength at lower temperatures. The fast setting epoxies (5-minutes epoxies) also failed to provide enough strength to resist the applied torque. The type that was ultimately used was a 24-hours epoxy. With this epoxy, 80%-85% the tests resulted in a failure in the asphalt concrete surface mix.

Figure 3.8 shows an example of the Torque-Time relationship for a test where the failure happened between the epoxy and the steel plate. As can be noted, the failure between the epoxy and the steel plate was always an abrupt, brittle failure, where the torsional resistance recorded suddenly drops to almost zero. It was also observed that the shape of the curve at the beginning was similar to the tests where the failure happens in the pavement.

Figure 3.8: Torque-Time Relationship in case of an Epoxy Failure

Consequently, it was suggested to use the data accumulated prior to failure in the epoxy to calculate the shear stiffness of the pavement material using the slope of the initial straight line. This is further investigated through the experimental program.

3.4.3 Effect of the Strain Rate

Pilot tests showed that the strain rate had a noticeable effect on the results of the InSiSST. The results obtained from tests done at different speeds on the same type of pavement and at the same temperature were significantly different. This is expected, as the response of the asphalt concrete mixes is known to be rate-dependant. The speed of the motor in the existing testing facility can be controlled, such that the maximum possible angular speed of the steel plate can be as high as 0.223-rpm, which would provide a relatively low strain rate. Lower strain rates would allow for the viscous effects in the pavement to be predominant, resulting in lower shear stiffness and shear strength values. The effect of the speed of the test, or the

strain rate used to apply the torsion on the pavement surface and its relationship to the actual viscous properties of the asphalt concrete mix are investigated analytically.

3.4.4 Effect of Temperature

The asphalt concrete mixes are temperature sensitive materials. The properties of the material may range from being a linear elastic material at lower temperature to viscoelastoplastic material at higher temperature. As the current testing facility is an in-situ tester, the prevailing temperature at the time of testing would have a significant effect on the results. The effect of temperature has to be investigated. Previous studies (e.g. Meyer 1978) suggested that a temperature shift curve could be developed for asphalt concrete mixes to correct the results with respect to temperature. The effect of temperature would be investigated through the experimental program by testing the same asphalt concrete mix at different prevailing temperature.

3.5 Summary

In this Chapter, a detailed overview of the InSiSST facility, including the data acquisition and interpretation, was presented. A discussion of the different variables affecting the results obtained using the InSiSST was also discussed. Based on the discussion presented in this chapter, the following issues and problems were identified

- The actual strain rate during in-situ testing might not be constant, affecting the actual relationship between the angular displacement and the recorded torque. The effect of the actual strain rate on the material parameters calculated based on the collected data will be investigated through both the analytical modelling and the experimental program
- A number of different variables affecting the material parameters during field testing such as the temperature, the diameter of the steel plate used during testing, and the nominal

motor speed during loading, were identified. The effect of temperature and the diameter of the steel plate will be investigated through the experimental program, while the effect of the loading speed will be investigated through the analytical modelling in relation with the viscoelastic properties of the asphalt concrete mix.

In the following chapter, the problem of applying a forced angular displacement to the surface of a half space, better known as the Reissner-Sagoci problem, will be investigated and modelling the asphalt concrete mix under the prescribed loading conditions will be analysed.

CHAPTER 4

4 THEORETICAL INVESTIGATION

4.1 The Reissner-Sagoci Problem

The problem of applying a torsional moment to the surface of a half-space is known in the literature under the name of *The Reissner-Sagoci Problem* (RSP), as Reissner and Sagoci (1944) were the first to address this problem in the 1940's. In this problem, a torque is applied to the surface of the half space through forcing a circular area of the surface to rotate about an axis passing through its centre and normal to the surface of the half space, as shown in Figure 4.1. Figure 4.2 shows the co-ordinate system and the non-vanishing stresses. They showed that in this case, and using the cylindrical co-ordinates (r, θ, z) the only non-vanishing stresses are the two shear stresses $\tau_{z\theta}$ and $\tau_{r\theta}$. They showed that these non-vanishing stresses are a function of the shear modulus, G , and the circumferential displacement u_θ such that:

$$[4.1] \quad \tau_{z\theta} = G \frac{\partial u_\theta}{\partial z}$$

$$[4.2] \quad \tau_{r\theta} = G \left(\frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r} \right)$$

Figure 4.1: Applying a Torsion to a Circular Area on the Surface of a Half Space

The RSP is a mixed boundary value problem, such that the displacement is defined on one section of the boundary while the stress is defined on the other. The general boundary conditions for this problem are that the displacement inside the loaded circular area on the surface is a function of the radius and time, and that the area on the surface outside the loaded area is stress free, such that

$$[4.3] \quad u_{\theta} = f(r, t) \quad 0 \leq r \leq a \quad \text{and} \quad z=0$$

$$[4.4] \quad \tau_{z\theta} = 0 \quad r > a \quad \text{and} \quad z=0$$

In their paper, Reissner and Sagoci proposed a mathematical solution for the static case using the oblate spheroidal co-ordinates to model the stress field in a linear elastic isotropic and homogeneous half space under a static torque. Sagoci (1944) extended the solution to the dynamic problem. However, both of these solutions were rather cumbersome and difficult to use.

Figure 4.2: Co-ordinate system and stresses

Sneddon (1947) was the first to introduce an effective solution for the RSP. He solved the static problem using the Hankel transform, which reduced the problem to a pair of dual integrals that have already been solved in the literature. The approach used by Sneddon was utilised by a number of researchers who were able to solve the problem for a number of variations, including the application of the torque to a layer fully bonded to the half space, the application of the torque to a cylinder, in addition to a wide variety of material properties.

Yi-Yuan Yu (1954) was able to find the response of a half space and of a layer to a specified torsional stress applied over a circular region. Bycroft (1956) obtained an approximate solution of a number of dynamic problems. Ufliand (cited in Collins 1962) setup the dual integral equations of the static RSP for an elastic layer of finite thickness, which were reduced to a Fredholm equation of the second kind and solved them numerically. Collins (1962) was able to define an explicit relationship between the torque and the rotation for the same problem. In 1966, Sneddon revised his solution for the static RSP for a half space and presented a simple solution based on his elementary solution of the dual integral equation.

Other researchers considered the RSP for an inclusion in the half space. Luco (1976) considered a rigid rod embedded in an elastic layer of a finite thickness, which is fully bonded to a half space. Dhaliwal et al (1979) solved the static RSP for a semi infinite elastic cylinder embedded in an elastic half space, and in then he considered the torsion of a hemisphere embedded in a half space (Dhaliwal et al 1981).

The investigation of the RSP problem for non-homogeneous media started in the early 1970's. The main approach to address the problem was to assume a specific mathematical expression for the shear modulus and then solve the original boundary value problem. As an example, Kassir (1970) introduced a solution for a half space of shear modulus varying as a function of depth, such that $G = az^b$, where a and b are constants. Singh (1972) considered the case where the shear modulus varies as a function of the radius, such that $G = ar^b$. Chuaprasert and Kassir (1973) analysed the half space, with a shear modulus in the form of $G = a(1 + z/b)^c$. George (1976) considered a semi-infinite cylinder with a shear modulus varying exponentially, such that $G = ae^{-br}$. Selvadurai et al (1986) considered a half space with $G = G_1 + G_2e^{-az}$, where G_1 and G_2 are constants, thus assuming that the shear modulus would have a value as z approached infinity.

A number of researchers addressed the problem of the transversely isotropic half spaces. Selvadurai (1980) considered the torsional rotation of a embedded disc. Erguven (1982) solved the RSP when assuming the variation of the constants as a power function. He then addressed the problem of a transevrelly isotropic layer bonded to a transversely isotropic half space (Erguven 1986). Hanson (1996) gave an explicit solution for a transversely isotropic half space.

4.2 Linear Elastic Solution

A brief account of the linear elastic solution is presented. It is a combination of the work of a number of researchers who used the different approaches to address the RSP for a linear elastic isotropic material. The problem is formulated using Equations [4.1] through [4.4], where the following equation must be satisfied

$$[4.5] \quad \frac{\partial^2 u_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r^2} + \frac{\partial^2 u_\theta}{\partial z^2} = \frac{\gamma}{G} \frac{\partial^2 u_\theta}{\partial t^2}$$

where γ is the unit mass of the half space material. A traditional approach to solving this kind of partial differential equations is to use the Hankel transform to reduce this equation into a simpler form that can be solved more easily. The Hankel transform is used to remove one of the variables from the original equation to facilitate its solution. Consequently, using the inverse Hankel transform, an explicit solution for the stress field can be obtained. The transformation is carried out by introducing a corresponding variable, $\bar{u}_\theta$, as a function of the original variable, u_θ , by multiplying a kernel, in this case the kernel is $rJ_1(r\zeta)$, and integration from zero to infinity such that:

$$[4.6] \quad \bar{u}_\theta = \int_0^\infty r u_\theta J_1(r\zeta) dr ,$$

where $J_1(r\zeta)$ is the Bessel Function of the first order and ζ is the transformation variable. On transforming Equation [4.5], the variable r would be removed from the equation and the resulting equation would be

$$[4.7] \quad \left(\frac{\gamma}{G} \frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial z^2} + \zeta^2 \right) \bar{u}_\theta = 0$$

Once the solution for the previous equation is obtained, and $\bar{u}_\theta(z, t, \zeta)$ is evaluated, the original variable, u_θ , can be evaluated using an inverse Hankel transform, such that:

$$[4.8] \quad u_\theta = \int_0^\infty \zeta \bar{u}_\theta(z, t, \zeta) J_1(r\zeta) d\zeta$$

Substituting Equation [4.8] into the boundary value Equations [4.3] and [4.4], then,

$$[4.9] \quad \int_0^\infty \zeta \bar{u}_\theta(0, t, \zeta) J_1(r\zeta) d\zeta = f(r, t) \quad 0 \leq r \leq a$$

$$[4.10] \quad \int_0^\infty \zeta \frac{\partial \bar{u}_\theta(0, t, \zeta)}{\partial z} J_1(r\zeta) d\zeta = 0 \quad r > a$$

In case of the static loading, the function $f(r, t)$ would be a function of r only and $\partial/\partial t$ would equal to zero. Equation [4.7] is reduced to an ordinary differential equation, with the solution:

$$[4.11] \quad \bar{u}_\theta = A(\zeta) e^{-\zeta z} + B(\zeta) e^{\zeta z}$$

Since u_θ , and subsequently, $\bar{u}_\theta$ tend to zero as z tends to ∞ , then the function $B(\zeta)$ has to equal to zero. This would reduce Equations [4.9] and [4.10] to the dual integral equations:

$$[4.12] \quad \int_0^\infty \zeta A(\zeta) J_1(r\zeta) d\zeta = f(r) \quad 0 \leq r \leq a$$

$$[4.13] \quad \int_0^\infty \zeta^2 A(\zeta) J_1(r\zeta) d\zeta = 0 \quad r > a$$

These two equations can be reduced to the Fredholm dual integral equations of the second type and solved (Sneddon 1966). If the forced angular displacement at $0 \leq r \leq a$ was a linear function in r , such that $f(r) = \Phi r$, a simple form of the solution for the displacement and stress fields can be presented at any point (r, z) in the half space under static loading (Hanson and Puja 1997), such that:

$$[4.14] \quad u_{\theta} = \frac{4\Phi r}{\pi} \left(\frac{1}{2} \sin^{-1} \left(\frac{C_1}{r} \right) + \frac{C_1 \sqrt{r^2 - C_1^2}}{2r^2} \right)$$

$$[4.15] \quad \tau_{r\theta} = -\frac{4G\Phi}{\pi} \left(\frac{C_1^2 \sqrt{a^2 - C_1^2}}{r (C_2^2 - C_1^2)} \right)$$

$$[4.16] \quad \tau_{z\theta} = -\frac{4G\Phi}{\pi} \left(\frac{C_1^3 \sqrt{a^2 - C_1^2}}{r^2 (C_2^2 - C_1^2)} \right)$$

where $C_1 = \frac{1}{2} \left(\sqrt{(r+a)^2 + z^2} - \sqrt{(r-a)^2 + z^2} \right)$, and

$$C_2 = \frac{1}{2} \left(\sqrt{(r+a)^2 + z^2} + \sqrt{(r-a)^2 + z^2} \right)$$

The torque, T , required to cause the angle of twist, Φ , can be calculated by integrating the shear stress, $\tau_{z\theta}$, at the surface over the loaded area, as shown in Equation

$$[4.17] \quad T = \int_{\theta=0}^{2\pi} \int_{r=0}^a \tau_{z\theta}(r,0) \cdot dr \cdot d\theta = \frac{16}{3} G \Phi a^3$$

4.3 Modelling the Asphalt Concrete Material under the InSiSST Loading Conditions

The InSiSST facility uses the same loading pattern described by the Reissner-Sagoci problem, such that a steel plate fastened to the asphalt concrete mix surface is forced to rotate about an axis normal to the surface, forcing a circular area of the surface of the mix to rotate. The linear elastic solution cannot be used to evaluate the displacement field and the stress field in the pavement material for the following reasons:

- The asphalt concrete mix can exhibit some viscous properties, especially at higher temperatures. In such case, the shear modulus, G , is not constant and changes with time

depending on the loading history. Consequently, as a minimum, a linear viscoelastic model should be assumed, and the shear modulus would be a function of time, t , and should be considered as a variable in the solution

- The output angular velocity from the motor and gearbox combination in the existing testing facility can be controlled to have a maximum value of only 0.223-rpm. This loading rate is rather low, and considering the viscoelastic properties of the asphalt concrete mix, the time variable has to be considered in the function defining the boundary conditions $f(r,t)$.
- The capacity of the current facility is not high enough to ensure a constant strain rate loading. Although this assumption was considered at the early stages of the analysis, in-situ testing showed that loading rate might not be constant depending on the asphalt concrete mix.

The function $f(r,t)$ and the viscoelastic formulation of the asphalt concrete mix would be discussed in the following sections.

4.3.1 Loading Function

As mentioned earlier in Section 3.2, the angular displacement during the load application using the InSiSST is not linear with time, depending on the strength of the pavement material being tested. Thus the assumption of a constant strain rate loading might not be a valid assumption, as the loading function would change from one testing location to the other.

Figure 3.4 shows a sample of the actual strain rate observed during testing. Subsequently, to analyse the asphalt concrete mix under the effect of the InSiSST, the relationship between the angular displacement and time should be mathematically modelled. The model shown in Equation [4.18] was capable of modelling the actual angular

displacement (up to time t_3 as shown in Figure 3.1) with a coefficient of determination (R^2) of up to 98%. The general form of the loading function such that:

$$[4.18] \quad f(r,t) = a.t.e^{b.(t-c)}$$

where a , b , and c are constants and t is the time step. The selected function can represent any form of the loading function similar to the displacement functions shown in Figure 3.3, by changing the constants in the equation. Obviously, the linear relationship between the time and angular displacement, the constant strain rate loading case, can be modelled by setting the constant b to zero.

4.3.2 Viscoelastic Material Properties

The asphalt concrete material is not a linear elastic material, although it has been traditionally modelled as so in the literature. The properties of the asphalt concrete mix can range from being linear elastic, at low temperatures and high strain rate, to viscoelastoplastic material at higher temperatures and lower strain rates. The condition at which the asphalt concrete mix is currently being modelled involves moderate temperatures and a moderate strain rate. However, the loading stage at which the material is being modelled is at the earlier stages of loading, prior to the failure of the sample.

Due to the fact that the strain rate applied is not high enough compared to typical values of the relaxation time of the asphalt concrete mix, the material would exhibit some viscous behaviour and the material model should consider such behaviour. On the other hand, since the early and moderate stages of the loading are modelled prior to reaching the plastic zone and failure of the sample, the plastic deformation would not be considered in the analysis. Consequently, the material would be modelled as a viscoelastic material.

(a) Applied Constant

(b) Elastic

(c) Viscous

(d) Viscoelastic

Figure 4.3: Strain Response for Elastic, Viscous and Viscoelastic Materials

Viscoelastic materials, generally, exhibit an increase in strain under a sustained stress, or a relaxation of stress under sustained strains. Figure 4.3 shows the difference in the behaviour of linear elastic, viscous and viscoelastic materials under the effect of a sustained stress over a period of time. In general, for a viscoelastic material, the shear modulus decreases with time, and the different models used in the literature differ in the form the mathematical relationship between the shear modulus and time is represented. The time dependant component of the elastic strain was modelled by a number of researchers through different mathematical models. Haddock et al. (1994) used a logarithmic function to describe this relationship. Bittiato et al. (1978) used a power function. Henrikson (1984) used an exponential function, while Fernando et al. (1997) used a parabolic function. Theoretically, any of these functions could be used to model the viscoelastic relationship between the stress and strain, as long as the time component is present in the function.

For the purpose of modelling the asphalt concrete mix, a generalized exponential model could be used, such that at any time t , the shear modulus G_t would be:

$$[4.19] \quad G_t = G_0 + G_1 e^{-\frac{t}{\lambda}}$$

where G_0 is the shear modulus at time $t = \infty$, G_1 is a constant and λ is the relaxation time. The relaxation time is defined as the ratio between the viscosity and elasticity of a material. The exponential model was used as it provides a simpler mathematical presentation for the mathematical derivation. Figure 4.4 shows the variation of the shear modulus G_t with time.

Figure 4.4: Variation of the shear stiffness with time for a Viscoelastic Material

4.3.3 Problem Formulation

Using Equations [4.18] and [4.19] to formulate the problem would result in the following set of equations

$$[4.20] \quad \tau_{tz\theta} = G_t \frac{\partial u_{t\theta}}{\partial z}$$

$$[4.21] \quad \tau_{tr\theta} = G_t \left(\frac{\partial u_{t\theta}}{\partial r} - \frac{u_{t\theta}}{r} \right)$$

Subject to the boundary conditions:

$$[4.22] \quad u_{t\theta} = a.t.e^{b.(t-c)} \quad 0 \leq r \leq a \quad \text{and} \quad z=0$$

$$[4.23] \quad \tau_{tz\theta} = 0 \quad r > a \quad \text{and} \quad z=0$$

Equation [4.7] in the case of the viscoelastic formulation still holds. However, in this case, the shear modulus, G , would be presented by Equation [4.19]. On substituting into the boundary value Equations [4.3] and [4.4], then,

$$[4.24] \quad \int_0^{\infty} \zeta \bar{u}_\theta(0, t, \zeta) J_1(r\zeta) d\zeta = a.t.e^{b.(t-c)} \quad 0 \leq r \leq a$$

$$[4.25] \quad \int_0^{\infty} \zeta \frac{\partial \bar{u}_\theta(0, t, \zeta)}{\partial z} J_1(r\zeta) d\zeta = 0 \quad r > a$$

The mixed boundary value problem can not be directly solved using the previously described techniques, and the solution might not be a closed form solution. Consequently, another approach would be adopted for defining the displacement and stress fields in the half space. A numerical approach using the Finite Element Method (FEM) was used to solve the problem on time steps such that at each time step the boundary conditions, the shear modulus and solution of the previous time step are considered in the analysis.

4.4 Summary

In this chapter, the theoretical background and the previous work completed by a number of researchers for solving the problem of applying a forced angular displacement to a circular area on the surface of a half space, better known in the literature as the Reissner-Sagoci problem (RSP), was presented. The solution for the linear elastic material properties was then presented.

The loading conditions as prescribed by the InSiSST facility are similar to the RSP. Subsequently, the same formulation of the RSP was used to model the stresses and strains in the asphalt concrete mix under the effect of the InSiSST. However, due to the viscoelastic properties of the asphalt concrete mix and the actual strain rate during loading, the boundary value problem was not solved using mathematical methods, and a numerical approach using the FEM was adopted. The next chapter describes the development, validation and results of the analysis using the FEM.

CHAPTER 5

5 FINITE ELEMENT MODELLING

This Chapter describes the development, validation, and analysis results of the Finite Element Model (FEM) used for the analytical investigation of the behaviour of the asphalt concrete mixes under the loading conditions prescribed by the InSiSST facility. As presented in Chapter 4, the development of a mathematical closed form solution to define the stress and displacement fields for this problem is a complex task. The complexity arises from the introduction of the time variable to account for the viscoelastic properties of the asphalt concrete mix and the characteristics of the load application, as prescribed during in-situ testing. Furthermore, the change in the geometry during testing may be large enough to invalidate the assumption of small strains. Subsequently, the large displacement assumption has to be considered in the analysis, to investigate the effect of such assumption on the analysis results.

A numerical approach was used in the analysis, where a FEM was developed and solved with the following objectives:

- Investigation the effect of the variation in the loading function, as described by Equation [4.18] in Chapter 4 and Figure 3.3 in Chapter 3 on the shear stiffness calculated using the torque and angular displacement.
- Studying the effects of the viscoelastic properties of the asphalt concrete mix on the calculated shear stiffness.

5.1 Model Development

The FEM is designed to investigate the behaviour of the asphalt concrete material under the loading conditions prescribed by the InSiSST facility during field testing. The model is developed and solved using the COSMOS-M[®] software package (Cosmos 1999). In developing the model, the geometry of the asphalt concrete pavement, the material properties of the asphalt concrete mix, and the variability in the loading pattern as prescribed by the InSiSST are considered. The following subsections describe the development of the FEM in terms of the geometry, boundary conditions, loading pattern and material properties.

5.1.1 Model Geometry

The asphalt concrete pavement is constructed as a layered structure over an infinite subgrade. The thickness of each layer is generally very small compared to its horizontal dimensions. As a result, the pavement structure can be considered as a number of layers with infinite horizontal dimensions and width finite thickness resting over an infinite half space. In a cylindrical co-ordinate system, the geometry of the problem is considered to extend infinitely in the r -direction, with an infinite depth in the positive z -direction.

To accommodate the unlimited boundaries in the horizontal plane, an extended model with relatively large dimensions and fully restrained edges was used. The dimensions of the model are set large enough such that the actual displacements and stresses near the edge of the model would be negligible compared to the displacements and stresses near the loaded area. Subsequently, the FEM should have a cylindrical shape, such that the forced displacement is prescribed over a circular area near the centre of the cylinder, while the sides and the bottom face of the cylinder are totally fixed.

To accommodate the layered nature of the pavement structure, a number of layers each defined by different material properties and a finite thickness were considered in the

preliminary stages of the analysis. The top layer in the model represents the asphalt concrete material, where the loading is applied, while the other layers represent the other base and subbase layers. The bottom most layer representing the subgrade has a relatively large thickness such that the actual displacements and stresses near the edge of the model would be negligible compared to the displacements and stresses near the loaded area. However, it was noted that the loading pattern, as prescribed by the InSiSST, results in a localized stress concentration near the edges of the loaded area and that the stresses and displacements in the half space dampen quickly along the depth from the surface and practically vanish beyond a relatively small depth. Figure 5.1 shows the shear stress $\tau_{z\theta}$ in an r - z plane and as can be noted, the stresses are almost negligible at a relatively small depth.

Trial models were used to determine the dimensions of the FEM and it was found that when the thickness of the top layer was more than or equal to the diameter of the loaded area, the effect of the bottom layers was negligible. Furthermore, full restraint of the lower surface of the FEM did not affect the stress distribution and values if the vertical dimension of the model was equal to one-and-a-half the diameter of the loaded area.

Figure 5.1: Shear Stress Distribution in an r - z Plane

Figure 5.2: FEM Geometry and Boundary Conditions

Based on the previous discussion, the resulting FEM was selected as a cylindrically shaped structure with a diameter 10 times the diameter of the central loaded area and height one-and-a-half times the diameter of the loaded area. The loaded area is a circularly shaped area at the centre of the top surface of the cylinder. Assuming the diameter of the loaded area to be 0.1-m, the FEM will have a diameter of 1.0-m and a height of 0.15-m. Figure 5.2 shows the model geometry and the imposed boundary conditions.

5.1.2 Selection of Elements

The model geometry described in the previous section is a three-dimensional geometry consisting of one homogeneous material. A three-dimensional 8-node brick element was selected for the analysis. The dimensions of the elements were varied according to their proximity to the loaded area, where the elements closer to the loaded area generally had smaller dimensions than those near the edges of the FEM.

The brick element requires extra carefulness during meshing, such that the aspect ratio of the different elements would not affect the accuracy of the analysis. An aspect ratio of unity is optimal from the standpoint of solution accuracy and equation conditioning. However, aspect ratios from 10 to 100 are not uncommon in the pavement literature (Hjelmstad 1997). Consequently, while varying the dimensions of the elements, the aspect ratio of these elements was kept as near to unity as possible, especially near the loading zone where the variation of the aspect ratio might significantly affect the resulting displacements and stresses. Typically, the largest aspect ratios are found in the remote regions of the finite element mesh, where their effect is practically negligible.

The dimensions, number of elements, and configuration of the finite element mesh were selected after running a number of trial models and going through a number of iterations for mesh refinement. The final configuration provided the optimum balance between the number of elements and the accuracy of the results.

Figure 5.3: Finite Element Mesh

It should be noted that a 20-node brick element was used in a number of the trial models. However, the 20-node brick element did not provide much improvement to accuracy of the results and significantly increased the solution time. The final model used for the analysis had 1380 elements with 1662 nodes. Figure 5.3 shows the finite element mesh used in the analysis.

5.1.3 Material Properties

The asphalt concrete mix is modelled in the FEM as a linear viscoelastic material. The FEM model was initially solved using a linear elastic material and the linear viscoelastic material model was later introduced in the model. The linear elastic material model is used to validate the FEM against the linear elastic mathematical solution available in the literature, while the viscoelastic material model is used to investigate the variation in the shear stiffness evaluated using the InSiSST facility due to the variation in the viscous properties of the asphalt concrete mix.

The linear elastic material model is fully defined using the elastic modulus and Poisson's ratio, while the viscoelastic behaviour of the material requires defining the temporal variation in the material properties. The material model used in the analysis is the generalized Maxwell model, which is available in the material library in the COSMOS-M[®] software to model the viscoelastic material behaviour. The generalized Maxwell model is shown in Figure 5.4. The material model is defined using an elastic spring and a series of Maxwell units arranged in parallel. As a minimum, one Maxwell unit has to be used in the model to represent the viscoelastic component of the material behaviour, but any number of additional Maxwell units can be used to describe more complex viscoelastic material behaviour. The material model and the material parameters are related as shown using Equations [5.1] through [5.3].

Figure 5.4: Generalized Maxwell Model as defined by COSMOS Program

$$[5.1] \quad G_i = G_o g_i$$

$$[5.2] \quad \eta_i = G_i \lambda_i^G$$

$$[5.3] \quad G_t = G_o \left(1 - \sum_{i=1}^n g_i \left(1 - e^{-\frac{t}{\lambda_i^G}} \right) \right)$$

where G_o is the initial shear modulus, G_t is the shear modulus at time t , G_i , η_i and λ_i are the i^{th} shear modulus, viscosity and relaxation time, respectively.

Each Maxwell unit has an elastic component and a viscous component. The elastic component is defined in terms of the shear modulus, while the viscous component is defined in terms of the viscosity or relaxation time. The elastic and viscous components are defined in the FEM as expressed in Equations [5.1] and [5.2], respectively. Equation [5.3] defines the overall shear modulus used in the analysis as a function of time and Figure 5.5 shows the variation of the shear modulus by time for a given set of g_i and λ_i . It should be noted that if g_i is set to zero, the model is reduced to a fully elastic model having its shear modulus equal to the initial shear modulus, G_o .

Figure 5.5: Variation of Shear Modulus with Time as Modelled in the FEM

5.1.4 Loading and Analysis Control

The loading as prescribed by the InSiSST is simulated in the FEM by applying a forced angular displacement over the loaded area. The in-situ loading is applied using a rigid steel plate. Subsequently, the angular displacement along the radius of the loaded area in the FEM is constant. As shown by Equation [4.17] in Chapter 4, the total torque is the integration of the shear stresses $\tau_{z\theta}$ on the surface of the half space under the loading plate. However, as the FEM are discrete analysis method and the stress values are defined at the nodes only, the torque is calculated by numerically integrating the shear stress over the loaded area, using the Simpson's rule.

The viscoelastic analysis is carried out through time steps controlled through a time curve defined as an input for the FEM analysis. At each time step, the material properties and the stiffness matrix are recalculated and used, together with the results of the previous time step, in the analysis until a solution is reached through a number of iterations. The Newton-Raphson iteration technique is utilized in the analysis to converge to a solution. If a solution

could not be reached, the time step is reduced and the analysis is repeated until the analysis converge to a solution.

The time curve defines the relationship between the prescribed displacement and analysis time. The actual strain rate from the in-situ testing can be simulated in the FEM analysis by appropriately defining the time curve. As an example, the different strain rate shown in Figure 3.4, in Chapter 3, can be simulated in the analysis using the time curve.

5.2 Model Verification - Linear Elastic Solution

The FEM was solved using linear elastic material properties to verify the geometry, boundary conditions and analysis results against the linear elastic mathematical solution available in the literature. The two main outputs from the FEM used to verify the model were the displacement at the surface outside of the loaded area and the shear stress $\tau_{z\theta}$ directly beneath the loaded area. The displacement at the surface ($z=0$) and outside the loaded area ($r > a$) is calculated using Equation [4.14], while the shear stress $\tau_{z\theta}$ is calculated using Equation [4.16].

The displacement results from both methods, the FEM and the mathematical closed form solution, agreed very closely. The error in the displacement values outside of the loaded area was very small. However, due to the fully restraint edges, the error increased as the distance from the loaded area increased. The error at a distance of $r=0.17$ -m, where the circumferential displacement was equal to 1% of the prescribed displacement at the edge of the loaded area, was 15%. This was deemed an acceptable error considering the relatively small displacement at such distance. Figure 5.6 shows the displacement results from the FEM and the mathematical solution versus radial distance from the loaded area.

Figure 5.6: Displacement Results for the Mathematical Model and the FEM at $z=0$

The results of the shear stress $\tau_{z\theta}$ from both methods were also very highly correlated. The error in the shear stress was very small near the centre and increased to approximately 10% at a radius 44-mm, where the radius of the loaded area is 50-mm. It should be noted that the gradual increase in the error was expected, since the analytical model in Equation [4.16] is not defined at $r = a$. Thus the calculated stress approaches infinity as r approaches a , while the FEM simulation produces finite values over the entire model. However, the FEM gave a very high stress value along the radius. Figure 5.7 shows a comparison between the shear stress $\tau_{z\theta}$ results from the FEM and the mathematical solution at various points along the radius under the loaded area.

The results shown in Figure 5.6 and Figure 5.7 suggest that the selected model geometry, imposed boundary conditions and the load application procedures can be used for further analysis as they simulate the actual conditions of the idealized mathematical model.

Figure 5.7: Stress Results for the Mathematical Model and the FEM at $z=0$

5.3 Modelling the InSiSST Loading Conditions

The FEM developed and validated in the previous sections is used to model the asphalt concrete mix under the effect of the InSiSST facility. Actual data from in-situ testing was used as input for the analysis. The torque and the angular displacement are recorded over time during in-situ testing, where the torque-displacement relationship is then defined. If the angular displacement is not recorded, the strain rate is assumed constant and the angular displacement is calculated using Equation 3.2 in Chapter 3. However, the actual strain rate can significantly vary depending on the pavement condition, as shown in Figure 3.4 in Chapter 3. Furthermore, at higher temperatures, the viscoelastic properties of the asphalt concrete mix are more prevalent and can significantly affect the measured shear stiffness. Consequently, analyses were performed to study the sensitivity of the evaluated shear

stiffness to the variation in the actual strain rate and to investigate the effect of the viscoelastic material properties on the actual shear stiffness.

It should be noted that the in-situ testing data interpretation differs from the FEM analysis results. During in-situ testing, torque and angular displacement are recorded over time and used to calculate the shear stiffness of the asphalt concrete mix. However, during FEM analysis, the angular displacement and the shear stiffness are pre-defined and the analysis results are used to calculate the torque as the integration of the surface shear stress $\tau_{z\theta}$ over the loaded area.

5.3.1 FEM Calibration

The output data from one of the in-situ tests was used for calibrating the FEM model. The data shown in Figure 5.8 is the corrected torque recorded over time during one of the in-situ tests. The loading steel plate used in that particular test was 125-mm and the pavement temperature during testing was 10°C. The total loading time (t_3) was 3.4-s and maximum torque was achieved at 2.6-s (t_2), and was recorded at 830-Nm. The angular displacement was not recorded during this test. However, assuming a constant strain rate, the shear stiffness can be calculated using Equation [4.17] in Chapter 4, where it was found to be 40-Nm.

To calibrate the FEM, the shear stiffness measured from the in-situ testing and the angular displacement as a function of time, assuming a constant strain rate, were used to solve the FEM. The torque was calculated using the shear stresses at time 2.6-s and was found to be 830-Nm, which demonstrate that the developed FEM was successfully able to model the loading conditions.

Figure 5.8: Actual Loading Function for the Testing Facility

5.3.2 Effect of Actual Strain Rate on Measured Shear Stiffness

The linear elastic material model, considering the large displacement assumption, is used in the sensitivity analysis to investigate the variation in the measurement of the shear stiffness of the asphalt concrete mix as a result of the variation in the actual strain rate during in-situ testing. The viscoelastic model was not used in this investigation, as the viscous component of the material behaviour is constant in the different analysis runs, as the failure in all cases occurs at the same pre-determined time step. Subsequently, the linear elastic material model was deemed sufficient. However, the closed form mathematical solution for the linear elastic material is not suitable to be used in this case as the failure angle might be large, such that the small displacement assumption in the mathematical solution might be invalidated.

In this analysis, the torque data shown in Figure 5.8 is used in the FEM analysis. The total loading time used in the analysis was 3.4-s, which corresponds to a total angular

displacement of 0.079-rad (4.5°), as calculated using Equation [3.2]. The maximum torque and the failure of the sample occurred at 2.6-s, where the maximum torque was 830-Nm. The relationship between the angular displacement and time was assumed to vary according to Equation [4.22] in Chapter 4, where the constants a , b , and c were adjusted to model different strain rate functions used in the analysis. Figure 5.9 shows the different functions used in the analysis. These strain rates were selected such that the actual angular displacement at failure represented a percentage of the angular displacement at failure, assuming a constant strain rate. The percentages used in the analysis are 100% (the constant strain rate), 67%, 33%, 15%, and 5% of the total angular displacement (t_2).

Each strain rate was solved for five different shear stiffness values. Using each shear stiffness value, the torque was calculated at the time step corresponding to the 2.6-s failure time. For each strain rate function, the shear stiffness corresponding to the 830-Nm torque was calculated by interpolation along the five points analysis results curve.

Figure 5.9: Variation of Displacement by Time during Loading

Figure 5.10 shows the relationship between the actual angle at failure and the shear stiffness, such that in all cases, the torque at failure was the prescribed 830-Nm. As expected from the mathematical model, the higher shear stiffness of the material would result in a smaller angular displacement at failure. A reduction of the angular displacement by 67% (from 0.3-rad to 0.1-rad) resulted in an increase in the shear stiffness by 190% (from 40-MPa to 116-MPa).

The large displacement assumption did not seem to have a significant effect on the analysis results. According to the mathematical model, which uses a small displacement approximation, a reduction in the angular displacement at failure of 67% is expected to result in an increase of the measured shear stiffness by 210%.

The previous results show the high sensitivity of the calculated shear stiffness to the accurate measurement of the angular displacement. However, at higher temperature, where the angular displacement at failure is high, this accurate measurement of the angular displacement at failure did not seem to have a significant effect on the shear stiffness.

Figure 5.10: Variation of the Shear Stiffness by Angular Displacement

5.3.3 Effects Viscoelastic Material Properties on In-Situ Shear Stiffness

The asphalt concrete mixes can be generally described as viscoelastic materials at most service conditions (Zaghloul and White 1993). Subsequently, the viscoelastic material properties were introduced in the FEM analysis to evaluate the effect of such properties on the in-situ shear stiffness. The viscoelastic material properties used in the analysis were based on previous work documented in the literature (Huang 1993, Zaghloul and White 1993). The viscoelastic material models shown in Figure 5.11 were used in the FEM analysis to investigate the effect of the viscoelastic properties on the torque measurements recorded over time during in-situ testing, where each material model is represented using the variation in the shear stiffness over time under constant loading conditions. The variables defining each of these models are shown in Table 5.1. The range covered by these models represents the asphalt concrete viscoelastic properties over a large range of service conditions.

Figure 5.11: Viscoelastic Material Profiles

Table 5.1: Viscoelastic Profiles for the FEM Analysis

	Elastic	VE-1	VE-2	VE-3	VE-4
G_o	1850	1850	1700	1550	1400
g	0.1	0.2	0.3	0.45	0.6
τ	100	1.5	1	0.9	0.8

Figure 5.12 shows the resulting torque-displacement relationship for each of the viscoelastic material models shown in Figure 5.11. It should be noted that the maximum torque occurs at 2.6-s (t_2) and the FEM does not model the failure of the pavement. Subsequently, the results are shown only up to time t_2 . The FEM analysis results shows that the viscoelastic properties significantly affect the measured torque values over time. The higher the effect of the viscous properties of the material, the lower the maximum torque required to fail the asphalt concrete mixture. It can be noted that as the viscous properties of the asphalt concrete mix become more prevalent, the relationship between the torque and the angular displacement ceases to be linear.

Figure 5.12: Effect of Viscous Properties on the Measured Torque

5.3.4 Relationship between the Viscous Properties and the Total Loading Time

The previous discussion showed that the viscous properties of the asphalt concrete mix during in-situ testing significantly affects the shear stiffness measured using the InSiSST. However, the effect of the viscous properties has to be investigated considering the relationship between the total loading time (t_3) for the in-situ testing and the relaxation time (τ) of the asphalt concrete mix. If the total loading time is much less than the relaxation time, the viscous properties are not expected to have a significant effect on the measured shear stiffness. However, if the total loading time were much greater than the relaxation time of the mix, the viscous properties would significantly affect the results.

The FEM analysis was carried out to investigate the effect of the relationship between the total loading time and the relaxation time on the analysis results. The torque data shown in Figure 5.8 was again used in analysis, considering constant strain rate loading conditions. The total loading time considered in the analysis was 3.4-s and the viscoelastic material profiles used in the analysis is shown in Table 5.2, where the percentages shown in the represents the ratio between the total loading time and the relaxation time of the material.

Figure 5.13 shows the effect of the relationship between the loading time and the relaxation time of the material on the torque-displacement relationship for the in-situ testing results. Each of the curves shown in the figure represents the viscoelastic analysis results for the corresponding viscoelastic material profile shown in Table 5.2.

Table 5.2: Viscoelastic Profiles for the Relaxation Time Analysis

t_3/τ	50%	100%	200%	400%	800%
G_o	1650	1650	1650	1650	1650
g	0.6	0.6	0.6	0.6	0.6
τ	1.7	3.4	6.8	13.6	27.2

Figure 5.13: Effect of the Relaxation time on the Torque-displacement Relationship

The FEM analysis results shows that when the loading time was less than the relaxation time of the material, the viscous properties effects on the analysis were almost negligible and the relationship between the torque and the angular displacement in this case was linear. However, at slower loading rates, where the loading time is a multiple of the relaxation time, the viscoelastic properties became more prevalent and the relationship between the torque and angular displacement becomes non-linear. Furthermore, as the ratio between the total loading time and the relaxation time of the asphalt concrete mixes increases, the torque required for failing the sample decreases.

The asphalt concrete mixes can be generally described as viscoelastic materials at most service conditions. The observed relationship between the torque and the angular displacement obtained for the majority of the field testing samples was non-linear indicating the significant effects of the viscous properties of the asphalt concrete mixes on the analysis results and that the total loading time was much higher than the relaxation time of the

material. Figure 3.5 in Chapter 3 shows a typical example of the relationship between the torque and angular displacement obtained from in-situ testing using the InSiSST. The current capacity of the InSiSST facility and its current configuration that provides limited loading rates causes the testing conditions for the majority of the in-situ test samples to fall in the zone where the viscous properties of the asphalt concrete mix will significantly affect the evaluation of the shear stiffness of the asphalt concrete mix.

5.4 Summary

In this chapter, a three-dimensional Finite Element Model (FEM) was developed and analysed to investigate the behaviour of the asphalt concrete mixes under the loading conditions prescribed during in-situ testing using the InSiSST facility. The model was first solved using a linear elastic material model to validate its accuracy against the mathematical solution and to investigate the sensitivity of the shear stiffness measurements to the actual strain rate during in-situ testing. A linear viscoelastic material model was then introduced to the FEM analysis to investigate the effect of the viscous properties on the shear stiffness measured using the InSiSST facility.

The large displacement assumption was used in the sensitivity analysis to investigate the variation in the measurement of the shear stiffness of the asphalt concrete mix as a result of the variation in the actual strain rate during in-situ testing. The analysis 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. At constant strain rate loading conditions, the effect of the large displacement becomes more prevalent, while the sensitivity to the actual angular displacement at failure decreases. As the strain rate becomes non-linear, the shear stiffness becomes more sensitive to the variation in the actual angular displacement at failure. Subsequently, 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.

The viscoelastic properties were found to have a significant effect on the shear stiffness of the asphalt concrete mixes. As the viscous properties of the mix become more prevalent, the torque required to fail the sample decreases and the relationship between the torque and angular displacement becomes non-linear. The effect of the strain rate was again examined in terms of the relationship between the total loading time during in-situ testing and the relaxation time of the asphalt concrete mix. It was shown that if the total loading time were less than or equal to the relaxation time of the asphalt concrete mix, the measured shear stiffness would not be affected by the viscous properties of the mix.

The observed relationship between the torque and the angular displacement obtained for the majority of the field testing samples was non-linear indicating the effects of the viscous properties of the asphalt concrete mixes on the results of analysis. It also shows that the total loading time was much higher than the relaxation time of the material. The capacity of the InSiSST facility and its current configuration that provides limited loading rates causes the testing conditions for the majority of the in-situ test samples to fall in the zone where the viscous properties of the asphalt concrete mix would affect the evaluation of the shear stiffness of the asphalt concrete mix.

CHAPTER 6

6 EXPERIMENTAL INVESTIGATION

The experimental investigation includes in-situ testing of a number of asphalt pavement sections with different asphalt concrete surface mixes, and laboratory testing on core samples recovered from the some of the pavement sections tested during the in-situ testing. The experimental investigation was designed to achieve the following objectives:

- Investigating the correlation between in-situ measured shear properties using the InSiSST and laboratory evaluated material properties of asphalt concrete.
- Identifying the material property, from either the in-situ or the laboratory that best correlates with the field rutting of pavement sections.
- Investigating the effect of temperature and the steel plate diameter used for the testing on the in-situ shear properties.
- Investigating the relationship between field rutting of asphalt pavement sections and the in-situ shear properties of the asphalt concrete mixture.
- Investigating the actual strain rate during in-situ testing and its effect on the calculated shear stiffness.

All the in-situ testing was completed using the InSiSST facility, while the laboratory testing was completed on cores recovered from the tested field sections. The core samples were extracted from the field and transported to the laboratory for testing. No laboratory-fabricated samples were used in the testing program, to ensure the consistency between the field and laboratory testing results.

The in-situ testing program was completed on Carleton University campus and on the Long Term Pavement Performance (LTPP) test site, near Petawawa, Ontario. Testing in the Carleton University campus was completed on two different asphalt concrete sections with different asphalt concrete mixtures properties, while the testing on the LTPP site was carried out on six different asphalt concrete sections, where these sections had identical cross sections, but different asphalt concrete surface layer.

Testing on Carleton University campus was carried out over a long period of time and was mainly looking at the different factors affecting the InSiSST facility testing results, such as the effect of the temperature, plate diameter, and the strain rate. The correlation between the field and laboratory testing results, in addition to the relationship between the rutting performance and the shear properties of the asphalt concrete mixtures was addressed through the in-situ testing of the six test sections at the LTPP site.

6.1 In-Situ Testing on Carleton University Campus

Two different asphalt pavement sections were tested on Carleton University campus. The first section, 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 kg/m^3 . Table shows the aggregate gradation details of the HL3 mix.

Carleton-1 section has been in-service since 1992 and the pavement surface is intact with almost no visible surface distresses. It 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 asphalt concrete mixture on the surface of the pavement, which is the tested layer, is aged and rather stiff.

The second pavement section, Section Carleton-2, to be tested on campus is a test section that was constructed specifically for the testing and validation of the InSiSST facility. The section is 3.0-m wide by 10.0-m long and was constructed using a standard Ontario HL3 85/100 mix, where the asphalt concrete layer thickness was 100-mm. The section was poorly compacted, with an average in-situ density of 2.06 kg/m^3 , to provide a rather weak asphalt concrete mixture. The purpose of having a weak asphalt concrete mix is to have different mixtures of varying strengths when validating the in-situ testing facility.

6.1.1 In-Situ Testing on Section Carleton-1

Several sets of in-situ testing were completed on this pavement section. The main objective of testing on this section was to investigate the effect of the variation in the prevailing temperature on the properties of the asphalt concrete mixture. Testing was completed at different temperature. However, there was not 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 due to errors in the data acquisition system. The results of each set of tests were summarised and the weather conditions were recorded. Table 6.1 shows a summary of the number of tests and the weather conditions during testing.

Table 6.1: Weather Condition during In-Situ testing on Section Carleton-1

Test set	Date	# of Samples	Weather Conditions	Air Temperature (°C)	Pavement Temperature (°C)
1	Jul 31, 2000	7	Sunny	24	28
2	Aug 4, 2000	5	Sunny	26	35
3	Aug 25, 2000	4	Sunny	24	31
4	Nov 25, 2000	3	Overcast	2	5
5	Sep 15, 2001	4	Sunny	18	22
6	Aug 1, 2002	4	Sunny	32	44

6.1.2 In-Situ Testing on Section Carleton-2

The asphalt concrete mixture in this section was tested to investigate the effect the plate size on the test results. The steel plate diameters used for testing were 75-mm, 100-mm, 125mm and 150-mm. For each plate size, the sample size averaged from 3 to 5 tests. However, due to a number of different conditions, the actual number of samples tested was sometimes less than the number planned. Table 6.2 shows the number of samples actually tested this pavement section for each plate diameter and the average pavement temperature during testing.

It can be noted from the table that sometimes not all the diameters were presented; while in other cases the number of samples was different from one plate size to the other. The reason is that in-situ testing required a long period of time; it was sometimes not possible to complete all the planned sections in one session. This also resulted in the variation of the prevailing temperature during testing. Consequently, in-situ testing on this section was completed at different temperatures. This provided the opportunity of assessing the effect of the temperature on the results of the InSiSST. However, sometimes not all the required samples were tested.

Table 6.2: In-Situ Tests on Section Carleton-2

Steel Plate Diameter (mm)	Average Temperature (°C)				
	6	8	22	28	44
75	5	5	1	-	-
100	5	5	3	-	-
125	-	-	4	4	3
150	4	4	3	-	1

6.2 In-Situ Testing at the LTPP Test Site in Petawawa

Test sections at an in-service Long Term Pavement Performance (LTPP) test site were tested as part of the experimental testing program. The LTPP project has started in 1987 by the Strategic Highway Research Program (SHRP) as part of the National Research Council. As part of the LTPP studies, the FHWA and state and provincial departments of transportation are collecting data from more than 2,400 pavement test sections in North America. The data are being collected in a database known as the LTPP National Information Management System (NIMS). The database includes data for the monitored environmental conditions, traffic, inventory, performance, maintenance, materials, and rehabilitation for each test section. The LTPP project has two main types of studies; General Purpose Studies (GPS) and Specific Purpose Studies (SPS). The SPS-9A study is a specific study in the LTPP program for the validation of the SHRP asphalt specifications and mix design (SuperPave). Any SPS-9 testing site includes a number of adjacent test sections with identical pavement structures however the surface layer in each section was designed using different mix design procedures. Consequently, as all other variables are the same for all sections, any variation in performance would be attributed to the performance of the asphalt concrete mix.

As part of the experimental program, The test sections at the SPS-9A LTPP test site 870900 near Petawawa, Ontario was tested in the summer 2000. The SPS-9A test sites include six adjacent test sections. The test site was constructed in April 1997 and is composed of three core sections, sections 870901 through 870903, and three supplemental sections, sections 870960 through 870962, with a total of six adjacent sections.

Table 6.3 shows the properties of the asphalt concrete mixes used as the top layers for the six test sections on the LTPP site, while Table 6.4 shows the as-built results for the different test sections as measured during the quality control inspection. It is worth noting.

However, the all of the sections are a part of a controlled experiment and were constructed using high quality materials. Consequently, given that these sections are relatively new, it is expected variation of the test results might not be significantly high.

A typical LTPP test section is 150-m in length, with an approach and a leave section with varying lengths. The central 150-m section is where the yearly performance data are collected and no coring is allowed within. The approach and leave were constructed with the same structural properties of the central stretch are reserved for coring and other destructive testing. The In-situ testing was completed on an approximately 60-m on either the approach or the leave stretches.

Table 6.3: Petawawa SPS-9A LTPP Test Sections 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 6.4: As-Built Properties of Asphalt Concrete Mixes at the LTPP Test Section

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

* Bulk Relative Density (kg/m^3)

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

Testing was carried out using 100-mm diameter steel plates. The air temperature during the testing period ranged between 27°C and 32°C, and the pavement temperature ranged between 33°C and 39°C. Five tests per section were deemed adequate as a sample size; however, seven tests were taken at each test section to compensate for any errors during testing. Five of the seven samples done using the InSiSST were along the lane centre line. The pavement material in the lane centre line is the least trafficked pavement across the lane and it would provide the nearest approximation to the pavement properties just after construction.

6.3 In-Situ Evaluation of the Effect of Strain Rate

The InSiSST facility was originally designed to apply a forced angular displacement to the surface of the asphalt concrete surface at a constant rate, thus providing a constant strain rate loading conditions. However, visual observations during in-situ testing showed that the actual strain rate might not be constant. Furthermore, the sensitivity analysis using the FEM analysis showed that the actual strain rate has a significant effect on the material properties calculated using the InSiSST measured torque. Although this was observed at later stages of this research, it was essential for the completion of the study objectives to further investigate the actual strain rate during in-situ testing.

The InSiSST facility was designed such that the rate of the angular displacement can be controlled during testing. In its current configuration, the maximum rate of angular displacement, or strain rate, that can be applied is 0.233 rpm. This rate is not very fast. However, the failure of the pavement in this case requires between 2-s and 5-s. The total time during which the test is completed is, in most case, less than 8-s. Consequently, manually measuring the angular displacement with time is not feasible. To overcome this problem, it was suggested to record the entire testing process using a digital video camera, where the

testing process would then be downloaded to a computer and viewed at a much lower speed. This would allow the recording of the angular displacement at time intervals as small as 0.033-s.

The setup used in the field to record the actual angular displacement during testing and the data compilation process to link the measured torque measurements to the recorded angular displacement, in addition to the experimental program are presented in the following subsections.

6.3.1 Angular Displacement Recording

A steel pointer was customized to the required length and painted with a bright colour to be visible during the video recording. This steel pointer was taped to the steel plate to and used over the scale taped to the pavement surface, such that as the steel plate moves, the pointer would move on the scale and the angular displacement can be measured at point in time. Figure 6.1 shows the scale used and the steel pointer taped to the steel plate surface. The scale was plotted on a white sheet of paper. A circle defining the centre of the scale and the location of the steel plate was also plotted, where it was removed, such that the scale would fit in the required location to ensure the correct alignment of the scale, steel plate and the pointer. The scale had plotted to allow the measurement of the angle with a 0.5-s accuracy. Increasing the accuracy of the scale was not possible, given the size of the steel frame of the InSiSST.

A digital video camera was used to record the testing procedure. The camera was placed on a tripod above the InSiSST facility during testing to allow for a normal line of sight for recording the movement of the pointer over the graduated scale. Figure 6.2 and Figure 6.3 show the position of the camera the setup used for recording the angular displacement.

Figure 6.1: Steel Pointer and Scale for Measuring the Angle

Figure 6.2: Position of the Camera for Recording the Angular Displacement

Figure 6.3: Set-up for Recording the Angular Displacement

6.3.2 Data Interpretation

The recorded data were transferred to the computer in the form of a movie clip and the entire testing process was viewed as images, frame-by-frame, to record the angular displacement with time. The software had the capability of showing 30 frame per second, which enabled the recording of the angular displacement with time with an accuracy of 0.033-s. Figure 6.4 shows the torque and angular displacement against time for a sample tests.

Figure 6.4: In-Situ Testing Torque and Angular Displacement Data

As can be noted from the figure, the rate of loading was not linear, which will result in a non-linear relationship between the torque and the angular displacement. The recorded torque values and the angular displacement readings are corrected for the irregularities at the beginning of the test. The torque values are corrected as described earlier in Chapter 3. The angular displacement is corrected by shifting the readings to start at the point of intersection of the corrected torque tangent with the horizontal axis and subtracting this small shift value from all the subsequent angular displacement values.

The torque and the corresponding angular displacement are then cross-referenced, using the time steps, to plot the torque-displacement relationship. Figure 6.5 shows this relationship for the previously presented data. It should be noted that the torque and the angular displacement are measured separately and then cross-referenced. This might result in some inaccuracy when defining the exact start of the torque data as compared to the exact start of the angular displacement measurements.

Figure 6.5: Torque-Angular Displacement Relationship

6.3.3 Field Verification of the Actual Strain Rate

Measuring the angular displacement using the video recording was not always available during in-situ testing. Furthermore, the video recording compilation to determine the angular displacement with time is a rather time consuming process, such that it would not be practical to use it for a large-scale testing program. Subsequently, this technique was used in a limited number of in-situ tests on Carleton University Campus to verify the actual strain rate during loading and investigate specific variables.

The objectives of these in-situ tests are to examine the actual strain rate and its effect on the calculated shear stiffness, to investigate the effect of the steel plate diameter on the calculated shear stiffness, to investigate the epoxy failure tests, and to investigate the effect of the boundary conditions on the actual strain rate.

Table 6.5: In-Situ Testing for Field Verification

Test set	Number of samples	Plate Diameter (mm)	Pavement Section	Pavement Temperature (°C)	Test Type	Failure Type
1	3	125	Carleton-1	44	Flush	Pavement
2	3	125	Carleton-2	44	Flush	Pavement
3	3	100	Carleton-1	40	Flush	Epoxy
4	3	100	Carleton-1	30	Partially cored	Pavement

As can be noted, some of these objectives have been previously addressed. However, in this experimental program they will be addressed in terms of the actual angular displacement rather than assuming constant strain rate loading conditions, which might not be true in some cases. Testing was carried out on the test sections on Carleton University campus. Both section, Carleton-1 and Carleton-2, were tested. Table 6.5 shows the sections tested and the number of tests per section

Investigating the Actual Strain Rate

The actual strain rate is examined through the first set of in-situ tests. Three tests, using 125-mm steel plates, are completed on section Carleton-1. This section was tested earlier to evaluate the effect of temperature on the asphalt concrete mix properties. Section Carleton-2 was tested using the same steel plate diameter and at the same temperature to evaluate the effect of the strength of the asphalt concrete mix on the actual strain rate. As mentioned earlier, the asphalt concrete mix is section Carleton-2 was very weak as it was not compacted.

Investigating the Data from Epoxy Failure Samples

In some cases, during the in-situ testing, failure sometimes happened between the epoxy and the steel plate, rather than in the actual pavement material. This failure was attributed to the cleanliness of the steel plate and to improper mixing of the epoxy. However, it was assumed that the recorded data prior to failure could be used to evaluate the shear

stiffness of the asphalt concrete mix. A third set of testing was carried out to investigate this hypothesis. Four tests were completed using 100-mm steel plates, where the failure happened between the epoxy and the steel plate rather than in the actual pavement. The data recorded prior to the failure are then compared to data from samples that failed in the pavement to evaluate whether the asphalt concrete mix properties calculated from the samples, where the failure happened between the steel plate and the epoxy, is consistent with the properties calculated from the samples that failed in the pavement or not.

Investigating the Effect of Boundary Condition on the Actual Strain Rate

All the in-situ testing done throughout this experimental program has been done such that the steel plate was fastened to the surface of the pavement. Consequently, the pavement is considered to be a half space with infinite dimensions in the horizontal direction and the positive vertical direction. However, this set of testing was completed by partially coring the pavement section before placing the steel plate on the surface of the pavement. Figure 6.6 shows a schematic of the test setup.

As can be noted from the figure, the asphalt concrete layer is partially cored to a specific height that is less than the total thickness of the layer. The torque is applied to the surface of the asphalt concrete and the tested sample is a cylinder, rather than a half space. In this case, the Reissner Sagoci approach cannot be used to calculate the shear properties of the pavement and Equations [6.3] and [6.4] in Chapter 6 should be used instead. However, since the same asphalt concrete mixture was tested, the shear properties calculated from this approach should be similar to the properties evaluated through the flush testing.

Figure 6.6: Schematic of the Partial Coring Test

6.4 Laboratory Testing

Six core samples were collected from each of the LTPP test section, in addition to the Carleton-2 test section and transported to the Civil and Environmental Laboratory at Carleton University for testing. All cores samples were 100-mm in diameter. The objectives of the laboratory testing was: (a) to evaluate a fundamental material property, such as the resilient modulus, for the different mixes, (b) to determine laboratory shear properties of the mixes, and (c) to investigate the correlation between the laboratory evaluated resilient modulus and shear properties of the asphalt concrete mixes, with the field results and rutting of these mixes. The cores were taken from locations in the proximity of the locations where the shear testing were carried out, along the lane centreline.

Laboratory testing included torsion on asphalt concrete samples to evaluate the shear properties of the pavement and diametrical resilient modulus testing to determine a resilient modulus of the pavement cores. Table 6.6 shows the number of cores for each of the

laboratory tests. Non-destructive resilient modulus testing was performed on three samples from each set, while direct torsion testing was completed on all five samples to determine the shear strength and shear stiffness of the mix. It should be noted that the asphalt concrete mix of the Carleton-2 section was rather weak and the resilient modulus testing on them was not possible, as they failed under the small repetitive loading.

Table 6.6: Laboratory Testing for Cores Recovered from Test Sections

Test Section	Measurements and Densities	Indirect Tensile Test	Resilient Modulus Test	Torsion Test
870901	6	1	3	5
870902	6	1	3	5
870903	6	1	3	5
870960	6	1	3	5
870961	6	1	3	5
870962	6	1	3	5
Carleton-2	6	-	-	5

6.4.1 Indirect Tensile and Diametrical Resilient Modulus Testing

The diametrical compression test also known as the indirect tensile test or the Brazilian test was developed in the 1940's. This test is widely used to determine the material properties of materials such as asphalt pavements and Portland cement concrete. The cylindrical specimen is subjected to a compressive load along a diametrical plane, resulting in a nearly uniform tensile stress over a significant portion of the loaded plane (Thaulaw 1957). This test is widely accepted due to its simplicity and the well-developed theoretical solutions for the stresses and strains for an elastic material. The presence of a uniform tension in the middle section of the specimen, resembling the tension at the bottom of the surface layer in flexible pavement has gained the indirect tensile test wide acceptance (Zhang 1997).

The diametrical test was further developed to routinely test the asphalt pavement materials and to simulate the traffic induced repeated loading by subjecting the specimen to

repeated pulse/rate (ASTM 1987; SHRP 1993). Asphalt concrete cylindrical cores are subjected to a non-destructive load to determine its elastic parameters. Modulus of Elasticity, traditionally known as the Resilient Modulus (M_R) in the pavement literature, and Poisson's ratio are determined. During the test the asphalt concrete cylindrical samples are subjected to cyclic vertical loading along a diametrical plane. The load used ranges between 10% and 50% of the load required failing the sample in a standard indirect tensile test. The lower end of the load, near 10%, is usually used in to determine the resilient modulus, while the higher values are used to determine the fatigue life of the mix.

The laboratory testing was carried out according to standard test method for indirect tension test for resilient modulus of bituminous mixtures (ASTM D 4123-82). However, testing was completed at only one temperature and using one frequency. The core samples were tested at room temperature (20°C) and at 0.33-Hz loading frequency. The resilient modulus represents the average ratio between the constant stress and the maximum strain for the loading cycles recorded with stable resilient deformations. The resilient modulus can be calculated using the following equations

$$[6.1] \quad M_R = \frac{P(\mu + 0.27)}{t\delta_h}$$

$$[6.2] \quad \mu = -3.59 \frac{\delta_h}{\delta_v} - 0.27$$

where P is the vertical load, μ is Poisson's ratio, t is the sample height, δ_h is the dynamic stable horizontal deformation and δ_v is the dynamic stable vertical deformation.

One core sample was tested in an indirect tensile test to determine the ultimate load needed to fail the sample P_{ult} and three cores were then subjected to the non-destructive resilient modulus test. The load used in the resilient modulus testing was 0.1 P_{ult} . The tested cores were then used in the torsion testing.

The objective of determining the resilient modulus of the recovered asphalt concrete cores was to determine a material property that has been used widely in the literature to determine the quality of the asphalt concrete mixes. However, in a recent study, Mostafa (2001) has shown that the correlation between the resilient modulus of the asphalt concrete and the laboratory shear properties was relatively weak. This is expected as the load application during measuring the resilient modulus results in tensile stresses, which mainly address the binder strength properties rather than the mix properties.

6.4.2 Laboratory Torsion Testing

Asphalt concrete cylindrical cores would be subjected to a torsion test to determine the shear strength and shear stiffness. For a cylinder of height L and radius r , the maximum shear stress or the shear strength and the shear stiffness can be determine using the following formulae (Higdon et al 1990)

$$[6.3] \quad \tau_{max} = \frac{T.r}{J}$$

$$[6.4] \quad G = \frac{T.L}{J.\Phi}$$

where T is the torque, J is the polar moment of inertia and Φ is the angle of twist. The objective of using the torsion test is to determine laboratory shear properties of the asphalt concrete mix. The laboratory determined properties would be correlated to the field-determined indices and the long-term performance of the pavement mixes.

The torsion test is not a standard ASTM test for asphalt concrete mixes. Sosa (1986) used hollow asphalt concrete sample in an oscillatory torsion test to determine the asphalt mix properties. Zahw (1995) applied torsion to solid asphalt cylinders to determine the shear properties. As mentioned earlier, the results obtained by Zahw showed a high correlation

between the shear stiffness and rutting. The same approach used by Zahw would be utilised in the proposed study.

Torsion test would be carried out using the same facility used in the field. Testing was completed at room temperature (20°C), using a custom made assembly. The gearbox and the motor controller together with the data acquisition system were assembled on a fixed steel setup in the laboratory. Utilizing the same gearbox and the motor control used in the in-situ testing for the laboratory testing ensures that the testing speed and data acquisition for both the in-situ testing and laboratory testing are similar.

6.5 Summary

In this chapter, the experimental program planned and carried out in this thesis was described. The program included both in-situ testing using the InSiSST and laboratory testing to determine the resilient modulus and shear properties.

In-situ testing was carried on Carleton University Campus and at an LTPP test site. On Carleton University Campus, two asphalt concrete pavement sections were tested. Sections Carleton-1 was had a stiff surface asphalt concrete layer, while sections Carleton-2 was deliberately poorly compacted to provide a weak asphalt concrete mix. The objective of the field-testing on Carleton University campus is to investigate the effect of different variables on the field measurements using the InSiSST facility.

Six similar pavement sections, with different asphalt pavement surface mix at the SPS-9A 870900 LTPP site near Petawawa, Ontario were tested using the InSiSST. The objective of testing was to investigate the relationship between the in-situ shear properties of the asphalt concrete mixes against the rutting performance for these sections. Laboratory testing was completed on core samples recovered from the six LTPP test section, in addition to cores from sections Carleton-2. Laboratory testing includes resilient modulus testing and

torsion testing. The results and data analysis of the experimental program for both the field and the laboratory testing are presented in Chapter 7.

CHAPTER 7

7 EXPERIMENTAL PROGRAM RESULTS AND DATA

ANALYSIS

The data collected during the experimental investigation for both the in-situ testing and the laboratory testing programs are analysed and presented in this chapter. The rutting data collected from the SPS-9A test sections are also presented and the investigation of the relationship between the rutting in these sections and the shear stiffness of the asphalt concrete surface mix is presented.

As mentioned earlier, the angular displacement, in most cases, was not measured during testing. Subsequently, in interpreting the data for the samples where the angular displacement was not recorded, it was assumed that relationship between the applied angular displacement and time was linear, that is loading was under constant strain rate conditions.

The analysis of the data includes performance of the statistical significance test for the different data sets with the objective of examining the hypothesis that the mean shear stiffness evaluated for different test sections were different. A bivariate analysis is then used to identify the asphalt concrete property that most correlates with the rutting results from the field and finally a regression analysis model is developed to represent the relationship between the shear properties of the asphalt concrete mixes and rutting of the pavement sections.

7.1 In-Situ Testing On Carleton University Campus

As described in Section 6.1, in-situ testing was completed using the InSiSST facility on Carleton University campus on two different asphalt pavement sections. The torque data were collected through the torque cell. However, the angular displacement was calculated, assuming a constant strain rate loading, as the video recoding facilities at the time of completing these tests were not available. The absence of actual measurements of the angular displacement will affect the accuracy of calculation of the material properties of the different asphalt concrete mixes. However, as will be shown later, this should not affect the ranking of the mixes. The different material properties described in Section 3.2 are calculated and presented. The summaries of the results, in terms of the mean and the coefficient of variation (CoV) are presented.

7.1.1 Results of In-Situ Testing on Section Carleton-1

In-situ testing on Section Carleton-1 was performed in late July, August, late November 2000, September 2001, and August 2002. Testing was carried out to examine the InSiSST facility ability to evaluate the in-situ material properties of the asphalt concrete mixtures. As the testing was carried out on the same asphalt concrete mix using the same testing procedures and loading rate, the results were used to investigate the effect of temperature on the measured shear stiffness of asphalt concrete mix.

All tests were done using a 100-mm diameter steel plate. In some cases the failure of the sample happened between the epoxy and the steel plate, as described in Section 3.3.2. The reason for the failure in the bonding between the epoxy and the steel plate was attributed to the smooth and/or greasy surface of the steel plates, which substantially decreased the cohesion between the epoxy and the steel plate. Although the failure did not happen in the pavement, the results obtained from the test were used to calculate the initial shear stiffness

(G_i) of the asphalt concrete mix, using Equation [3.3]. The results of the data validation testing, presented later in this Chapter, showed the data collected prior to failure can be used to calculate the initial shear stiffness of the asphalt concrete mix, albeit the failure happened between the steel plate and the epoxy. The initial shear stiffness was preferred over other calculated material properties as it allowed the inclusion of the samples that failed in the bond between the steel plate and the epoxy, in the analysis.

Table 7.1 summarises the results of these tests. The results of individual tests are presented in Appendix A. It should be noted that 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 $\pm 2^\circ\text{C}$.

Figure 7.1 shows the calculated initial shear stiffness versus the average temperature at which the tests were performed, for this particular asphalt concrete mix. Only six data points are available. However, a model was fitted to the data to model the variation in the shear stiffness with temperature. The variation of the asphalt concrete mix properties with temperature is well documented in the literature and the results obtained from this analysis shows that this variation can have a significant effect on the in-situ measurement of the shear stiffness. The temperature variation has to be accounted for using a temperature shift curve to adjust the in-situ measurement to a standard temperature. Temperature shift curves can be developed for the in-situ shear stiffness of the asphalt concrete mixes (Meyer 1978). However, the development of such curve requires a large-scale experimental program, which is beyond the scope of this thesis.

An exponential function was fitted to the results with a coefficient of determination (R^2) of 66%, which shows a relatively good correlation, given the high variability expected from the

asphalt concrete mix. The model had the form shown in Equation [7.1], where G is the shear stiffness, α is the temperature, and A and B are constants

$$[7.1] \quad G = Ae^{-B\alpha}$$

Table 7.1: Results of In-Situ Testing on the Old Section at Carleton University Section

Test Set	Sample size	Pavement Temperature (°C)	Initial Shear Stiffness (G_i)	
			Mean (MPa)	CoV (%)
1	7	28	19.46	10.2
2	5	35	14.43	27.2
3	4	31	17.18	29.1
4	3	5	50.89	13.8
5	4	22	41.05	18.7
6	4	44	19.0	13.1

Figure 7.1: Variation of Initial Shear Stiffness with Temperature

7.1.2 Results of In-Situ Testing on Section Carleton-2

The shear properties of the asphalt concrete mixture used in constructing the pavement section on Carleton University campus were evaluated using the InSiSST. The asphalt concrete mix in this section is a standard Ontario mix HL3. However, it was a weak mix as it was not properly compacted. This was an advantage, as it allowed for testing using larger sizes steel plates, to investigate the effect of such variation on the results.

Table 7.2 shows the results of the initial shear stiffness for the tests carried out using different plate size diameters at different temperature, for all the tests done using the InSiSST on section Carleton-2. The data shown in the table is the summary of the tested samples and the results of the individual tests are presented in Appendix B. The initial shear stiffness was selected as in some cases, failure did not occur in the asphalt concrete mix, such that the other parameters could not be calculated. For the smaller plates, the failure sometimes occurred at the interface between the steel plate and the epoxy, while for the larger plates the test was sometimes stopped before failure, as the torque required for failing the sample would be higher than the capacity of testing facility. In some cases, only one data point was valid within a set and subsequently no CoV was presented. It should be noted that the CoV's are relatively high due to the poor compaction of the pavement section, which may have resulted in a non-homogenous asphalt concrete mix.

Table 7.2: Shear Stiffness measured on Section Carleton-2

Steel Plate Diameter (mm)	Average Temperature (°C)									
	6		8		22		28		44	
	Mean (Mpa)	CoV (%)	Mean (Mpa)	CoV (%)	Mean (Mpa)	CoV (%)	Mean (Mpa)	CoV (%)	Mean (Mpa)	CoV (%)
75	74.88	21.8	58.74	21.7	20.42	-	-	-	-	-
100	45.80	8.3	48.17	23.3	16.22	46.9	-	-	-	-
125	-	-	-	-	8.01	22.7	12.98	28.3	2.43	50.3
150	13.18	10.7	13.98	21.7	8.50	7.5	-	-	1.30	-

Figure 7.2 shows the variation in the in-situ shear stiffness with the temperature for the different steel plate diameters. As can be noted from the graph, as the temperature decreases, the measured stiffness decreases, which is expected. An exponential trend line was fitted to the results having the form shown in Equation [7.1], with a coefficient of determination of 99%, 97%, 72% and 98% for the steel plate diameters of 75-mm, 100-mm, 125-mm and 150-mm, respectively.

The coefficients of determination were rather high due to the limited amount of data. However, the results shows a trend that would require further investigation through more testing. Also, it should be noted that the initial shear stiffness calculated using different plate diameters was significantly different, which was not expected, since the shear stiffness is a material property. This can be explained by the effect of the strain rate. The larger the steel plate, the higher the resistance of the material, which reduces the actual strain rate. This was further verified through in-situ testing.

Figure 7.2: Variation in the Shear Stiffness with Temperature and Plate Diameter

The results shown in the previous table might suggest that the size of the plate used for testing could influence the measured stiffness. However, field testing showed that this is not the case, and that the plate size does not affect the shear stiffness measurements when the actual angular displacement is recorded.

The apparent variability in the shear stiffness evaluated using different plate sizes can be attributed to the relatively limited capacity of the InSiSST facility in its current configuration. The results presented in Figure 7.2 are calculated assuming constant strain rate loading conditions. However, this assumption might not be correct, especially for larger plates. As the plate size increases, the total torque required to achieve a particular angular displacement increases significantly and the actual angular displacement at failure is significantly less than the angular displacement at failure calculated using the constant strain rate assumption. Figure 7.3 shows an example of variation of the angular displacement by steel plate diameter used during testing.

Figure 7.3: Variation of Angular Displacement with Plate Size

As can be noted from the figure, the larger the plate used during testing the smaller the actual angular displacement at failure. The shear stiffness is calculated using Equation [3.3] and since the angular displacement used to calculate the shear stiffness was calculated assuming a constant strain rate loading, which is larger than the actual angular displacement, the shear stiffness determined using the larger steel plates seemed to be significantly less.

7.2 Field Testing at the LTPP SPS-9A Test Section

In-situ testing was completed on the Specific Pavement Studies SPS-9A LTPP test site 870900 on highway 17 near Petawawa, Ontario in summer 2000. The sample size for each section was five samples, located along the lane centreline. Table 7.3 shows a summary of the in-situ shear properties of the different sections as evaluated during in-situ testing. The results of individual samples are presented in Appendix C. Again; the asphalt concrete mix properties for the different sections were calculated assuming a constant strain rate loading. The results presented are only of these of the samples in the lane centreline only. It is worth noting that all of the sections are a part of a controlled experiment and are constructed using high quality materials. Consequently, given that the sections are relatively new, it was not expected that variation of the test results would be high. However, as will be shown later, the difference between sections was statistically significant.

Testing was completed using 100-mm diameter steel plates. The air temperature during the testing period ranged between 27°C and 32°C and the pavement temperature ranged between 33°C and 39°C. Due to some hardware problems at the time, data points were recorded every 1.0-sec. However, this time interval was deemed sufficient to be used in the calculation of the shear stiffness.

Table 7.3: Summary of In-Situ Testing Results at the 870900 LTPP Test Site

Test Section	G_i (MPa)		τ_{av} (MPa)		Φ_{max} (Rad.)		τ_{max} (MPa)		G_s (MPa)	
	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV
870901	16.66	8.9	4.83	8.9	0.0781	6.5	1.34	12.7	15.11	15.1
870902	13.90	14.3	0.96	13.5	0.0797	10.9	0.99	16.2	14.75	19.2
870903	15.93	14.4	2.76	24.2	0.0744	3.9	1.15	20.0	13.42	5.3
870960	14.00	10.9	1.44	15.5	0.0638	13.6	0.89	19.1	12.30	8.9
870961	12.13	6.0	1.91	23.5	0.0549	17.1	0.67	20.9	11.53	10.9
870962	14.78	6.7	2.45	79.6	0.0625	18.1	0.92	13.0	13.37	13.9

7.3 Laboratory Testing

Core samples were collected from each of the SPS-9A test sections and from the new test section constructed on campus, to be tested at the Civil and Environmental Laboratory at Carleton University. Laboratory testing included resilient modulus testing and torsion testing on the asphalt concrete core samples recovered from the field. As mentioned in Section 6.3, non-destructive resilient modulus testing was performed on 3 samples from each set, while direct torsion testing was then done on all five samples to determine the shear stiffness and the other material properties described in Section 3.2. The mix used in the newly constructed pavement section was weak, such that the resilient modulus testing could not be done on the cores recovered from the section. Only torsion testing was carried out on these cores.

During torsion testing, the same strain rate used in the field was used for laboratory testing and the temperature was kept at room temperature (approximately 20°C). Table 7.4 shows the results of the resilient modulus testing and the torsion testing completed on the asphalt concrete samples. The results shown in the table shows that the asphalt concrete mix for the test sections constructed at Carleton University was weaker than the other test sections and also the average density of the cores taken from this section was less than the

Table 7.4: Summary of Laboratory Testing Results

Test Section	Density (kg/m ³)		M_R (MPa)		G_i (MPa)		τ_{av} (MPa)		Φ_{max} (Rad.)	
	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV
870901	2350	0.5	1332.5	27.0	242.8	15.4	5.21	10.5	0.0384	24.1
870902	2291	0.8	1443.9	21.3	165.0	25.1	2.75	34.0	0.0281	19.1
870903	2312	0.7	2469.6	15.8	250.4	12.8	4.76	11.6	0.0323	10.7
870960	2319	0.5	1288.1	35.1	271.4	16.2	3.68	19.9	0.0293	12.4
870961	2363	0.8	1144.3	3.2	172.4	35.3	3.42	20.9	0.0294	18.9
870962	2348	0.6	1248.5	46.6	146.7	21.7	2.52	20.5	0.0325	34.5
Carleton-2	2064	2.1	-	-	79.65	24.0	0.89	22.4	0.0302	6.4

density of the other sections. This is expected given that the Carleton-2 at Carleton University was poorly compacted to results in a rather weak asphalt concrete mix.

7.4 Rutting at the LTPP SPS-9A (870900) Test Site

Rutting data for the sections at the SPS-9A test site was collected from the National Information Management System (NIMS), LTPP database and from Ministry of Transportation Ontario (MTO) records. Rutting for the LTPP test sections is evaluated using the cross sectional profile. Cross sectional profile data is collected for the 150-m section at 11 locations at a 30-m spacing. The SPS-9A test site at Petawawa was constructed in 1997. Rutting data are available for the year 1997, immediately after construction, and for the years 2000 and 2001.

When calculating the rut depths, it was noticed that all sections had some rutting in the 1997 survey, just after construction. This rutting cannot be attributed to traffic loading but rather to construction quality. Consequently, using the absolute rutting values 3 years after construction as a performance indicator might be misleading. In some cases, rutting for a particular section at a given year was less than the previous year, which was unexpected.

Consequently, it was suggested to use three different rutting indices for the analysis. The first index is the rutting rate in mm/year. The rutting rate is the average annual rutting over time assuming a linear relationship between rutting and time. It is calculated as the slope of the best-fit straight line for the available data from each section. Thompson and Nauman (1993), and Archilla and Madanat (2000) used the rutting per load repetition rate to evaluate pavement performance. However, as the traffic loading for all the testing sections is identical, it should be acceptable to use the rutting rate as a function of time rather than traffic loading.

The second rutting index is the absolute accumulated rutting over the four years period of the life of the pavement sections, such that the initial rutting in 1997 is subtracted from the current rutting value. The third rutting index is, again, the accumulated rutting over the four years period of the life of the pavement however, assuming that the rutting would not decrease over time. Consequently, as rutting depth calculated for Section 870902 for the year 2001 was less than that of the year 2000, the rutting reading for the year 2001 was discarded. Table 7.5 shows the rutting values, rutting rate and the accumulated rutting for the different test sections, while Figure 7.4 shows the rut depth for the different pavement sections at the LTPP test site. It should be noted that the pavement sections are fairly new and in a good condition. Consequently, the measured rut depths were generally small.

Table 7.5: Rutting at the 870900 LTPP Test Site

Section	Rut Depth (mm)			Rutting rate (mm/year)	Accumulated rutting (mm)	Accumulated rutting (mm) [§]
	Sep-97	Oct-00	Oct-01			
870901	1.367	1.362	1.441	0.0135	0.074	0.074
870902	0.864	1.550	1.335	0.1371	0.471	0.687
870903	0.666	0.923	1.189	0.1161	0.523	0.523
870960	1.408	1.796	1.909	0.1214	0.501	0.501
870961	1.375	2.348	2.610	0.3003	1.235	1.235
870962	0.658	0.627	0.936	0.0499	0.278	0.278

§ Rutting was assumed not to decrease, 2001 reading for 870902 discarded

Figure 7.4: Rutting of the 870900 SPS-9A test sections

7.5 In-Situ Evaluation of the Effect of Strain Rate

The InSiSST was originally designed to provide constant strain rate loading. However, field observations showed that the strain rate might not be constant. Field validation of the strain rate, outlined in Section 6.4, was carried out and the results are presented in this section.

Table 7.6 shows the results of each of the tested samples previously outlined in Table 6.5 in chapter 6 for sections Carleton-1 and Carleton-2. To examine the effect of the actual strain rate, the collected data was interpreted once using the actual recorded angular displacement and another time assuming a constant strain rate loading. In the first interpretation, the actual angle at failure ($\Phi_{failure}$), the total angle until the constant residual torque from friction is reached (Φ_{max}), the initial shear stiffness (G_i), the secant shear stiffness based on the actual angle at failure ($G_{s(failure)}$), and the secant shear stiffness based on the total angle ($G_{s(max)}$) were calculated. The data was again interpreted using the constant strain

rate loading assumption to enable the comparison with other data collected in the experimental program. The angle at failure (ϕ), the initial shear stiffness (G_i) and the secant shear stiffness (G_s) are calculated for each test sample. The ratio between the angle at failure calculated using both methods is presented in the table as a percentage.

The data presented in Table 7.6 addresses a number of issues that needed to be investigated to fully interpret the InSiSST data. As can be noted, in most cases, ϕ_{max} calculated using the actual strain rate was very close in value to the angle at failure (ϕ) using the constant strain rate, which proves the assumption that the total angle at the time t_3 , as shown in Figure 3.2, is the same angle regardless of the actual strain rate. Furthermore, the secant shear stiffness calculated using the actual ϕ_{max} was, again, very close to the secant shear stiffness calculated using the constant strain rate assumption. The difference in the values is attributed to the fact that most calculations are done manually, which sometimes can cause the differences in some results.

The data in shown in Table 7.6 shows that when the constant strain rate assumption is used for the calculations, the initial shear stiffness (G_i) and the secant shear stiffness (G_s) are generally close in value, with G_s usually slightly less than G_i . The only test sample that does not follow the trends discussed in this section is test sample 1-1 in Set 1, which failed at a very high torque values compared to the other sample (given that the capacity of the torque cell is about 1300-Nm). Figure 7.5 shows the Torque-Time curve for the test sample of this set and sample 1-1 shows high non-linearity near failure.

Table 7.6: Field Verification of the Actual Strain Rate Results

Test Set	Test Type	Temp	Test Sample	T_{max}	Actual Strain Rate					Constant Strain rate			Angle Ratio (%)
					$\phi_{failure}$	ϕ_{max}	G_I	$G_{s(failure)}$	$G_{s(max)}$	ϕ	G_I	G_s	
1	Flush	44	1-1	1170.4	0.0204	0.0733	81.61	43.98	12.26	0.0908	14.31	9.90	22.5
			1-2	878.2	0.0274	0.0698	61.26	24.65	9.66	0.0639	11.32	9.20	42.8
			1-3	935.5	0.0217	0.0716	62.88	33.04	10.04	0.0700	10.63	10.27	31.1
			Mean	994.68	0.0232	0.0716	68.59	33.89	10.65	0.0749	12.09	9.79	32.1
			CoV	15.6	15.87	2.4	16.5	28.6	13.2	18.79	16.2	5.5	31.7
2	Flush	44	2-1	141.7	0.0478	0.0593	23.30	2.28	1.83	0.0575	2.66	1.89	83.1
			2-2	179.0	0.0288	0.0480	22.80	4.77	2.86	0.0465	4.26	2.95	61.9
			2-3	285.8	0.0410	0.0524	16.56	5.35	4.19	0.0481	6.30	4.56	85.2
			Mean	155.6	0.0392	0.0523	20.89	4.13	2.96	0.0507	4.41	3.14	76.7
			CoV	71.6	24.58	10.8	18.0	39.6	39.9	11.7	41.4	42.9	16.8
3	Flush	40	3-1		0.0091		93.74			0.0528	17.05		17.2
			3-2		0.0155		52.12			0.0469	21.80		33.1
			3-3		0.0094		96.01			0.0492	18.15		19.1
			Mean		0.0113		80.62			0.0496	19.00		23.2
			CoV		32.01		30.6			6.0	13.1		37.5
4	Partial coring	30	4-1	310.7	0.0480	0.0625	74.00	26.37		0.0625	27.47	20.26	76.8
			4-2	298.0	0.0486	0.0607	46.58	24.98		0.0607	30.91	19.92	80.0
			4-3	395.9	0.0321	0.0498	92.26	37.67		0.0498	37.61	32.36	64.4
			Mean	334.8	0.0429	0.0577	70.94	29.68		0.0577	32.00	24.18	73.8
			CoV	15.9	21.8	11.9	32.4	23.5		11.9	16.1	29.3	11.2

Figure 7.5: Torque-Time Curve for Set 1 Test Samples

7.5.1 Actual Strain Rate during Loading

As can be noted from the results in Table 7.6, the actual angular displacement at failure was significantly different than the angular displacement at failure calculated using the constant strain rate loading assumption. Failure happened at an angle that is significantly less than the calculated angle. However, this variation was not constant, as it varied depending on the asphalt concrete mix conditions. Set 1 test samples are from Carleton-1 test section, where the surface layer is a stiff asphalt concrete mix that has been in service for almost 10-years. The ratio between the actual angular displacement at failure to angular displacement calculated assuming a constant strain rate loading condition ranged from 22% to 43%. However, for results of the Set 2 test samples, which were carried out on the weak asphalt concrete mix in section Carleton-2, the ratio ranged from 62% to 85%. This can be visually

noted from Figure 7.6 and Figure 7.7, where the actual angular displacements recorded during the testing for Set 1 and Set 2 samples are shown, respectively.

The actual strain rate for the stronger asphalt concrete mix (Set 1) is less than the weaker pavement (Set 2). Furthermore, the maximum torque at failure for Set 1 test samples was significantly higher than the maximum torque at failure for Set 2 test samples. It should be noted however, that the term “strength” in this case is a general description of the asphalt concrete mix condition with respect to the capacity of the testing facility. It is expected that if the capacity of the testing facility was higher, the actual strain rate would be different. The data for each of the previously sets of samples were compiled to develop the actual Torque-Angular Displacement curves. Figure 7.8 and Figure 7.9 show these curves for Set 1 and set 2, respectively.

Figure 7.6: Recorded Angular Displacement for Set 1 Test Samples

Figure 7.7: Recorded Angular Displacement for Set 2 Test Samples

Figure 7.8: Torque-Displacement Relationship for Set 1 Samples

Figure 7.9: Torque-Displacement Relationship for Set 2 Test Samples

7.5.2 Results for Samples Failed at the Interface between the Epoxy and the Plate

As mentioned earlier, some samples failed at the interface between the steel plate and the epoxy rather than in the asphalt concrete layer. During data analysis for these samples, it was assumed that the resistance prior to failure is due to the shear resistance of the asphalt concrete and not the resistance of the epoxy. Subsequently, the data collected prior to failure could be used to calculate the asphalt concrete mix properties. This assumption was verified through the data validation testing, where set 3 had three samples that failed in the epoxy and the actual angular displacement was recorded.

Figure 7.10 through Figure 7.12 show the results for Set 3 test samples. The results shown in Table 7.6 for Set 3 test samples, shows that the initial shear stiffness of the samples are consistent with the data in data set 1, considering the slight differences due to the steel plate diameter used in the analysis and the slight difference in the pavement temperature.

Figure 7.10: Recorded Angular Displacement for Set 3 Samples

Figure 7.11: Recorded Torque for Set 3 Test Samples

Figure 7.12: Torque-Displacement Relationship for Set 3 Samples

7.5.3 Effect of Boundary Condition on the Strain Rate

All the in-situ testing done throughout this experimental program has been done such that the steel plate was fastened directly to the surface of the pavement. Subsequently, the pavement was considered to be a half space with infinite dimensions in the horizontal direction and the positive vertical direction. However, Set 4 samples were tested by first partially coring the asphalt concrete layer before placing the steel plate on the surface of the pavement, as shown in Figure 6.6 in Chapter 6.

In this case, the tested sample is a cylinder with a finite height and not a half space. However, since the shear stiffness is a fundamental material property, the testing method should not have any bearing on the results. The results of Set 4 test samples shown in Table 7.6. The pavement temperature during testing had an average of about 30°C, which is significantly less than the pavement temperatures at which Set 1 through Set 3 were tested. It

is not expected that the results of Set 4 will be similar to Set 1, given the difference in the pavement temperature during testing and the different boundary conditions between the two testing procedures. It should be noted that the partial coring resulted in a cylindrical test samples that is not completely fixed at the bottom. The material continuity between the partially cored cylinder and the remaining thickness of the asphalt layer would results in a slight movement at the base of the cylinder, which is not accounted for during the angular displacement measurements. However, considering these differences, the average shear stiffness values for Set 4 is comparable to the shear stiffness values for Set 1.

Figure 7.13 through Figure 7.15 show the results recorded for the samples in Set 4. As can be noted, the absence of lateral confinement due to coring has resulted in the angular displacement being almost linear with time, such that loading was at a constant strain rate. It should be noted also that the maximum torque recorded was significantly less than the maximum torque recorded for Set 1 test samples.

Figure 7.13: Recorded Angular Displacement for Set 4 Test Samples

Figure 7.14: Recorded Torque for Set 4 Test Samples

Figure 7.15: Torque-Angular Displacement Relationship for Set 4 Test Samples

7.6 Statistical Analysis

The previously presented in-situ and laboratory data are statistically analysed to evaluate the relationship between the different in-situ and laboratory measured material properties and rutting of the asphalt concrete mixes. Analysis of Variance (ANOVA) is performed on the data collected from both the in-situ and the laboratory testing to test the significance of variation in the collected data. The bivariate analysis technique is then used to identify the material property that most correlates with rutting. The selected material property is then used in a regression analysis with the selected rutting index to develop a preliminary relationship between rutting of the asphalt concrete mix and its shear properties.

7.6.1 Analysis of Variance (ANOVA)

The results shown in Table 7.3 and Table 7.4, for the in-situ and laboratory test sections were generally close and the difference of the means between the sections might appear to be statistically insignificant. Subsequently, the ANOVA analysis was carried out to test the hypothesis that the means of different sections are statistically different. In this case, the null hypothesis would be that the mean value of a particular material property for a specific section comes from the same population of the other sections; that is the difference in the means is not statistically significant. In this case, the null hypothesis is set as $H_0: \mu_{870901} = \mu_{870902} = \mu_{870903} = \mu_{870960} = \mu_{870961} = \mu_{870962}$, where μ_{870901} , μ_{870902} , μ_{870903} , μ_{870960} , μ_{870961} and μ_{870962} are the mean values of any material property for the respective sections.

At a specific confidence level, $1-\alpha$, the null hypothesis is rejected if the calculated F-static is greater than the F-critical calculated at α and the statistical degrees of freedom for the treatments, or number of sections, and the total error in the tests. A confidence level of 95% was selected to test the null hypothesis for the field and laboratory results. The results of the ANOVA analysis are shown in Table 7.7.

Table 7.7: ANOVA Analysis for Field and Laboratory Testing Results

		Source of Variation	SS	df	MS	F-static	P-value	F-critical	Null Hypothesis
In-Situ Testing Results	Shear Stiffness	Section	64.95	5	12.99	6.2846	0.0007	2.6207	Rejected
		Error	49.61	24	2.07				
		Total	114.56	29					
	Maximum Strain	Section	0.0025	5	4.94E-04	7.7615	0.0002	2.6207	Rejected
		Error	0.0015	24	6.36E-05				
		Total	0.0040	29					
	Average Strength	Section	1.342	5	0.268	10.1101	2.65E-05	2.6207	Rejected
		Error	0.637	24	0.027				
		Total	1.979	29					
Laboratory Testing Results	Shear Stiffness	Section	69741.0	5	13948.2	7.7514	0.0002	2.6207	Rejected
		Error	43186.7	24	1799.4				
		Total	112927.6	29					
	Maximum Strain	Section	0.0003	5	6.98E-05	1.4146	0.2547	2.6207	Accepted
		Error	0.0012	24	4.93E-05				
		Total	0.0015	29					
	Average Strength	Section	7.19	5	1.44	12.3529	5.34E-06	2.6207	Rejected
		Error	2.80	24	0.12				
		Total	9.99	29					
	Resilient Modulus	Section	3615126	5	723025.1	4.7130	0.0130	3.1059	Rejected
		Error	1840919	12	153409.9				
		Total	5456045	17					

The null hypothesis is rejected if $F\text{-static} > F\text{-critical}$

As can be noted from the results, the null hypothesis was rejected for all the test results, with the exception of the maximum strain for the laboratory test results. This means that all the other tests, or calculated results, the differences in the means are statistically significant, which imply that both the in-situ testing and laboratory testing results are able to identify and differentiate between different asphalt concrete mixes.

7.6.2 Bivariate Analysis

Bivariate analysis was performed to examine the correlation between the rutting indices, as criterion variables and the different indices calculated from the field and the laboratory, as

predictor variables. The bivariate correlation coefficients were computed for each pair of variables, including the correlation between the criterion variables and each predictor variable, as well as the inter-correlation between each pair of the predictor variables. The correlation coefficient, R , between any two particular variables is a measure of the degree of linear association between these two variables. It is the square root of coefficient of determination, R^2 . A negative correlation coefficient would indicate inverse correlation and the strength of this correlation depend on the value of absolute value of the coefficient.

Table 7.8 shows the correlation matrix between the different field and laboratory results for the six sections at the 870900 SPS-9A LTPP test site and rutting at these sections. As can be noted, the linear inter-correlation between the rutting indices is rather high, 99%, indicating that using any of them should yield the same results. Obviously, this is due to the rather well behaved performance of the sections, with the exception of section 870902, and the relatively small values of the rutting.

The inter-correlation between the field-testing results shows that, in general, the strain is the least correlating with other calculated values. The correlation coefficients between the shear stiffness, and the average maximum shear stress were generally high indicating that either of them should be sufficient to represent the properties of the pavement. The inter-correlation between the laboratory-testing results, again, shows that the maximum strain least correlates with the other calculated values and that the correlation coefficients between the shear stiffness and the average maximum shear stress are generally high. The correlation between the resilient modulus and the other laboratory shear results ranged between 9% and 47% indicated a rather weak correlation.

Table 7.8: Correlation Matrix between Shear Indices and Rutting for All LTPP Sections

	Rutting			Field Testing Results				Laboratory Testing Results			
	Rutting rate	Accumulated rutting	Accumulated [§] rutting	G_I	τ_{av}	ϕ_{max}	τ_{max}	G_I	ϕ_{max}	τ_{max}	M_R
Rutting	Rutting rate	1.00	0.99	0.99	-0.87	-0.56	-0.59	-0.80	-0.68	-0.28	-0.14
	Accumulated rutting		1.00	0.98	-0.85	-0.51	-0.66	-0.81	-0.63	-0.26	-0.11
	Accumulated rutting [§]			1.00	-0.88	-0.61	-0.54	-0.80	-0.72	-0.35	-0.12
Field Testing Results	G_I				1.00	0.76	0.69	0.95	0.81	0.66	0.49
	τ_{av}					1.00	0.30	0.74	0.99 [*]	0.75	0.12
	ϕ_{max}						1.00	0.83	0.35	0.39	0.44
	τ_{max}							1.00	0.78	0.70	0.44
Laboratory Testing Results	G_I								1.00	0.30	0.40
	ϕ_{max}									1.00	0.09
	τ_{max}										1.00
	M_R										1.00

[§] Rutting was assumed not to decrease, 2001 reading for 870902 discarded

Rutting indices had higher correlation coefficients with the field-testing results than the laboratory testing results, with the shear stiffness correlating highest with all rutting indices. The correlation between the in-situ shear stiffness results and rutting ranged between 80% and 90%, while for the laboratory stiffness results, the correlation coefficients ranged between 14% and 35%. On the other hand, the resilient modulus showed a very weak correlation with the rutting of the sections, with a correlation coefficient ranging between 11% and 14%.

7.6.3 Regression Analysis

Based on the bivariate analysis, the field shear stiffness was selected as the material property to characterize the asphalt concrete mixes. The rutting rate over the four-year period would also be selected to represent rutting of the pavement sections, as it gives a general idea of the pavement performance. Figure 7.16 shows a plot of the data points for the shear stiffness and the corresponding rutting rate for the six tested sections. The available data points are too few to conclude a mathematical relationship between the variables. However, the data plot shows a possible relationship between the rutting rate and the shear stiffness. Using logarithmic trend line for fitting, the following relationship between rutting rate (RR) and shear stiffness (G) was obtained:

$$[7.2] \quad RR = -0.7803 \ln(G_i) + 2.2091$$

The coefficient of determination for this relationship was 0.79. A linear trend line also resulted in a coefficient of determination of 0.76. It should be noted that the regression analysis is based on rutting data over 4-years of service, which is a relatively short period of service life. The rutting values are generally small and subsequently the inference range of the regressions analysis is limited. However, the presented results show a high potential for the in-situ shear testing to evaluate the rutting potential of asphalt concrete mixes.

Figure 7.16: Relationship between Rutting Rate and In-Situ Shear Stiffness

7.7 Summary

In this chapter, the results of the experimental program, outlined in Chapter 6, are presented. The in-situ testing results on the pavement sections on Carleton University campus were used to investigate the effect of temperature and diameter of the loading plate on the measured shear stiffness. Field-testing completed on the asphalt concrete sections on Carleton University campus showed that the shear stiffness of the asphalt concrete mixes, generally, decreased with higher temperatures, which is expected. The results suggested that the size of the plate used for testing can influence the measured stiffness. However, further investigation showed that the effect of the size of the loading plate on the measured shear stiffness was not significant, if the actual strain rate was measured.

Six test sections at the LTPP SPS-9A test site 870900 near Petawawa, Ontario, were tested using the InSiSST. Also, core samples were extracted from these sections and tested

in the laboratory. The sections were monitored since construction and rutting data was available. The total rutting depth for the sections was generally very small. Analysis of the testing results for both the field and the laboratory testing showed that the shear properties of the asphalt concrete mixes better correlate with rutting than the resilient modulus.

Regression analysis was used to develop a relationship between the in-situ shear stiffness and the rutting rate for the pavement sections. It should be noted that the rutting values used in the regression analysis were very small, due to the relatively short service life of the pavement sections. Using logarithmic trend line for fitting, a relationship between rutting rate (RR) and shear stiffness (G) was obtained, with a coefficient of determination of 76%.

CHAPTER 8

8 CONCLUSIONS AND RECOMMENDATIONS

The main objective of this thesis, among others, was to investigate the behaviour of the asphalt concrete mix under the effect of a forced angular displacement applied to the surface of the asphalt concrete pavement, as prescribed by the In-Situ Shear Stiffness Testing (InSiSST) facility. A research plan involving theoretical and numerical investigations of the effect of the application of a forced angular displacement to the surface of the asphalt concrete surface layer was carried out. The research plan also involved an experimental investigation including in-situ and laboratory testing on a number of different asphalt pavement sections.

In general, the thesis provided a number of significant enhancements to the developed InSiSST facility in terms of the data interpretation and analysis. However, the most significant contribution of this thesis was to introduce, for the first time, a framework relating the in-situ shear stiffness of the asphalt concrete mixes to the long-term performance of the asphalt concrete pavement in terms of rutting.

8.1 Conclusions

The Reissner-Sagoci problem, which is the problem of applying a forced angular displacement to a circular area on the surface of a half space, was investigated to examine the possibility of using the mathematical solution developed in the literature for this problem to model asphalt concrete mixes under the loading conditions prescribed by the InSiSST. A closed form solution for the partial differential equation developed to model the loading

conditions and viscoelastic material properties of the asphalt concrete. Subsequently, a numerical model approach using the Finite Element Method (FEM) was developed to investigate the variables affecting the measurements during in-situ testing.

The numerical investigation showed that the sensitivity of the shear stiffness of the asphalt concrete mixes, as evaluated by the InSiSST, was high to variation in the strain rate during loading. However, the sensitivity of the shear stiffness to the rate decreases at lower higher values of angular displacement.

The viscoelastic properties of the asphalt concrete mix were found to affect the relationship between the torque and the angular displacement during in-situ testing. The ratio between the total loading time and the relaxation time of the asphalt concrete mix is the governing factor in limiting the viscoelastic effects on the measured shear stiffness. At the current loading rate of the InSiSST facility and its current configuration that provides limited capacity, the testing conditions for the majority of the in-situ test samples would fall in the zone, where the viscous properties of the asphalt concrete mix would affect the evaluation of the shear stiffness of the asphalt concrete mixes.

A number of factors affecting the measured shear stiffness were investigated through the experimental program in this thesis. It was shown that the actual strain rate during in-situ testing was not always constant. The strain rate depended on the material properties as compared to the testing facility capacity. The higher the material resistance, the slower the strain rate at the early stages of loading. However, the total angle during the entire loading process found to be constant regardless of the actual strain rate.

The results obtained for the samples that failed at the interface between the epoxy and the loading plate before failure were shown to reflect the asphalt concrete mix properties. This conclusion has a significant impact on the proper use of the developed InSiSST. The careful selection of the epoxy can represent the breaking line between the acceptance and

rejection of a given mix. A failure occurring in the asphalt concrete mix at a given temperature would suggest a poor mix, while a failure occurring at the interface between the plate and the epoxy would suggest an acceptable mix. This conclusion might lead to the development of a fully non-destructive test. However, this is beyond the scope of this thesis.

Field-testing completed on the asphalt concrete sections on Carleton University campus showed that the shear stiffness of the asphalt concrete mixes, generally, decreased with higher temperatures, which is expected. The results suggested that the size of the plate used for testing can influence the measured stiffness. However, further investigation showed that the effect of the size of the loading plate on the measured shear stiffness was not significant, if the actual strain rate was measured.

Six test sections at the LTPP SPS-9A test site 870900 near Petawawa, Ontario, were tested using the InSiSST. Also, core samples were extracted from these sections and tested in the laboratory. The sections were monitored since construction and rutting data was available. The total rutting depth for the sections was generally very small. However, based on the available data and the testing results for both the field and the laboratory testing, the following can be concluded

- The shear properties of the asphalt concrete mixes were found to better correlate with rutting than the resilient modulus.
- The in-situ shear properties better correlate with rutting, compared to the laboratory results
- The in-situ shear stiffness had the highest correlation coefficient with rutting

The research presented in this thesis can be the basis for the development of a QC/QA framework for evaluating the compaction of the newly constructed asphalt concrete layers. In general poorer asphalt concrete mixes will fail at higher angular displacement and will have rather low shear stiffness. The suggested framework would utilize this observation. the

framework can be explained through Figure 8.1, which was based on the sensitivity analysis for the shear stiffness.

The newly constructed asphalt concrete layer is tested using the InSiSST and the angular displacement and shear stiffness at a predefined torque are determined and corrected for temperature. The shear stiffness and the angular displacement are plotted on a figure similar to Figure 8.1. If the results were found to be to the left of vertical line at point A, the asphalt concrete mix would be accepted. However, if it fell to the right of the line, then the pavement layer would require further compaction. The advantage of this procedure is that it would allow for a timely decision during construction were the pavement section is still not opened to traffic and the construction equipment are still on-site.

Figure 8.1: QC/QA framework

8.2 Recommendation and Future Work

The in-situ shear stiffness provided a new approach to characterize asphalt concrete mixes. The data used in this thesis show that the in-situ shear stiffness correlates well with rutting in pavement sections and can be used to predict the rutting potential in flexible pavement sections. Currently, the in-situ shear stiffness is being measured through the InSiSST facility. However, a number of enhancements to the InSiSST should be considered, to fully develop it as a useful tool for pavement engineers and practitioners. These enhancements include measuring the actual angular displacement through the data acquisition system and increasing the mechanical capacity of the testing facility, to enable testing the pavement at lower temperatures, where the viscoelastic properties are less prevalent.

8.2.1 Recommended Enhancements to the InSiSST

Accurate measurement of the angular displacement will allow for an accurate evaluation of the shear properties of the asphalt concrete mix. The results presented in this thesis show that accurately measuring the angular displacement with time would significantly enhance the accuracy of the relationship between the torque and the angular displacement, and subsequently more accurate evaluation of the material properties. It is recommended to modifying the current data acquisition system, whereby both the torque and the angular displacement are recorded with time during in-situ testing.

In its current configuration, the maximum torque that can be resisted by the InSiSST is approximately 1400-Nm, for both the stability during testing and the capacity of the torque cell. This is a rather low torque value that affects the efficiency of in-situ testing. Modifying the InSiSST to increase its capacity would enhance its use at lower temperatures, where the asphalt concrete mixes are stiffer, but the viscoelastic properties are less prevalent.

The maximum speed of the testing facility in its current condition is 0.233-rpm. This is a rather slow speed, and will generally allow the viscoelastic properties of the asphalt concrete mix to affect the in-situ testing results. It is recommended to modify the current facility to allow for testing at higher speeds. However, it should be noted that increasing the testing speed would cause the torque values to be much higher and subsequently, require increasing the capacity of the testing facility.

8.2.2 In-Situ Testing and Field Validation

The results presented in this thesis were for six test sections that were rather new, and the rutting data was available for 4-years only. Albeit the analysis showed good correlation between the shear stiffness and rutting, it is recommended to continually monitor these sections throughout their service life to evaluate the relationship between the shear stiffness measured at the early stages of the life of the asphalt concrete mix and the rutting near the end of the service life of the pavement sections.

Furthermore, it is also recommended to develop a large-scale parametric study, following the approach used in this thesis, where a large number of sections are selected to evaluate the shear stiffness of the asphalt concrete surface layers, and these sections are monitored throughout their service life to evaluate surface rutting throughout their life. The sections should be distributed over different environment zones, subjected to different service conditions, and designed using different mix design procedures.

8.2.3 Expansion of the Shear Stiffness Approach

The presented approach for measuring the in-situ shear stiffness of the asphalt concrete mixes is a relatively new approach and a lot of areas are still to be investigated. Currently, the in-situ shear stiffness is evaluated by applying a forced angular displacement to the surface of the pavement. An approach similar to the in-situ shear vane test used to evaluate the shear

resistance of soils can be developed to measure the shear resistance of the asphalt concrete mixes. A four-blade, or a three-blade, vane would be driven into the surface layer, or embedded during construction. The vane would be then forced to rotate through a forced angular displacement. The analysis procedures to calculate the shear stiffness in this case will be rather different than the current procedures due to the difference in the boundary condition, however this would eliminate the use of the epoxy, which sometimes fails prematurely during in-situ testing.

Another approach to evaluate the shear stiffness is to use dynamic loading rather than static loading. The dynamic loading is becoming widely accepted, as it can identify the stiffness of the material in terms of the dynamic modulus and the viscous component of the material properties in terms of the phase angle. However, adopting such approach would require significant modifications to the current configuration of the testing facility.

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APPENDIX A

Field Testing Results for Test Samples at Carleton-1 Test Section

Section ID	Carleton-1 Section
Sample ID	Old_Jul-31-00_8

Epoxy Failure

Date	31-Jul-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23931
Calibration - R _{min}	-73
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	28
Air Temp (°C)	24

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	1.65
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	6.55
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-80	0.0000	-0.17	-0.23
1.00	-33	0.0233	0.99	1.34
2.00	1940	0.0465	49.75	67.46
3.00	8179	0.0698	203.96	276.54
4.00	13565	0.0931	337.09	457.03
5.00	14296	0.1163	355.15	481.52
6.00	14860	0.1396	369.09	500.43
7.00	15334	0.1629	380.81	516.31
8.00	15722	0.1861	390.40	529.31
9.00	16106	0.2094	399.89	542.18
10.00	16479	0.2327	409.11	554.68
11.00	16826	0.2560	417.69	566.31
12.00	17162	0.2792	425.99	577.57
13.00	17503	0.3025	434.42	589.00
14.00	17841	0.3258	442.78	600.32
15.00	18198	0.3490	451.60	612.29
16.00	18494	0.3723	458.92	622.21
17.00	18821	0.3956	467.00	633.16
18.00	19136	0.4188	474.78	643.72
19.00	19417	0.4421	481.73	653.14
20.00	19718	0.4654	489.17	663.22
21.00	19985	0.4886	495.77	672.17
22.00	20251	0.5119	502.34	681.08
23.00	20478	0.5352	507.95	688.69
24.00	20702	0.5584	513.49	696.20
25.00	20926	0.5817	519.03	703.70
26.00	21171	0.6050	525.08	711.92
27.00	21400	0.6282	530.74	719.59

Carleton-1 Section

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
Old_Jul-31-00_1	100	841.23	0.1085	18.31	11.63
Old_Jul-31-00_2	100	-	-	17.36	-
Old_Jul-31-00_3	100	-	-	19.97	-
Old_Jul-31-00_4	100	-	-	17.80	-
Old_Jul-31-00_5	100	923.73	0.1284	19.77	10.79
Old_Jul-31-00_6	100	956.57	0.1411	19.70	10.17
Old_Jul-31-00_7	100	-	-	23.32	-
Mean		907.18	0.1260	19.46	10.86
St. Dev		59.42	0.0164	1.99	0.73
CoV		6.55	13.02	10.23	6.73
Old_Jul-31-00_8	125	-	-	6.55	-
Old_Jul-31-00_9	125	-	-	7.88	-

Section ID	Carleton-1 Section
Sample ID	Old_Aug-04-00_1

Date	04-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23928
Calibration - R_{min}	-85
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	26

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_r (cm)	

Maximum Torque (N.m.)	674.33
X-axis Intercept	1.68
Angle at Failure (rad)	0.0772
Initial Shear Stiffness (Mpa)	13.29
Secant Shear Stiffness (Mpa)	13.11

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-42	0.0000	1.06	1.44
1.00	27	0.0233	2.77	3.75
2.00	1981	0.0465	51.05	69.21
3.00	7258	0.0698	181.43	245.98
4.00	14968	0.0931	371.92	504.26
5.00	20045	0.1163	497.36	674.33
6.00	7832	0.1396	195.61	265.21
7.00	6617	0.1629	165.59	224.51
8.00	6447	0.1861	161.39	218.81
9.00	5863	0.2094	146.96	199.25
10.00	5571	0.2327	139.75	189.47
11.00	5250	0.2560	131.81	178.72
12.00	4900	0.2792	123.17	166.99
13.00	4762	0.3025	119.76	162.37
14.00	4733	0.3258	119.04	161.40
15.00	4669	0.3490	117.46	159.25
16.00	4708	0.3723	118.42	160.56
17.00	4603	0.3956	115.83	157.04
18.00	4531	0.4188	114.05	154.63
19.00	4393	0.4421	110.64	150.01
20.00	4171	0.4654	105.15	142.57
21.00	3887	0.4886	98.14	133.06
22.00	3720	0.5119	94.01	127.46

Section ID	Carleton-1 Section
Sample ID	Old_Aug-04-00_2

Date	04-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.75
Calibration - R _{max}	23974
Calibration - R _{min}	-32
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	
r _r (cm)	
h _r (cm)	

Maximum Torque (N.m.)	792.28
X-axis Intercept	2.49
Angle at Failure (rad)	0.0816
Initial Shear Stiffness (Mpa)	17.46
Secant Shear Stiffness (Mpa)	14.56

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-27	0.0000	0.12	0.17
0.75	0	0.0175	0.79	1.07
1.50	167	0.0349	4.92	6.67
2.25	1471	0.0524	37.15	50.36
3.00	4230	0.0698	105.33	142.81
3.75	9646	0.0873	239.19	324.30
4.50	16755	0.1047	414.88	562.51
5.25	21929	0.1222	542.76	735.88
6.00	23612	0.1396	584.35	792.28
6.75	8123	0.1571	201.55	273.26
7.50	7471	0.1745	185.43	251.41
8.25	7320	0.1920	181.70	246.35
9.00	7334	0.2094	182.05	246.82
9.75	7025	0.2269	174.41	236.47
10.50	6717	0.2443	166.80	226.15
11.25	6439	0.2618	159.93	216.83
12.00	5866	0.2792	145.77	197.63
12.75	5600	0.2967	139.19	188.72
13.50	5266	0.3141	130.94	177.53
14.25	5048	0.3316	125.55	170.22
15.00	4842	0.3490	120.46	163.32
15.75	4739	0.3665	117.91	159.87
16.50	4482	0.3839	111.56	151.26

Section ID	Carleton-1 Section
Sample ID	Old_Aug-04-00_7

Date	04-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23964
Calibration - R_{min}	-53
Steel Plate Diameter (mm)	125
Pavement Temp ($^{\circ}\text{C}$)	30
Air Temp ($^{\circ}\text{C}$)	24

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	3.15
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	10.86
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-53.00	0.0000	0.00	0.00
1.00	0.00	0.0233	1.31	1.78
2.00	527.00	0.0465	14.33	19.43
3.00	2605.00	0.0698	65.66	89.02
4.00	8348.00	0.0931	207.53	281.38
5.00	18249.00	0.1163	452.12	612.99
6.00	27452.00	0.1396	679.47	921.23
7.00	26926.00	0.1629	666.47	903.61
8.00	25171.00	0.1861	623.12	844.83
9.00	24029.00	0.2094	594.91	806.58
10.00	23102.00	0.2327	572.01	775.54
11.00	23818.00	0.2560	589.69	799.52
12.00	25020.00	0.2792	619.39	839.78
13.00	26790.00	0.3025	663.11	899.06
14.00	28137.00	0.3258	696.39	944.17
15.00	28524.00	0.3490	705.95	957.14
16.00	28430.00	0.3723	703.63	953.99
17.00	25802.00	0.3956	638.70	865.97
18.00	17617.00	0.4188	436.51	591.83
19.00	10647.00	0.4421	264.33	358.38
20.00	9484.00	0.4654	235.60	319.42
21.00	9113.00	0.4886	226.43	307.00
22.00	8861.00	0.5119	220.21	298.56

Carleton-1 Section

Sample ID	Steel Plate Diameter	T_{max}	ϕ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
Old_Aug-04-00_1	100	674.33	0.0772	13.29	13.11
Old_Aug-04-00_2	100	792.28	0.0816	17.46	14.56
Old_Aug-04-00_3	100	792.98	0.0602	20.06	19.76
Old_Aug-04-00_4	100	-	-	8.75	-
Old_Aug-04-00_5	100	-	-	12.89	-
Old_Aug-04-00_6	100	-	-	14.10	-
Mean		753.20	0.0730	14.43	15.81
St. Dev		68.30	0.0113	3.92	3.50
CoV		9.07	15.47	27.20	22.11
Old_Aug-04-00_7	125	-	-	10.86	-
Old_Aug-04-00_8	125	-	-	9.56	-

Section ID	Carleton-1 Section
Sample ID	Old_Aug-25-00_3

Date	25-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	24018
Calibration - R _{min}	0
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	33
Air Temp (°C)	24

Maximum Torque (N.m.)	726.14
X-axis Intercept	2.45
Angle at Failure (rad)	0.0826
Initial Shear Stiffness (Mpa)	15.39
Secant Shear Stiffness (Mpa)	13.19

Failure Dimensions	
r _o (cm)	10.4
r _i (cm)	6.2
h _i (cm)	1.5

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0.00	0.0000	0.00	0.00
1.00	349.00	0.0233	8.62	11.69
2.00	1103.00	0.0465	27.25	36.94
3.00	3873.00	0.0698	95.67	129.71
4.00	11228.00	0.0931	277.36	376.05
5.00	18003.00	0.1163	444.72	602.95
6.00	21681.00	0.1396	535.57	726.14
7.00	3904.00	0.1629	96.44	130.75
8.00	3453.00	0.1861	85.30	115.65
9.00	3108.00	0.2094	76.77	104.09
10.00	3005.00	0.2327	74.23	100.64
11.00	2839.00	0.2560	70.13	95.08
12.00	2832.00	0.2792	69.96	94.85
13.00	2774.00	0.3025	68.52	92.91
14.00	2723.00	0.3258	67.26	91.20
15.00	2624.00	0.3490	64.82	87.88
16.00	2713.00	0.3723	67.02	90.86
17.00	2672.00	0.3956	66.00	89.49
18.00	2609.00	0.4188	64.45	87.38
19.00	2407.00	0.4421	59.46	80.61
20.00	2345.00	0.4654	57.93	78.54
21.00	2343.00	0.4886	57.88	78.47

Section ID	Carleton-1 Section
Sample ID	Old_Aug-25-00_4

Date	25-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23956
Calibration - R _{min}	-60
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	24

Failure Dimensions	
r _o (cm)	10.8
r _i (cm)	5.0
h _r (cm)	0.8

Maximum Torque (N.m.)	549.11
X-axis Intercept	2.73
Angle at Failure (rad)	0.0760
Initial Shear Stiffness (Mpa)	14.78
Secant Shear Stiffness (Mpa)	10.84

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	1.48	2.01
1.00	24	0.0233	2.08	2.81
2.00	63	0.0465	3.04	4.12
3.00	1780	0.0698	45.46	61.63
4.00	8357	0.0931	207.94	281.92
5.00	15664	0.1163	388.45	526.67
6.00	16334	0.1396	405.00	549.11
7.00	3868	0.1629	97.04	131.57
8.00	3213	0.1861	80.86	109.63
9.00	2872	0.2094	72.43	98.21
10.00	2811	0.2327	70.93	96.16
11.00	2801	0.2560	70.68	95.83
12.00	2785	0.2792	70.28	95.29
13.00	2806	0.3025	70.80	96.00
14.00	2807	0.3258	70.83	96.03
15.00	2765	0.3490	69.79	94.62
16.00	2617	0.3723	66.13	89.67
17.00	2568	0.3956	64.92	88.02
18.00	2586	0.4188	65.37	88.63
19.00	2459	0.4421	62.23	84.37
20.00	2086	0.4654	53.02	71.88
21.00	1983	0.4886	50.47	68.43

Carleton-1 Section

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	G_s
		Nm	Rad	MPa	MPa
Old Aug-25-00 1	100	932.64	0.0931	15.56	15.02
Old Aug-25-00 2	100	610.03	0.0372	24.63	24.63
Old Aug-25-00 3	100	726.14	0.0826	15.39	13.19
Old Aug-25-00 4	100	549.11	0.0760	14.78	10.84
Mean		704.48	0.0722	17.59	15.92
St. Dev		168.91	0.0244	4.70	6.05
CoV		23.98	33.81	26.74	38.01

Section ID	Carleton-1 Section
Sample ID	Old_Nov-25-00_1

Epoxy and Pavement Failure

Date	25-Nov-00
Weather	Overcast
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	23952
Calibration - R _{min}	-56
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	5
Air Temp (°C)	3

Failure Dimensions		
r _o (cm)		-
r _i (cm)		2.11
h _r (cm)		-
Initial Shear Stiffness (Mpa)		33.27
Secant Shear Stiffness (Mpa)		-

Maximum Torque (N.m.)	-
X-axis Intercept	2.11
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	33.27
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-23	0.0000	0.82	1.11
0.20	0	0.0047	1.38	1.88
0.40	93	0.0093	3.68	4.99
0.60	176	0.0140	5.73	7.77
0.80	295	0.0186	8.67	11.76
1.00	473	0.0233	13.07	17.72
1.20	745	0.0279	19.79	26.84
1.40	1094	0.0326	28.42	38.53
1.60	1513	0.0372	38.77	52.57
1.80	2053	0.0419	52.12	70.66
2.00	2903	0.0465	73.12	99.14
2.20	4358	0.0512	109.08	147.89
2.40	6216	0.0558	155.00	210.15
2.60	7848	0.0605	195.33	264.83
2.80	10050	0.0652	249.75	338.61
3.00	13572	0.0698	336.78	456.62
3.20	15922	0.0745	394.86	535.36
3.40	18475	0.0791	457.95	620.90
3.60	20783	0.0838	514.99	698.23
3.80	22791	0.0884	564.61	765.51
4.00	24481	0.0931	606.37	822.13
4.20	27854	0.0977	689.73	935.15
4.40	28167	0.1024	697.46	945.63
4.60	32006	0.1070	792.34	1074.26
4.80	34923	0.1117	864.42	1172.00
5.00	35298	0.1163	873.69	1184.56
5.20	35225	0.1210	871.89	1182.12
5.40	35441	0.1256	877.22	1189.35

Section ID	Carleton-1 Section
Sample ID	Old_Nov-25-00_2

Epoxy and Pavement Failure

Date	25-Nov-00
Weather	Overcast
Test Speed (rpm)	1800
Data Recording (sec)	0.20
Calibration - R _{max}	23792
Calibration - R _{min}	-79
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	5
Air Temp (°C)	2

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	1.20
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	20.81
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-48	0.0000	0.77	1.04
0.20	-38	0.0047	1.02	1.38
0.40	27	0.0093	2.63	3.57
0.60	182	0.0140	6.49	8.80
0.80	509	0.0186	14.61	19.81
1.00	1151	0.0233	30.57	41.45
1.20	2286	0.0279	58.78	79.70
1.40	3406	0.0326	86.62	117.44
1.60	4161	0.0372	105.38	142.88
1.80	5737	0.0419	144.55	195.99
2.00	7581	0.0465	190.38	258.13
2.20	9369	0.0512	234.82	318.38
2.40	11310	0.0558	283.07	383.79
2.60	13521	0.0605	338.02	458.29
2.80	15955	0.0652	398.52	540.31
3.00	17480	0.0698	436.42	591.70
3.20	19299	0.0745	481.63	653.00
3.40	20509	0.0791	511.70	693.78
3.60	20051	0.0838	500.32	678.34
3.80	20014	0.0884	499.40	677.10
4.00	22379	0.0931	558.18	756.79
4.20	24363	0.0977	607.49	823.65
4.40	26962	0.1024	672.09	911.23
4.60	29687	0.1070	739.82	1003.06
4.80	30113	0.1117	750.40	1017.41

Section ID	Carleton-1 Section
Sample ID	Old_Nov-25-00_3

Epoxy and Pavement Failure

Date	25-Nov-00
Weather	Overcast
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	23956
Calibration - R_{min}	-66
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	5
Air Temp (°C)	2

Failure Dimensions	
r_o (cm)	
r_r (cm)	
h_r (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	1.32
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	26.31
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-25.00	0.0000	1.01	1.37
0.20	0.00	0.0047	1.63	2.21
0.40	137.00	0.0093	5.01	6.80
0.60	441.00	0.0140	12.52	16.98
0.80	955.00	0.0186	25.22	34.19
1.00	1706.00	0.0233	43.77	59.34
1.20	2703.00	0.0279	68.39	92.72
1.40	3807.00	0.0326	95.66	129.69
1.60	4856.00	0.0372	121.56	164.82
1.80	6093.00	0.0419	152.12	206.24
2.00	7898.00	0.0465	196.70	266.68
2.20	9876.00	0.0512	245.55	332.92
2.40	11648.00	0.0558	289.31	392.26
2.60	13510.00	0.0605	335.30	454.61
2.80	16190.00	0.0652	401.49	544.35
3.00	18405.00	0.0698	456.20	618.52
3.20	20572.00	0.0745	509.72	691.09
3.40	22725.00	0.0791	562.90	763.19
3.60	24921.00	0.0838	617.13	836.72
3.80	28443.00	0.0884	704.12	954.66
4.00	31523.00	0.0931	780.19	1057.80
4.20	34747.00	0.0977	859.82	1165.76
4.40	36902.00	0.1024	913.04	1237.92
4.60	35179.00	0.1070	870.49	1180.22

Carleton-1 Section

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	G_s
		Nm	Rad	MPa	MPa
Old_Nov-25-00_1	100	-	-	33.27	-
Old_Nov-25-00_2	100	-	-	20.81	-
Old_Nov-25-00_3	100	-	-	26.31	-
Mean		-	-	26.79	-
St. Dev		-	-	6.24	-
CoV		-	-	23.30	-

Section ID	Carleton-1 Section
Sample ID	Old_Sep-15-01_1

Date	15-Sep-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24007
Calibration - R_{min}	-35
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	28
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_r (cm)	

Maximum Torque (N.m.)	753.72
X-axis Intercept	0.87
Angle at Failure (rad)	0.0635
Initial Shear Stiffness (Mpa)	21.11
Secant Shear Stiffness (Mpa)	17.80

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-20	0.0000	0.37	0.50
0.20	42	0.0047	1.90	2.58
0.40	205	0.0093	5.92	8.03
0.60	432	0.0140	11.52	15.63
0.80	863	0.0186	22.16	30.05
1.00	1825	0.0233	45.90	62.23
1.20	3598	0.0279	89.65	121.55
1.40	5254	0.0326	130.52	176.96
1.60	6982	0.0372	173.16	234.78
1.80	8808	0.0419	218.22	295.87
2.00	11152	0.0465	276.07	374.30
2.20	13198	0.0512	326.56	442.75
2.40	15226	0.0558	376.61	510.61
2.60	17086	0.0605	422.51	572.84
2.80	19189	0.0652	474.40	643.20
3.00	20053	0.0698	495.72	672.11
3.20	21598	0.0745	533.85	723.81
3.40	22492	0.0791	555.91	753.72
3.60	22445	0.0838	554.75	752.14
3.80	14856	0.0884	367.47	498.23
4.00	8757	0.0931	216.97	294.17
4.20	7352	0.0977	182.29	247.16
4.40	6735	0.1024	167.07	226.51
4.60	6258	0.1070	155.30	210.55
4.80	6100	0.1117	151.40	205.27
5.00	6038	0.1163	149.87	203.19
5.20	5997	0.1210	148.86	201.82
5.40	5970	0.1256	148.19	200.92

Section ID	Carleton-1 Section
Sample ID	Old_Sep-15-01_2

Date	15-Sep-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24010
Calibration - R_{min}	-36
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	28
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions	
r_o (cm)	
r_r (cm)	
r_t (cm)	

Maximum Torque (N.m.)	884.86
X-axis Intercept	1.18
Angle at Failure (rad)	0.0562
Initial Shear Stiffness (Mpa)	25.37
Secant Shear Stiffness (Mpa)	23.63

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.89	1.20
0.20	32	0.0047	1.68	2.27
0.40	48	0.0093	2.07	2.81
0.60	56	0.0140	2.27	3.08
0.80	89	0.0186	3.08	4.18
1.00	543	0.0233	14.29	19.37
1.20	1480	0.0279	37.41	50.71
1.40	2888	0.0326	72.15	97.82
1.60	4578	0.0372	113.84	154.35
1.80	6910	0.0419	171.38	232.36
2.00	9642	0.0465	238.79	323.76
2.20	11994	0.0512	296.82	402.44
2.40	13920	0.0558	344.34	466.87
2.60	16910	0.0605	418.12	566.89
2.80	19217	0.0652	475.04	644.07
3.00	21708	0.0698	536.50	727.40
3.20	23408	0.0745	578.45	784.27
3.40	24756	0.0791	611.71	829.36
3.60	26415	0.0838	652.64	884.86
3.80	25796	0.0884	637.37	864.15
4.00	7206	0.0931	178.69	242.27
4.20	6318	0.0977	156.78	212.56
4.40	5872	0.1024	145.77	197.64
4.60	5490	0.1070	136.35	184.86
4.80	5043	0.1117	125.32	169.91
5.00	4815	0.1163	119.69	162.28
5.20	4685	0.1210	116.48	157.93
5.40	4566	0.1256	113.55	153.95

Section ID	Carleton-1 Section
Sample ID	Old_Sep-15-01_3

Epoxy Failure

Date	15-Sep-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24014
Calibration - R_{min}	-23
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	28
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.90
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	18.19
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0.00	0.0000	0.57	0.77
0.20	38.00	0.0047	1.51	2.04
0.40	71.00	0.0093	2.32	3.15
0.60	122.00	0.0140	3.58	4.85
0.80	466.00	0.0186	12.07	16.36
1.00	1246.00	0.0233	31.32	42.47
1.20	2598.00	0.0279	64.69	87.71
1.40	4134.00	0.0326	102.61	139.12
1.60	5790.00	0.0372	143.48	194.53
1.80	7550.00	0.0419	186.92	253.43
2.00	8360.00	0.0465	206.92	280.54
2.20	10395.00	0.0512	257.15	348.64
2.40	12406.00	0.0558	306.78	415.94
2.60	14711.00	0.0605	363.68	493.08
2.80	16631.00	0.0652	411.07	557.33
3.00	18407.00	0.0698	454.90	616.77
3.20	19929.00	0.0745	492.47	667.70
3.40	20423.00	0.0791	504.66	684.23
3.60	-36.00	0.0838	-0.32	-0.44
3.80	-37.00	0.0884	-0.35	-0.47
4.00	-35.00	0.0931	-0.30	-0.40
4.20	-30.00	0.0977	-0.17	-0.23
4.40	-24.00	0.1024	-0.02	-0.03
4.60	0.00	0.1070	0.57	0.77
4.80	0.00	0.1117	0.57	0.77
5.00	0.00	0.1163	0.57	0.77
5.20	40.00	0.1210	1.56	2.11
5.40	76.00	0.1256	2.44	3.31

Section ID	Carleton-1 Section
Sample ID	Old_Sep-15-01_4

Epoxy Failure

Date	15-Sep-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	24004
Calibration - R _{min}	-32
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	28
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.92
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	20.27
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.79	1.07
0.20	66	0.0047	2.42	3.28
0.40	124	0.0093	3.85	5.22
0.60	328	0.0140	8.89	12.05
0.80	689	0.0186	17.80	24.13
1.00	1459	0.0233	36.80	49.90
1.20	2649	0.0279	66.18	89.72
1.40	4481	0.0326	111.40	151.04
1.60	6002	0.0372	148.94	201.94
1.80	7642	0.0419	189.42	256.82
2.00	9660	0.0465	239.24	324.36
2.20	12415	0.0512	307.24	416.56
2.40	14264	0.0558	352.88	478.44
2.60	16201	0.0605	400.69	543.27
2.80	17965	0.0652	444.23	602.30
3.00	19846	0.0698	490.66	665.25
3.20	-23	0.0745	0.22	0.30
3.40	-37	0.0791	-0.12	-0.17
3.60	-30	0.0838	0.05	0.07
3.80	-30	0.0884	0.05	0.07
4.00	-28	0.0931	0.10	0.13
4.20	-32	0.0977	0.00	0.00
4.40	-31	0.1024	0.02	0.03
4.60	-28	0.1070	0.10	0.13
4.80	0	0.1117	0.79	1.07
5.00	-23	0.1163	0.22	0.30
5.20	-21	0.1210	0.27	0.37
5.40	0	0.1256	0.79	1.07

Carleton-1 Section

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
Old_Sep-15-01_1	100	753.72	0.0635	21.11	17.80
Old_Sep-15-01_2	100	884.86	0.0562	25.37	23.63
Old_Sep-15-01_3	100	-	-	18.19	-
Old_Sep-15-01_4	100	-	-	20.27	-
Mean		819.29	0.0598	21.24	20.71
St. Dev		92.73	0.0052	3.02	4.13
CoV		11.32	8.70	14.20	19.92

Section ID	Laboratory Entrance - Old Pavement
Sample ID	Old_Aug-31-02_2

Epoxy Failure

Date	01-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	24039
Calibration - R _{min}	-30
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	29

Data recorded @0.1-s but presented @0.2-s

Failure Dimensions	
r ₀ (cm)	
r ₁ (cm)	
r ₂ (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.73
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	17.10
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.74	1.00
0.20	84	0.0047	2.81	3.81
0.40	146	0.0093	4.34	5.88
0.60	258	0.0140	7.10	9.63
0.80	752	0.0186	19.28	26.14
1.00	1979	0.0233	49.52	67.14
1.20	3506	0.0279	87.16	118.18
1.40	5642	0.0326	139.81	189.56
1.60	6610	0.0372	163.68	221.91
1.80	7662	0.0419	189.61	257.07
2.00	9458	0.0465	233.88	317.10
2.20	11183	0.0512	276.40	374.75
2.40	13616	0.0558	336.37	456.06
2.60	15850	0.0605	391.44	530.72
2.80	17808	0.0652	439.71	596.16
3.00	18967	0.0698	468.28	634.90
3.20	33	0.0745	1.55	2.11
3.40	-34	0.0791	-0.10	-0.13
3.60	-32	0.0838	-0.05	-0.07
3.80	-29	0.0884	0.02	0.03
4.00	0	0.0931	0.74	1.00
4.20	0	0.0977	0.74	1.00
4.40	-21	0.1024	0.22	0.30
4.60	0	0.1070	0.74	1.00
4.80	0	0.1117	0.74	1.00
5.00	0	0.1163	0.74	1.00
5.20	0	0.1210	0.74	1.00

Section ID	Laboratory Entrance - Old Pavement
Sample ID	Old_Aug-31-02_3

Epoxy Failure

Date	01-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24052
Calibration - R_{min}	-30
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	29

Data recorded @0.1-s but presented @0.2-s

Failure Dimensions	
r_o (cm)	
r_t (cm)	
h_t (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.99
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	21.89
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	0	0.0000	0.74	1.00
0.20	88	0.0047	2.91	3.94
0.40	177	0.0093	5.10	6.91
0.60	272	0.0140	7.44	10.09
0.80	518	0.0186	13.50	18.30
1.00	1057	0.0233	26.78	36.31
1.20	2345	0.0279	58.51	79.33
1.40	4085	0.0326	101.38	137.45
1.60	6110	0.0372	151.27	205.09
1.80	8724	0.0419	215.67	292.41
2.00	10631	0.0465	262.65	356.11
2.20	12251	0.0512	302.56	410.22
2.40	14162	0.0558	349.64	474.05
2.60	16185	0.0605	399.48	541.63
2.80	17948	0.0652	442.92	600.52
3.00	19154	0.0698	472.63	640.80
3.20	-32	0.0745	-0.05	-0.07
3.40	-41	0.0791	-0.27	-0.37
3.60	-37	0.0838	-0.17	-0.23
3.80	-32	0.0884	-0.05	-0.07
4.00	29	0.0931	1.45	1.97
4.20	0	0.0977	0.74	1.00
4.40	66	0.1024	2.37	3.21
4.60	91	0.1070	2.98	4.04
4.80	105	0.1117	3.33	4.51
5.00	115	0.1163	3.57	4.84
5.20	126	0.1210	3.84	5.21

Section ID	Laboratory Entrance - Old Pavement
Sample ID	Old_Aug-31-02_4

Epoxy Failure

Date	01-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24053
Calibration - R_{min}	-30
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	45
Air Temp (°C)	35

Data recorded @0.1-s but presented @0.2-s

Failure Dimensions		
r_o (cm)		
r_f (cm)		
h_f (cm)		

Maximum Torque (N.m.)	-
X-axis Intercept	1.98
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	18.16
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-26	0.0000	0.10	0.13
0.20	31	0.0047	1.50	2.04
0.40	32	0.0093	1.53	2.07
0.60	28	0.0140	1.43	1.94
0.80	28	0.0186	1.43	1.94
1.00	54	0.0233	2.07	2.81
1.20	109	0.0279	3.42	4.64
1.40	182	0.0326	5.22	7.08
1.60	385	0.0372	10.22	13.86
1.80	849	0.0419	21.65	29.36
2.00	1761	0.0465	44.12	59.82
2.20	2612	0.0512	65.09	88.25
2.40	3739	0.0558	92.85	125.89
2.60	5124	0.0605	126.97	172.15
2.80	6743	0.0652	166.86	226.23
3.00	8470	0.0698	209.40	283.91
3.20	10163	0.0745	251.11	340.46
3.40	11821	0.0791	291.96	395.84
3.60	13530	0.0838	334.06	452.92
3.80	15274	0.0884	377.02	511.18
4.00	16943	0.0931	418.14	566.92
4.20	18170	0.0977	448.37	607.91
4.40	0	0.1024	0.74	1.00
4.60	0	0.1070	0.74	1.00
4.80	-25	0.1117	0.12	0.17
5.00	0	0.1163	0.74	1.00
5.20	0	0.1210	0.74	1.00

Laboratory Entrance - Old Pavement

Sample ID	Steel Plate Diameter	T_{max}	ϕ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
Old Aug-31-02 2	100	-	-	17.10	-
Old Aug-31-02 3	100	-	-	21.89	-
Old Aug-31-02 4	100	-	-	18.16	-
Mean		-	-	19.05	-
St. Dev		-	-	2.52	-
CoV		-	-	13.21	-

APPENDIX B

Field Testing Results for Test Samples at Carleton-2 Test Section

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_1

Epoxy Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23352
Calibration - R_{min}	-34
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions		
r_o (cm)		
r_l (cm)		
h_l (cm)		
Maximum Torque (N.m.)	-	
X-axis Intercept	0.68	
Angle at Failure (rad)	-	
Initial Shear Stiffness (Mpa)	82.04	
Secant Shear Stiffness (Mpa)	-	

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-20	0.0000	0.36	0.48
0.10	0	0.0023	0.86	1.17
0.20	44	0.0047	1.98	2.68
0.30	67	0.0070	2.56	3.47
0.40	107	0.0093	3.58	4.85
0.50	269	0.0116	7.69	10.42
0.60	537	0.0140	14.49	19.64
0.70	1045	0.0163	27.37	37.11
0.80	1855	0.0186	47.92	64.98
0.90	3337	0.0209	85.52	115.95
1.00	4949	0.0233	126.42	171.40
1.10	6427	0.0256	163.91	222.24
1.20	7390	0.0279	188.35	255.36
1.30	-46	0.0302	-0.30	-0.41
1.40	-47	0.0326	-0.33	-0.45
1.50	-48	0.0349	-0.36	-0.48
1.60	-48	0.0372	-0.36	-0.48
1.70	-47	0.0396	-0.33	-0.45
1.80	-46	0.0419	-0.30	-0.41
1.90	-46	0.0442	-0.30	-0.41
2.00	-46	0.0465	-0.30	-0.41
2.10	-47	0.0489	-0.33	-0.45
2.20	-46	0.0512	-0.30	-0.41
2.30	-46	0.0535	-0.30	-0.41
2.40	-45	0.0558	-0.28	-0.38
2.50	-47	0.0582	-0.33	-0.45
2.60	-45	0.0605	-0.28	-0.38
2.70	-47	0.0628	-0.33	-0.45
2.80	-46	0.0652	-0.30	-0.41

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_2

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23977
Calibration - R_{min}	-53
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	10.3
r_i (cm)	8.5
h_i (cm)	1.4

Maximum Torque (N.m.)	363.41
X-axis Intercept	0.86
Angle at Failure (rad)	0.0244
Initial Shear Stiffness (Mpa)	59.46
Secant Shear Stiffness (Mpa)	52.90

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-35	0.0000	0.44	0.60
0.10	0	0.0023	1.31	1.77
0.20	0	0.0047	1.31	1.77
0.30	0	0.0070	1.31	1.77
0.40	43	0.0093	2.37	3.21
0.50	76	0.0116	3.19	4.32
0.60	241	0.0140	7.26	9.84
0.70	429	0.0163	11.90	16.13
0.80	724	0.0186	19.18	26.01
0.90	1118	0.0209	28.91	39.20
1.00	1707	0.0233	43.45	58.92
1.10	2756	0.0256	69.35	94.03
1.20	3906	0.0279	97.75	132.53
1.30	5101	0.0302	127.25	172.53
1.40	6353	0.0326	158.16	214.44
1.50	7433	0.0349	184.83	250.59
1.60	8212	0.0372	204.06	276.67
1.70	9635	0.0396	239.20	324.31
1.80	10560	0.0419	262.03	355.27
1.90	10803	0.0442	268.03	363.41
2.00	9756	0.0465	242.18	328.36
2.10	8627	0.0489	214.31	290.56
2.20	7751	0.0512	192.68	261.24
2.30	6921	0.0535	172.19	233.46
2.40	6172	0.0558	153.70	208.38
2.50	5888	0.0582	146.68	198.88
2.60	5671	0.0605	141.33	191.61
2.70	5526	0.0628	137.75	186.76
2.80	5359	0.0652	133.62	181.17

Section ID	Carleton-2 Section (6°C)
Sample ID	New Nov-25-00 3

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23982
Calibration - R_{min}	-43
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions		
r_o (cm)	8.5	
r_i (cm)	7.0	
h_i (cm)	1.3	
Maximum Torque (N.m.)		303.38
X-axis Intercept		0.70
Angle at Failure (rad)		0.0211
Initial Shear Stiffness (Mpa)		57.37
Secant Shear Stiffness (Mpa)		51.09

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-22.00	0.0000	0.52	0.70
0.10	0.00	0.0023	1.06	1.44
0.20	86.00	0.0047	3.19	4.32
0.30	153.00	0.0070	4.84	6.56
0.40	278.00	0.0093	7.93	10.75
0.50	486.00	0.0116	13.06	17.71
0.60	781.00	0.0140	20.35	27.59
0.70	1174.00	0.0163	30.05	40.75
0.80	1697.00	0.0186	42.97	58.26
0.90	2445.00	0.0209	61.44	83.30
1.00	3504.00	0.0233	87.59	118.76
1.10	4689.00	0.0256	116.86	158.44
1.20	5561.00	0.0279	138.39	187.63
1.30	6548.00	0.0302	162.77	220.68
1.40	7438.00	0.0326	184.74	250.48
1.50	8479.00	0.0349	210.45	285.33
1.60	9018.00	0.0372	223.76	303.38
1.70	8995.00	0.0396	223.19	302.61
1.80	8287.00	0.0419	205.71	278.91
1.90	7237.00	0.0442	179.78	243.75
2.00	6252.00	0.0465	155.46	210.77
2.10	5268.00	0.0489	131.16	177.82
2.20	4791.00	0.0512	119.38	161.85
2.30	4576.00	0.0535	114.07	154.65
2.40	4483.00	0.0558	111.77	151.54
2.50	4363.00	0.0582	108.81	147.52
2.60	4324.00	0.0605	107.84	146.22
2.70	4237.00	0.0628	105.70	143.30
2.80	4152.00	0.0652	103.60	140.46

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_4

Epoxy Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23969
Calibration - R_{min}	-52
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.90
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	79.57
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-23	0.0000	0.72	0.97
0.10	0	0.0023	1.28	1.74
0.20	0	0.0047	1.28	1.74
0.30	0	0.0070	1.28	1.74
0.40	42	0.0093	2.32	3.15
0.50	47	0.0116	2.45	3.32
0.60	75	0.0140	3.14	4.25
0.70	185	0.0163	5.85	7.94
0.80	345	0.0186	9.81	13.29
0.90	704	0.0209	18.67	25.32
1.00	1651	0.0233	42.06	57.03
1.10	3131	0.0256	78.62	106.59
1.20	4691	0.0279	117.15	158.83
1.30	5987	0.0302	149.16	202.23
1.40	7375	0.0326	183.44	248.71
1.50	8954	0.0349	222.44	301.59
1.60	10820	0.0372	268.53	364.08
1.70	12917	0.0396	320.32	434.30
1.80	-42	0.0419	0.25	0.33
1.90	-62	0.0442	-0.25	-0.33
2.00	-59	0.0465	-0.17	-0.23
2.10	-56	0.0489	-0.10	-0.13
2.20	-56	0.0512	-0.10	-0.13
2.30	-55	0.0535	-0.07	-0.10
2.40	-56	0.0558	-0.10	-0.13
2.50	-53	0.0582	-0.02	-0.03
2.60	-51	0.0605	0.02	0.03
2.70	-42	0.0628	0.25	0.33
2.80	-42	0.0652	0.25	0.33

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_5 Epoxy Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23966
Calibration - R_{min}	-51
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.77
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	94.08
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-25	0.0000	0.64	0.87
0.10	0	0.0023	1.26	1.71
0.20	64	0.0047	2.84	3.85
0.30	135	0.0070	4.59	6.23
0.40	209	0.0093	6.42	8.71
0.50	261	0.0116	7.71	10.45
0.60	535	0.0140	14.48	19.63
0.70	977	0.0163	25.40	34.43
0.80	1564	0.0186	39.90	54.09
0.90	2986	0.0209	75.02	101.72
1.00	4319	0.0233	107.95	146.37
1.10	6102	0.0256	152.00	206.08
1.20	7795	0.0279	193.82	262.79
1.30	9589	0.0302	238.14	322.87
1.40	11765	0.0326	291.89	395.76
1.50	13844	0.0349	343.25	465.39
1.60	15649	0.0372	387.84	525.84
1.70	28	0.0396	1.95	2.65
1.80	-45	0.0419	0.15	0.20
1.90	-47	0.0442	0.10	0.13
2.00	-45	0.0465	0.15	0.20
2.10	-37	0.0489	0.35	0.47
2.20	-35	0.0512	0.40	0.54
2.30	-35	0.0535	0.40	0.54
2.40	-33	0.0558	0.44	0.60
2.50	-33	0.0582	0.44	0.60
2.60	-31	0.0605	0.49	0.67
2.70	-31	0.0628	0.49	0.67
2.80	0	0.0652	1.26	1.71

Carleton-2 Section

(60C)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New Nov-25-00 1	75	-	-	82.04	-
New Nov-25-00 2	75	363.41	0.0244	59.46	52.90
New Nov-25-00 3	75	303.38	0.0211	57.37	51.09
New Nov-25-00 4	75	-	-	79.57	-
New Nov-25-00 5	75	-	-	94.08	-
Mean		333.39	0.0228	74.50	52.00
St. Dev		42.44	0.0023	15.70	1.28
CoV		12.73	10.28	21.07	2.47

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_6

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23951
Calibration - R_{min}	-60
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	12.0
r_i (cm)	11.0
h_f (cm)	1.5

Maximum Torque (N.m.)	644.67
X-axis Intercept	0.80
Angle at Failure (rad)	0.0211
Initial Shear Stiffness (Mpa)	50.13
Secant Shear Stiffness (Mpa)	45.82

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-38	0.0000	0.54	0.74
0.10	0	0.0023	1.48	2.01
0.20	41	0.0047	2.50	3.38
0.30	65	0.0070	3.09	4.19
0.40	151	0.0093	5.21	7.07
0.50	301	0.0116	8.92	12.09
0.60	575	0.0140	15.69	21.27
0.70	1077	0.0163	28.09	38.09
0.80	2240	0.0186	56.83	77.05
0.90	3768	0.0209	94.59	128.24
1.00	5112	0.0233	127.80	173.27
1.10	6864	0.0256	171.09	231.96
1.20	9123	0.0279	226.91	307.65
1.30	11419	0.0302	283.64	384.56
1.40	14175	0.0326	351.74	476.90
1.50	16152	0.0349	400.59	543.13
1.60	18163	0.0372	450.28	610.50
1.70	19183	0.0396	475.49	644.67
1.80	18380	0.0419	455.64	617.77
1.90	10316	0.0442	256.39	347.61
2.00	7787	0.0465	193.90	262.89
2.10	7336	0.0489	182.75	247.78
2.20	7096	0.0512	176.82	239.74
2.30	6935	0.0535	172.84	234.34
2.40	6808	0.0558	169.70	230.09
2.50	6683	0.0582	166.62	225.90
2.60	6567	0.0605	163.75	222.02
2.70	6518	0.0628	162.54	220.37
2.80	6434	0.0652	160.46	217.56

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_7

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23974
Calibration - R_{min}	-51
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	12.0
r_i (cm)	10.5
h_r (cm)	1.4

Maximum Torque (N.m.)	644.19
X-axis Intercept	1.31
Angle at Failure (rad)	0.0304
Initial Shear Stiffness (Mpa)	46.25
Secant Shear Stiffness (Mpa)	31.75

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-25	0.0000	0.64	0.87
0.10	0	0.0023	1.26	1.71
0.20	0	0.0047	1.26	1.71
0.30	46	0.0070	2.40	3.25
0.40	96	0.0093	3.63	4.92
0.50	194	0.0116	6.05	8.20
0.60	266	0.0140	7.83	10.61
0.70	336	0.0163	9.56	12.96
0.80	409	0.0186	11.36	15.40
0.90	521	0.0209	14.13	19.15
1.00	747	0.0233	19.71	26.72
1.10	1143	0.0256	29.49	39.98
1.20	1751	0.0279	44.50	60.33
1.30	2555	0.0302	64.36	87.25
1.40	3766	0.0326	94.26	127.80
1.50	5332	0.0349	132.93	180.23
1.60	6727	0.0372	167.38	226.94
1.70	8609	0.0396	213.86	289.95
1.80	10052	0.0419	249.49	338.27
1.90	12692	0.0442	314.69	426.66
2.00	14916	0.0465	369.61	501.13
2.10	17421	0.0489	431.47	585.00
2.20	19189	0.0512	475.13	644.19
2.30	20834	0.0535	515.76	699.27
2.40	22146	0.0558	548.16	743.20
2.50	23126	0.0582	572.36	776.01
2.60	23245	0.0605	575.30	780.00
2.70	20674	0.0628	511.81	693.92
2.80	12098	0.0652	300.02	406.77

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_8

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23976
Calibration - R _{min}	-50
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r _o (cm)	11.2
r _i (cm)	10.5
h _i (cm)	1.6

Maximum Torque (N.m.)	668.44
X-axis Intercept	1.21
Angle at Failure (rad)	0.0303
Initial Shear Stiffness (Mpa)	43.28
Secant Shear Stiffness (Mpa)	33.13

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-23.00	0.0000	0.67	0.90
0.10	0.00	0.0023	1.23	1.67
0.20	0.00	0.0047	1.23	1.67
0.30	27.00	0.0070	1.90	2.58
0.40	84.00	0.0093	3.31	4.49
0.50	176.00	0.0116	5.58	7.57
0.60	285.00	0.0140	8.27	11.22
0.70	433.00	0.0163	11.93	16.17
0.80	650.00	0.0186	17.29	23.44
0.90	919.00	0.0209	23.93	32.44
1.00	1259.00	0.0233	32.32	43.83
1.10	1739.00	0.0256	44.18	59.90
1.20	2617.00	0.0279	65.86	89.29
1.30	3583.00	0.0302	89.71	121.64
1.40	4868.00	0.0326	121.45	164.66
1.50	6020.00	0.0349	149.89	203.23
1.60	7661.00	0.0372	190.42	258.17
1.70	9618.00	0.0396	236.74	323.69
1.80	11653.00	0.0419	288.99	391.82
1.90	13759.00	0.0442	341.00	462.33
2.00	15883.00	0.0465	393.45	533.45
2.10	17973.00	0.0489	445.06	603.42
2.20	19915.00	0.0512	493.02	668.44
2.30	21662.00	0.0535	536.16	726.93
2.40	23471.00	0.0558	580.83	787.50
2.50	24481.00	0.0582	605.77	821.31
2.60	23856.00	0.0605	590.34	800.39
2.70	18769.00	0.0628	464.72	630.07
2.80	14790.00	0.0652	366.46	496.85

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_9

Epoxy Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23957
Calibration - R_{min}	-55
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	6
Air Temp (°C)	3

Maximum Torque (N.m.)	862.33
X-axis Intercept	0.91
Angle at Failure (rad)	0.0325
Initial Shear Stiffness (Mpa)	48.22
Secant Shear Stiffness (Mpa)	39.74

Failure Dimensions	
r_o (cm)	11.2
r_i (cm)	10.5
h_i (cm)	1.6

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-35	0.0000	0.49	0.67
0.10	-32	0.0023	0.57	0.77
0.20	0	0.0047	1.36	1.84
0.30	44	0.0070	2.45	3.32
0.40	103	0.0093	3.90	5.29
0.50	243	0.0116	7.36	9.98
0.60	425	0.0140	11.86	16.08
0.70	845	0.0163	22.24	30.15
0.80	1439	0.0186	36.91	50.05
0.90	2385	0.0209	60.29	81.74
1.00	3633	0.0233	91.12	123.55
1.10	5197	0.0256	129.77	175.94
1.20	6770	0.0279	168.64	228.64
1.30	8746	0.0302	217.46	294.84
1.40	10879	0.0326	270.16	366.29
1.50	13128	0.0349	325.73	441.63
1.60	15433	0.0372	382.68	518.85
1.70	17546	0.0396	434.89	589.64
1.80	19220	0.0419	476.26	645.72
1.90	20564	0.0442	509.46	690.74
2.00	22338	0.0465	553.30	750.17
2.10	23940	0.0489	592.88	803.84
2.20	25686	0.0512	636.02	862.33
2.30	27412	0.0535	678.67	920.15
2.40	26883	0.0558	665.60	902.43
2.50	3202	0.0582	80.48	109.11
2.60	3263	0.0605	81.98	111.15
2.70	3298	0.0628	82.85	112.33
2.80	3194	0.0652	80.28	108.84

Section ID	Carleton-2 Section (6°C)
Sample ID	New Nov-25-00_10

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23966
Calibration - R_{min}	-55
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	10.5
r_i (cm)	10.0
h_i (cm)	1.7

Maximum Torque (N.m.)	726.08
X-axis Intercept	0.73
Angle at Failure (rad)	0.0298
Initial Shear Stiffness (Mpa)	40.79
Secant Shear Stiffness (Mpa)	36.58

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-27	0.0000	0.69	0.94
0.10	0	0.0023	1.36	1.84
0.20	65	0.0047	2.96	4.02
0.30	153	0.0070	5.14	6.97
0.40	268	0.0093	7.98	10.82
0.50	459	0.0116	12.70	17.21
0.60	757	0.0140	20.06	27.19
0.70	1329	0.0163	34.18	46.35
0.80	2474	0.0186	62.46	84.69
0.90	4012	0.0209	100.45	136.19
1.00	5421	0.0233	135.25	183.38
1.10	7068	0.0256	175.93	238.53
1.20	8705	0.0279	216.37	293.35
1.30	10399	0.0302	258.21	350.08
1.40	12500	0.0326	310.10	420.44
1.50	14544	0.0349	360.58	488.89
1.60	16377	0.0372	405.86	550.27
1.70	18073	0.0396	447.75	607.06
1.80	19572	0.0419	484.77	657.26
1.90	20824	0.0442	515.70	699.19
2.00	21627	0.0465	535.53	726.08
2.10	19549	0.0489	484.20	656.49
2.20	5477	0.0512	136.64	185.25
2.30	5207	0.0535	129.97	176.21
2.40	4967	0.0558	124.04	168.17
2.50	4706	0.0582	117.59	159.43
2.60	4527	0.0605	113.17	153.44
2.70	4321	0.0628	108.08	146.54
2.80	4222	0.0652	105.64	143.23

Carleton-2 Section**(6oC)**

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New Nov-25-00 6	100	644.67	0.0211	50.13	45.82
New Nov-25-00 7	100	644.19	0.0304	46.25	31.75
New Nov-25-00 8	100	668.44	0.0303	43.28	33.13
New Nov-25-00 9	100	862.33	0.0325	48.22	39.74
New Nov-25-00 10	100	726.08	0.0298	40.79	36.58
Mean		709.14	0.0288	45.74	37.40
St. Dev		91.90	0.0044	3.75	5.64
CoV		12.96	15.42	8.20	15.08

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_11

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23973
Calibration - R _{min}	-66
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	6
Air Temp (°C)	3

Test Stopped Prior to Failure

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _r (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.78
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	11.55
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-41	0.0000	0.62	0.84
0.10	-32	0.0023	0.84	1.14
0.20	0	0.0047	1.63	2.21
0.30	92	0.0070	3.90	5.29
0.40	253	0.0093	7.87	10.67
0.50	570	0.0116	15.70	21.28
0.60	1055	0.0140	27.67	37.51
0.70	1656	0.0163	42.50	57.62
0.80	2655	0.0186	67.16	91.05
0.90	3823	0.0209	95.98	130.14
1.00	5123	0.0233	128.07	173.64
1.10	6537	0.0256	162.97	220.95
1.20	8264	0.0279	205.34	278.41
1.30	9923	0.0302	246.54	334.26
1.40	11328	0.0326	281.21	381.27
1.50	13220	0.0349	327.91	444.58
1.60	15036	0.0372	372.73	505.35
1.70	16760	0.0396	415.28	563.04
1.80	18402	0.0419	455.80	617.99
1.90	19928	0.0442	493.47	669.05
2.00	21371	0.0465	529.08	717.34
2.10	23333	0.0489	577.50	782.99
2.20	24796	0.0512	613.61	831.95
2.30	27352	0.0535	676.70	917.48
2.40	29665	0.0558	733.78	994.88
2.50	31612	0.0582	781.84	1060.03
2.60	33415	0.0605	826.34	1120.36
2.70	34830	0.0628	861.26	1167.71

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_12

Test Stopped Prior to Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23974
Calibration - R_{min}	-51
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_i (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.93
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	13.90
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-27	0.0000	0.59	0.80
0.10	-24	0.0023	0.67	0.90
0.20	35	0.0047	2.12	2.88
0.30	115	0.0070	4.10	5.56
0.40	201	0.0093	6.22	8.44
0.50	339	0.0116	9.63	13.06
0.60	545	0.0140	14.72	19.96
0.70	883	0.0163	23.07	31.27
0.80	1428	0.0186	36.52	49.52
0.90	2097	0.0209	53.05	71.92
1.00	3351	0.0233	84.01	113.91
1.10	4964	0.0256	123.85	167.91
1.20	6535	0.0279	162.64	220.51
1.30	7757	0.0302	192.82	261.43
1.40	9411	0.0326	233.67	316.81
1.50	11395	0.0349	282.66	383.24
1.60	13791	0.0372	341.83	463.46
1.70	16363	0.0396	405.35	549.57
1.80	18716	0.0419	463.45	628.36
1.90	21030	0.0442	520.60	705.84
2.00	23607	0.0465	584.24	792.12
2.10	27078	0.0489	669.95	908.33
2.20	30674	0.0512	758.76	1028.74
2.30	33459	0.0535	827.53	1121.98
2.40	34016	0.0558	841.29	1140.63
2.50	34024	0.0582	841.49	1140.90
2.60	34172	0.0605	845.14	1145.86
2.70	34320	0.0628	848.80	1150.81
2.80	34448	0.0652	851.96	1155.10

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_13

Test Stopped Prior to Failure

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23964
Calibration - R _{min}	-55
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	6
Air Temp (°C)	3

Failure Dimensions		
r _o (cm)		
r _i (cm)		
h _i (cm)		
Maximum Torque (N.m.)		-
X-axis Intercept		0.89
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		12.55
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-23.00	0.0000	0.79	1.07
0.10	0.00	0.0023	1.36	1.84
0.20	55.00	0.0047	2.72	3.68
0.30	75.00	0.0070	3.21	4.35
0.40	120.00	0.0093	4.32	5.86
0.50	221.00	0.0116	6.82	9.24
0.60	391.00	0.0140	11.02	14.94
0.70	753.00	0.0163	19.96	27.06
0.80	1497.00	0.0186	38.34	51.98
0.90	1978.00	0.0209	50.22	68.09
1.00	2687.00	0.0233	67.73	91.83
1.10	4265.00	0.0256	106.71	144.68
1.20	5837.00	0.0279	145.54	197.33
1.30	7792.00	0.0302	193.83	262.80
1.40	9534.00	0.0326	236.86	321.14
1.50	11280.00	0.0349	279.99	379.61
1.60	13414.00	0.0372	332.70	451.08
1.70	15827.00	0.0396	392.31	531.89
1.80	17714.00	0.0419	438.92	595.09
1.90	19490.00	0.0442	482.79	654.57
2.00	20516.00	0.0465	508.13	688.93
2.10	22685.00	0.0489	561.71	761.57
2.20	25120.00	0.0512	621.85	843.12
2.30	28325.00	0.0535	701.02	950.46
2.40	31567.00	0.0558	781.10	1059.03
2.50	33976.00	0.0582	840.61	1139.71
2.60	34040.00	0.0605	842.19	1141.86
2.70	34246.00	0.0628	847.28	1148.76
2.80	34414.00	0.0652	851.43	1154.38

Section ID	Carleton-2 Section (6°C)
Sample ID	New_Nov-25-00_14

Date	25-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23982
Calibration - R _{min}	-44
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	6
Air Temp (°C)	3

Test Stopped Prior to Failure

Failure Dimensions		
r _o (cm)		
r _i (cm)		
h _r (cm)		
Maximum Torque (N.m.)		-
X-axis Intercept		0.60
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		14.73
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-24	0.0000	0.49	0.67
0.10	61	0.0023	2.59	3.52
0.20	130	0.0047	4.30	5.83
0.30	323	0.0070	9.06	12.29
0.40	686	0.0093	18.03	24.44
0.50	1314	0.0116	33.53	45.47
0.60	2204	0.0140	55.51	75.26
0.70	3431	0.0163	85.81	116.35
0.80	5087	0.0186	126.71	171.79
0.90	6838	0.0209	169.94	230.41
1.00	9041	0.0233	224.35	304.17
1.10	11321	0.0256	280.65	380.51
1.20	13680	0.0279	338.90	459.49
1.30	16011	0.0302	396.46	537.53
1.40	18412	0.0326	455.75	617.92
1.50	20720	0.0349	512.75	695.19
1.60	22843	0.0372	565.17	766.27
1.70	24919	0.0396	616.44	835.78
1.80	28143	0.0419	696.05	943.72
1.90	30836	0.0442	762.55	1033.88
2.00	32363	0.0465	800.26	1085.01
2.10	34408	0.0489	850.76	1153.48
2.20	35186	0.0512	869.97	1179.52
2.30	34786	0.0535	860.09	1166.13
2.40	34925	0.0558	863.53	1170.79
2.50	35095	0.0582	867.73	1176.48
2.60	35247	0.0605	871.48	1181.57
2.70	35392	0.0628	875.06	1186.42
2.80	35547	0.0652	878.89	1191.61

Carleton-2 Section

(6oC)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
New_Nov-25-00_11	150	-	-	11.55	-
New_Nov-25-00_12	150	-	-	13.90	-
New_Nov-25-00_13	150	-	-	12.55	-
New_Nov-25-00_14	150	-	-	14.73	-
Mean		-	-	13.18	-
St. Dev		-	-	1.41	-
CoV		-	-	10.73	-

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_11

Test Stopped before Failure

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23934
Calibration - R_{min}	-89
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Failure Dimensions		
r_o (cm)		0.73
r_l (cm)		-
h_l (cm)		12.53
Maximum Torque (N.m.)		-
X-axis Intercept		0.73
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		12.53
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-43	0.0000	1.14	1.54
0.10	25	0.0023	2.82	3.82
0.20	143	0.0047	5.73	7.77
0.30	365	0.0070	11.21	15.20
0.40	712	0.0093	19.78	26.82
0.50	1107	0.0116	29.54	40.05
0.60	1612	0.0140	42.01	56.96
0.70	2345	0.0163	60.11	81.50
0.80	3676	0.0186	92.98	126.07
0.90	5074	0.0209	127.51	172.88
1.00	6058	0.0233	151.81	205.83
1.10	7092	0.0256	177.35	240.45
1.20	9077	0.0279	226.37	306.92
1.30	11053	0.0302	275.18	373.09
1.40	13061	0.0326	324.77	440.33
1.50	15138	0.0349	376.06	509.87
1.60	17190	0.0372	426.74	578.58
1.70	19086	0.0396	473.57	642.07
1.80	20869	0.0419	517.60	701.78
1.90	22978	0.0442	569.69	772.40
2.00	25435	0.0465	630.37	854.67
2.10	28930	0.0489	716.69	971.70
2.20	31323	0.0512	775.79	1051.83
2.30	32993	0.0535	817.03	1107.75

Section ID	Carleton-2 Section (8°C)
Sample ID	New Nov-08-00 12

Data Error

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23944
Calibration - R_{min}	-73
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_f (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	-
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	-
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00		0.0000	1.80	2.45
0.10		0.0023	1.80	2.45
0.20		0.0047	1.80	2.45
0.30		0.0070	1.80	2.45
0.40		0.0093	1.80	2.45
0.50		0.0116	1.80	2.45
0.60		0.0140	1.80	2.45
0.70		0.0163	1.80	2.45
0.80		0.0186	1.80	2.45
0.90		0.0209	1.80	2.45
1.00		0.0233	1.80	2.45
1.10		0.0256	1.80	2.45
1.20		0.0279	1.80	2.45
1.30		0.0302	1.80	2.45
1.40		0.0326	1.80	2.45
1.50		0.0349	1.80	2.45
1.60		0.0372	1.80	2.45
1.70		0.0396	1.80	2.45
1.80		0.0419	1.80	2.45
1.90		0.0442	1.80	2.45
2.00		0.0465	1.80	2.45
2.10		0.0489	1.80	2.45
2.20		0.0512	1.80	2.45
2.30		0.0535	1.80	2.45

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_14

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23942
Calibration - R _{min}	-64
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Test Stopped before Failure

Failure Dimensions		
r _o (cm)	7.8	
r _i (cm)	6.8	
h _i (cm)	2.6	
Maximum Torque (N.m.)		-
X-axis Intercept		0.39
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		10.60
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-41	0.0000	0.57	0.77
0.10	0	0.0023	1.58	2.14
0.20	105	0.0047	4.18	5.66
0.30	261	0.0070	8.03	10.89
0.40	741	0.0093	19.90	26.97
0.50	1735	0.0116	44.46	60.28
0.60	3276	0.0140	82.55	111.92
0.70	4658	0.0163	116.70	158.23
0.80	5848	0.0186	146.11	198.10
0.90	6925	0.0209	172.73	234.19
1.00	7922	0.0233	197.37	267.60
1.10	9409	0.0256	234.12	317.43
1.20	11613	0.0279	288.59	391.28
1.30	14513	0.0302	360.27	488.45
1.40	16863	0.0326	418.34	567.20
1.50	18653	0.0349	462.58	627.18
1.60	20269	0.0372	502.52	681.33
1.70	21830	0.0396	541.10	733.64
1.80	23169	0.0419	574.20	778.50
1.90	24646	0.0442	610.70	828.00
2.00	26140	0.0465	647.62	878.06
2.10	28233	0.0489	699.35	948.19
2.20	30276	0.0512	749.84	1016.65
2.30	32049	0.0535	793.66	1076.06

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_15

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23979
Calibration - R _{min}	-36
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Test Stopped before Failure

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	11.0
h _i (cm)	1.3
Maximum Torque (N.m.)	
X-axis Intercept	0.96
Angle at Failure (rad)	
Initial Shear Stiffness (Mpa)	15.29
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-22	0.0000	0.35	0.47
0.10	0	0.0023	0.89	1.21
0.20	61	0.0047	2.40	3.25
0.30	125	0.0070	3.98	5.39
0.40	235	0.0093	6.70	9.08
0.50	358	0.0116	9.73	13.20
0.60	572	0.0140	15.02	20.37
0.70	920	0.0163	23.62	32.02
0.80	1406	0.0186	35.63	48.30
0.90	2048	0.0209	51.49	69.81
1.00	2804	0.0233	70.16	95.13
1.10	4136	0.0256	103.07	139.75
1.20	5898	0.0279	146.60	198.77
1.30	8108	0.0302	201.20	272.79
1.40	10386	0.0326	257.48	349.10
1.50	12726	0.0349	315.29	427.48
1.60	15157	0.0372	375.35	508.90
1.70	17656	0.0396	437.09	592.61
1.80	20136	0.0419	498.36	675.68
1.90	22601	0.0442	559.26	758.25
2.00	24996	0.0465	618.43	838.47
2.10	27819	0.0489	688.17	933.03
2.20	30892	0.0512	764.09	1035.96
2.30	33250	0.0535	822.34	1114.95

Carleton-2 Section

(8oC)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New Nov-08-00 11	150	-	-	12.53	-
New Nov-08-00 12	150	-	-	-	-
New Nov-08-00 13	150	-	-	17.51	-
New Nov-08-00 14	150	-	-	10.60	-
New Nov-08-00 15	150	-	-	15.29	-
Mean		-	-	13.98	-
St. Dev		-	-	3.04	-
CoV		-	-	21.74	-

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_6

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23519
Calibration - R_{min}	-59
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	8
Air Temp (°C)	6

Epoxy Failure

Failure Dimensions		
r_o (cm)		
r_i (cm)		
h_i (cm)		
Maximum Torque (N.m.)		-
X-axis Intercept		0.55
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		64.53
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-45	0.0000	0.35	0.48
0.10	-43	0.0023	0.40	0.55
0.20	0	0.0047	1.48	2.01
0.30	75	0.0070	3.37	4.57
0.40	133	0.0093	4.83	6.55
0.50	465	0.0116	13.19	17.88
0.60	1959	0.0140	50.78	68.85
0.70	4123	0.0163	105.23	142.68
0.80	7799	0.0186	197.73	268.09
0.90	10400	0.0209	263.18	356.83
1.00	12676	0.0233	320.45	434.48
1.10	14803	0.0256	373.98	507.04
1.20	16641	0.0279	420.23	569.75
1.30	0	0.0302	1.48	2.01
1.40	0	0.0326	1.48	2.01
1.50	0	0.0349	1.48	2.01
1.60	0	0.0372	1.48	2.01
1.70	0	0.0396	1.48	2.01
1.80	0	0.0419	1.48	2.01
1.90	0	0.0442	1.48	2.01
2.00	0	0.0465	1.48	2.01
2.10	0	0.0489	1.48	2.01
2.20	0	0.0512	1.48	2.01
2.30	0	0.0535	1.48	2.01
2.40	0	0.0558	1.48	2.01
2.50	0	0.0582	1.48	2.01
2.60	0	0.0605	1.48	2.01
2.70	0	0.0628	1.48	2.01
	0			

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_7

Epoxy Failure

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23948
Calibration - R _{min}	-78
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	8
Air Temp (°C)	6

Maximum Torque (N.m.)	-
X-axis Intercept	1.04
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	34.24
Secant Shear Stiffness (Mpa)	-

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-75	0.0000	0.07	0.10
0.10	0	0.0023	1.93	2.61
0.20	-21	0.0047	1.41	1.91
0.30	99	0.0070	4.37	5.93
0.40	141	0.0093	5.41	7.33
0.50	198	0.0116	6.82	9.24
0.60	278	0.0140	8.79	11.92
0.70	444	0.0163	12.89	17.48
0.80	701	0.0186	19.24	26.08
0.90	1060	0.0209	28.10	38.10
1.00	1579	0.0233	40.92	55.48
1.10	2263	0.0256	57.81	78.38
1.20	3166	0.0279	80.11	108.61
1.30	4399	0.0302	110.56	149.89
1.40	5711	0.0326	142.95	193.82
1.50	7209	0.0349	179.95	243.97
1.60	8805	0.0372	219.36	297.41
1.70	10334	0.0396	257.11	348.60
1.80	11864	0.0419	294.90	399.83
1.90	13473	0.0442	334.63	453.70
2.00	15079	0.0465	374.29	507.47
2.10	16533	0.0489	410.19	556.15
2.20	334	0.0512	10.17	13.79
2.30	490	0.0535	14.03	19.02
2.40	724	0.0558	19.80	26.85
2.50	678	0.0582	18.67	25.31
2.60	665	0.0605	18.35	24.88
2.70	654	0.0628	18.08	24.51
	632			

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_8

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23896
Calibration - R _{min}	-128
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	8
Air Temp (°C)	6

Failure in Epoxy and Pavement

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Maximum Torque (N.m.)	576.22
X-axis Intercept	0.79
Angle at Failure (rad)	0.0213
Initial Shear Stiffness (Mpa)	43.30
Secant Shear Stiffness (Mpa)	40.55

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-49.00	0.0000	1.95	2.65
0.10	30.00	0.0023	3.90	5.29
0.20	93.00	0.0047	5.46	7.40
0.30	199.00	0.0070	8.08	10.95
0.40	402.00	0.0093	13.09	17.75
0.50	748.00	0.0116	21.63	29.33
0.60	1075.00	0.0140	29.71	40.28
0.70	1267.00	0.0163	34.45	46.71
0.80	1720.00	0.0186	45.64	61.88
0.90	2659.00	0.0209	68.83	93.32
1.00	4183.00	0.0233	106.47	144.35
1.10	5594.00	0.0256	141.31	191.59
1.20	7917.00	0.0279	198.68	269.37
1.30	10115.00	0.0302	252.96	342.97
1.40	12722.00	0.0326	317.35	430.26
1.50	14597.00	0.0349	363.65	493.04
1.60	16077.00	0.0372	400.20	542.60
1.70	17081.00	0.0396	425.00	576.22
1.80	16596.00	0.0419	413.02	559.98
1.90	-94.00	0.0442	0.84	1.14
2.00	-99.00	0.0465	0.72	0.97
2.10	-95.00	0.0489	0.81	1.10
2.20	-86.00	0.0512	1.04	1.41
2.30	-86.00	0.0535	1.04	1.41
2.40	-86.00	0.0558	1.04	1.41
2.50	-89.00	0.0582	0.96	1.31
2.60	-85.00	0.0605	1.06	1.44
2.70	-82.00	0.0628	1.14	1.54
	-82.00			

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_9

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23965
Calibration - R _{min}	-62
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	8
Air Temp (°C)	6

Epoxy Failure

Failure Dimensions	
r _o (cm)	11.5
r _r (cm)	11.0
h _r (cm)	1.3

Maximum Torque (N.m.)	-
X-axis Intercept	0.74
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	52.84
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-54	0.0000	0.20	0.27
0.10	-22	0.0023	0.99	1.34
0.20	79	0.0047	3.48	4.72
0.30	181	0.0070	6.00	8.14
0.40	375	0.0093	10.79	14.63
0.50	810	0.0116	21.53	29.19
0.60	1777	0.0140	45.41	61.57
0.70	2923	0.0163	73.71	99.94
0.80	4298	0.0186	107.66	145.97
0.90	5797	0.0209	144.68	196.16
1.00	7526	0.0233	187.37	254.04
1.10	9482	0.0256	235.67	319.53
1.20	11005	0.0279	273.28	370.52
1.30	13309	0.0302	330.17	447.65
1.40	15748	0.0326	390.40	529.31
1.50	18057	0.0349	447.41	606.61
1.60	19993	0.0372	495.22	671.43
1.70	-95	0.0396	-0.81	-1.10
1.80	-97	0.0419	-0.86	-1.17
1.90	-96	0.0442	-0.84	-1.14
2.00	-92	0.0465	-0.74	-1.00
2.10	-92	0.0489	-0.74	-1.00
2.20	-92	0.0512	-0.74	-1.00
2.30	-92	0.0535	-0.74	-1.00
2.40	-92	0.0558	-0.74	-1.00
2.50	-92	0.0582	-0.74	-1.00
2.60	-92	0.0605	-0.74	-1.00
2.70	-92	0.0628	-0.74	-1.00
	-92			

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_10

Date	08-Nov-00
Weather	Sunny
Test Speed (pm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23974
Calibration - R_{min}	-60
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	8
Air Temp (°C)	6

Failure Dimensions	
r_o (cm)	11.5
r_i (cm)	11.0
h_i (cm)	1.3

Maximum Torque (N.m.)	653.19
X-axis Intercept	0.59
Angle at Failure (rad)	0.0237
Initial Shear Stiffness (Mpa)	45.89
Secant Shear Stiffness (Mpa)	41.34

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-65	0.0000	-0.12	-0.17
0.10	51	0.0023	2.74	3.72
0.20	130	0.0047	4.69	6.36
0.30	377	0.0070	10.79	14.63
0.40	791	0.0093	21.01	28.48
0.50	1802	0.0116	45.97	62.32
0.60	3081	0.0140	77.54	105.13
0.70	4239	0.0163	106.12	143.89
0.80	5168	0.0186	129.06	174.98
0.90	7012	0.0209	174.58	236.70
1.00	8532	0.0233	212.10	287.57
1.10	10961	0.0256	272.06	368.87
1.20	13272	0.0279	329.11	446.22
1.30	15415	0.0302	382.01	517.94
1.40	17151	0.0326	424.87	576.04
1.50	18596	0.0349	460.54	624.41
1.60	19456	0.0372	481.77	653.19
1.70	19142	0.0396	474.02	642.68
1.80	15597	0.0419	386.51	524.03
1.90	10910	0.0442	270.80	367.16
2.00	5042	0.0465	125.95	170.76
2.10	5236	0.0489	130.74	177.25
2.20	5195	0.0512	129.72	175.88
2.30	4937	0.0535	123.36	167.25
2.40	4833	0.0558	120.79	163.77
2.50	4839	0.0582	120.94	163.97
2.60	4770	0.0605	119.23	161.66
2.70	4721	0.0628	118.02	160.02
	4668			

Carleton-2 Section

(8oC)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New Nov-08-00 6	100	-	-	64.53	-
New Nov-08-00 7	100	-	-	34.24	-
New Nov-08-00 8	100	576.22	0.0213	43.30	40.55
New Nov-08-00 9	100	-	-	52.84	-
New Nov-08-00 10	100	653.19	0.0237	45.89	41.34
Mean		614.70	0.0225	48.16	40.95
St. Dev		54.43	0.0017	11.32	0.56
CoV		8.85	7.48	23.50	1.38

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_11

Test Stopped before Failure

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23934
Calibration - R_{min}	-89
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Failure Dimensions	
r_o (cm)	
r_i (cm)	
h_r (cm)	

Maximum Torque (N.m.)	-
X-axis Intercept	0.73
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	12.53
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-43	0.0000	1.14	1.54
0.10	25	0.0023	2.82	3.82
0.20	143	0.0047	5.73	7.77
0.30	365	0.0070	11.21	15.20
0.40	712	0.0093	19.78	26.82
0.50	1107	0.0116	29.54	40.05
0.60	1612	0.0140	42.01	56.96
0.70	2345	0.0163	60.11	81.50
0.80	3676	0.0186	92.98	126.07
0.90	5074	0.0209	127.51	172.88
1.00	6058	0.0233	151.81	205.83
1.10	7092	0.0256	177.35	240.45
1.20	9077	0.0279	226.37	306.92
1.30	11053	0.0302	275.18	373.09
1.40	13061	0.0326	324.77	440.33
1.50	15138	0.0349	376.06	509.87
1.60	17190	0.0372	426.74	578.58
1.70	19086	0.0396	473.57	642.07
1.80	20869	0.0419	517.60	701.78
1.90	22978	0.0442	569.69	772.40
2.00	25435	0.0465	630.37	854.67
2.10	28930	0.0489	716.69	971.70
2.20	31323	0.0512	775.79	1051.83
2.30	32993	0.0535	817.03	1107.75

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_12

Data Error

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	23944
Calibration - R _{min}	-73
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Maximum Torque (N.m.)	-
X-axis Intercept	-
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	-
Secant Shear Stiffness (Mpa)	-

Failure Dimensions	
r _o (cm)	
r _i (cm)	
h _i (cm)	

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00		0.0000	1.80	2.45
0.10		0.0023	1.80	2.45
0.20		0.0047	1.80	2.45
0.30		0.0070	1.80	2.45
0.40		0.0093	1.80	2.45
0.50		0.0116	1.80	2.45
0.60		0.0140	1.80	2.45
0.70		0.0163	1.80	2.45
0.80		0.0186	1.80	2.45
0.90		0.0209	1.80	2.45
1.00		0.0233	1.80	2.45
1.10		0.0256	1.80	2.45
1.20		0.0279	1.80	2.45
1.30		0.0302	1.80	2.45
1.40		0.0326	1.80	2.45
1.50		0.0349	1.80	2.45
1.60		0.0372	1.80	2.45
1.70		0.0396	1.80	2.45
1.80		0.0419	1.80	2.45
1.90		0.0442	1.80	2.45
2.00		0.0465	1.80	2.45
2.10		0.0489	1.80	2.45
2.20		0.0512	1.80	2.45
2.30		0.0535	1.80	2.45

Section ID	Carleton-2 Section (8°C)
Sample ID	New Nov-08-00_14

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23942
Calibration - R_{min}	-64
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Test Stopped before Failure

Failure Dimensions	
r_o (cm)	7.8
r_r (cm)	6.8
h_r (cm)	2.6

Maximum Torque (N.m.)	-
X-axis Intercept	0.39
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	10.60
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-41	0.0000	0.57	0.77
0.10	0	0.0023	1.58	2.14
0.20	105	0.0047	4.18	5.66
0.30	261	0.0070	8.03	10.89
0.40	741	0.0093	19.90	26.97
0.50	1735	0.0116	44.46	60.28
0.60	3276	0.0140	82.55	111.92
0.70	4658	0.0163	116.70	158.23
0.80	5848	0.0186	146.11	198.10
0.90	6925	0.0209	172.73	234.19
1.00	7922	0.0233	197.37	267.60
1.10	9409	0.0256	234.12	317.43
1.20	11613	0.0279	288.59	391.28
1.30	14513	0.0302	360.27	488.45
1.40	16863	0.0326	418.34	567.20
1.50	18653	0.0349	462.58	627.18
1.60	20269	0.0372	502.52	681.33
1.70	21830	0.0396	541.10	733.64
1.80	23169	0.0419	574.20	778.50
1.90	24646	0.0442	610.70	828.00
2.00	26140	0.0465	647.62	878.06
2.10	28233	0.0489	699.35	948.19
2.20	30276	0.0512	749.84	1016.65
2.30	32049	0.0535	793.66	1076.06

Section ID	Carleton-2 Section (8°C)
Sample ID	New_Nov-08-00_15

Date	08-Nov-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	23979
Calibration - R_{min}	-36
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	8
Air Temp (°C)	6

Test Stopped before Failure

Failure Dimensions	
r_o (cm)	11.5
r_i (cm)	11.0
h_i (cm)	1.3

Maximum Torque (N.m.)	
X-axis Intercept	0.96
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	15.29
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-22	0.0000	0.35	0.47
0.10	0	0.0023	0.89	1.21
0.20	61	0.0047	2.40	3.25
0.30	125	0.0070	3.98	5.39
0.40	235	0.0093	6.70	9.08
0.50	358	0.0116	9.73	13.20
0.60	572	0.0140	15.02	20.37
0.70	920	0.0163	23.62	32.02
0.80	1406	0.0186	35.63	48.30
0.90	2048	0.0209	51.49	69.81
1.00	2804	0.0233	70.16	95.13
1.10	4136	0.0256	103.07	139.75
1.20	5898	0.0279	146.60	198.77
1.30	8108	0.0302	201.20	272.79
1.40	10386	0.0326	257.48	349.10
1.50	12726	0.0349	315.29	427.48
1.60	15157	0.0372	375.35	508.90
1.70	17656	0.0396	437.09	592.61
1.80	20136	0.0419	498.36	675.68
1.90	22601	0.0442	559.26	758.25
2.00	24996	0.0465	618.43	838.47
2.10	27819	0.0489	688.17	933.03
2.20	30892	0.0512	764.09	1035.96
2.30	33250	0.0535	822.34	1114.95

Carleton-2 Section

(8oC)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
New Nov-08-00 11	150	-	-	12.53	-
New Nov-08-00 12	150	-	-	-	-
New Nov-08-00 13	150	-	-	17.51	-
New Nov-08-00 14	150	-	-	10.60	-
New Nov-08-00 15	150	-	-	15.29	-
Mean		-	-	13.98	-
St. Dev		-	-	3.04	-
CoV		-	-	21.74	-

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_1

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24000
Calibration - R_{min}	-29
Steel Plate Diameter (mm)	75
Pavement Temp (°C)	22
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions	
r_o (cm)	10.0
r_r (cm)	9.0
h_r (cm)	1.2

Maximum Torque (N.m.)	91.16
X-axis Intercept	1.21
Angle at Failure (rad)	0.0188
Initial Shear Stiffness (Mpa)	20.24
Secant Shear Stiffness (Mpa)	17.28

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-19.00	0.0000	0.25	0.33
0.20	65.00	0.0047	2.32	3.15
0.40	77.00	0.0093	2.62	3.55
0.60	128.00	0.0140	3.88	5.26
0.80	256.00	0.0186	7.04	9.54
1.00	447.00	0.0233	11.75	15.93
1.20	675.00	0.0279	17.38	23.57
1.40	965.00	0.0326	24.54	33.28
1.60	1362.00	0.0372	34.35	46.57
1.80	1834.00	0.0419	46.00	62.37
2.00	2249.00	0.0465	56.25	76.26
2.20	2544.00	0.0512	63.53	86.14
2.40	2694.00	0.0558	67.23	91.16
2.60	2680.00	0.0605	66.89	90.69
2.80	2553.00	0.0652	63.75	86.44
3.00	2418.00	0.0698	60.42	81.92
3.20	2281.00	0.0745	57.04	77.33
3.40	2141.00	0.0791	53.58	72.64
3.60	1947.00	0.0838	48.79	66.15
3.80	1822.00	0.0884	45.70	61.96
4.00	1768.00	0.0931	44.37	60.16
4.20	1720.00	0.0977	43.18	58.55
4.40	1687.00	0.1024	42.37	57.45
4.60	1664.00	0.1070	41.80	56.68
4.80	1650.00	0.1117	41.46	56.21
5.00	1634.00	0.1163	41.06	55.67
5.20	1625.00	0.1210	40.84	55.37
5.40	1605.00	0.1256	40.35	54.70

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_5

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24010
Calibration - R_{min}	-27
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r_o (cm)	11.7
r_r (cm)	11.0
r_t (cm)	1.4

Maximum Torque (N.m.)	131.45
X-axis Intercept	0.70
Angle at Failure (rad)	0.0165
Initial Shear Stiffness (Mpa)	25.14
Secant Shear Stiffness (Mpa)	11.97

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.67	0.90
0.10	60	0.0023	2.15	2.91
0.20	70	0.0047	2.39	3.25
0.30	88	0.0070	2.84	3.85
0.40	195	0.0093	5.48	7.43
0.50	422	0.0116	11.08	15.03
0.60	743	0.0140	19.01	25.77
0.70	1172	0.0163	29.59	40.12
0.80	1888	0.0186	47.27	64.09
0.90	2551	0.0209	63.63	86.27
1.00	3098	0.0233	77.13	104.58
1.10	3513	0.0256	87.38	118.47
1.20	3762	0.0279	93.52	126.80
1.30	3878	0.0302	96.39	130.68
1.40	3901	0.0326	96.95	131.45
1.50	3834	0.0349	95.30	129.21
1.60	3738	0.0372	92.93	126.00
1.70	3625	0.0396	90.14	122.22
1.80	3510	0.0419	87.30	118.37
1.90	3389	0.0442	84.32	114.32
2.00	3282	0.0465	81.68	110.74
2.10	3192	0.0489	79.45	107.72
2.20	3131	0.0512	77.95	105.68
2.30	3092	0.0535	76.99	104.38
2.40	3063	0.0558	76.27	103.41
2.50	3018	0.0582	75.16	101.90
2.60	2970	0.0605	73.97	100.30
2.70	2906	0.0628	72.39	98.15
	2850			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_6

Data not Recorded Correctly

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	23948
Calibration - R_{min}	-78
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	22
Air Temp (°C)	20

(Data recorded at 0.1-s, but presented at 0.2-s)

Failure Dimensions		
r_o (cm)		
r_i (cm)		
h_t (cm)		
Maximum Torque (N.m.)		-
X-axis Intercept		-
Angle at Failure (rad)		-
Initial Shear Stiffness (Mpa)		-
Secant Shear Stiffness (Mpa)		-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00		0.0000	1.93	2.61
0.20		0.0047	1.93	2.61
0.40		0.0093	1.93	2.61
0.60		0.0140	1.93	2.61
0.80		0.0186	1.93	2.61
1.00		0.0233	1.93	2.61
1.20		0.0279	1.93	2.61
1.40		0.0326	1.93	2.61
1.60		0.0372	1.93	2.61
1.80		0.0419	1.93	2.61
2.00		0.0465	1.93	2.61
2.20		0.0512	1.93	2.61
2.40		0.0558	1.93	2.61
2.60		0.0605	1.93	2.61
2.80		0.0652	1.93	2.61
3.00		0.0698	1.93	2.61
3.20		0.0745	1.93	2.61
3.40		0.0791	1.93	2.61
3.60		0.0838	1.93	2.61
3.80		0.0884	1.93	2.61
4.00		0.0931	1.93	2.61
4.20		0.0977	1.93	2.61
4.40		0.1024	1.93	2.61
4.60		0.1070	1.93	2.61
4.80		0.1117	1.93	2.61
5.00		0.1163	1.93	2.61
5.20		0.1210	1.93	2.61
5.40		0.1256	1.93	2.61

Section ID	Carleton-2 Section (22°C)
Sample ID	New May-20-01_7

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	24022
Calibration - R _{min}	-29
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r _o (cm)	12.0
r _i (cm)	10.5
h _i (cm)	1.4

Maximum Torque (N.m.)	137.66
X-axis Intercept	0.37
Angle at Failure (rad)	0.0217
Initial Shear Stiffness (Mpa)	11.81
Secant Shear Stiffness (Mpa)	9.50

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	0.00	0.0000	0.72	0.97
0.10	51.00	0.0023	1.97	2.68
0.20	80.00	0.0047	2.69	3.65
0.30	126.00	0.0070	3.82	5.18
0.40	294.00	0.0093	7.97	10.80
0.50	687.00	0.0116	17.66	23.95
0.60	1249.00	0.0140	31.53	42.74
0.70	1830.00	0.0163	45.86	62.18
0.80	2389.00	0.0186	59.65	80.87
0.90	2892.00	0.0209	72.06	97.70
1.00	3334.00	0.0233	82.96	112.48
1.10	3704.00	0.0256	92.09	124.85
1.20	3969.00	0.0279	98.62	133.72
1.30	4087.00	0.0302	101.54	137.66
1.40	4057.00	0.0326	100.80	136.66
1.50	3891.00	0.0349	96.70	131.11
1.60	3642.00	0.0372	90.56	122.78
1.70	3364.00	0.0396	83.70	113.48
1.80	3183.00	0.0419	79.23	107.43
1.90	3084.00	0.0442	76.79	104.12
2.00	3020.00	0.0465	75.21	101.98
2.10	2962.00	0.0489	73.78	100.04
2.20	2925.00	0.0512	72.87	98.80
2.30	2891.00	0.0535	72.03	97.66
2.40	2847.00	0.0558	70.95	96.19
2.50	2795.00	0.0582	69.66	94.45
2.60	2752.00	0.0605	68.60	93.01
2.70	2713.00	0.0628	67.64	91.71

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_8

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	24067
Calibration - R _{min}	50
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	11.0
h _t (cm)	1.3

Maximum Torque (N.m.)	107.21
X-axis Intercept	0.53
Angle at Failure (rad)	0.0204
Initial Shear Stiffness (Mpa)	11.80
Secant Shear Stiffness (Mpa)	7.87

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	49	0.0000	-0.02	-0.03
0.10	57	0.0023	0.17	0.23
0.20	169	0.0047	2.94	3.99
0.30	242	0.0070	4.74	6.43
0.40	357	0.0093	7.58	10.28
0.50	565	0.0116	12.72	17.25
0.60	840	0.0140	19.52	26.46
0.70	1126	0.0163	26.58	36.04
0.80	1462	0.0186	34.88	47.29
0.90	2006	0.0209	48.32	65.51
1.00	2499	0.0233	60.50	82.02
1.10	2841	0.0256	68.95	93.48
1.20	3082	0.0279	74.90	101.55
1.30	3212	0.0302	78.11	105.91
1.40	3251	0.0326	79.08	107.21
1.50	3217	0.0349	78.24	106.07
1.60	3106	0.0372	75.49	102.36
1.70	2938	0.0396	71.34	96.73
1.80	2799	0.0419	67.91	92.07
1.90	2708	0.0442	65.66	89.02
2.00	2646	0.0465	64.13	86.95
2.10	2580	0.0489	62.50	84.74
2.20	2527	0.0512	61.19	82.96
2.30	2490	0.0535	60.28	81.72
2.40	2445	0.0558	59.16	80.22
2.50	2417	0.0582	58.47	79.28
2.60	2385	0.0605	57.68	78.21
2.70	2364	0.0628	57.16	77.50
	2353			

Carleton-2 Section**(22oC)**

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New May-20-01 5	100	131.45	0.0165	25.14	11.97
New May-20-01 6	100	-	-	-	-
New May-20-01 7	100	137.66	0.0217	11.81	9.50
New May-20-01 8	100	107.21	0.0204	11.80	7.87
Mean		125.44	0.0195	16.25	9.78
St. Dev		16.09	0.0027	7.70	2.06
CoV		12.83	14.00	47.36	21.10

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_9

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24054
Calibration - R_{min}	30
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r_o (cm)	15.0
r_i (cm)	14.0
h_r (cm)	1.7

Maximum Torque (N.m.)	163.57
X-axis Intercept	0.46
Angle at Failure (rad)	0.0219
Initial Shear Stiffness (Mpa)	5.85
Secant Shear Stiffness (Mpa)	5.73

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	25	0.0000	-0.12	-0.17
0.10	30	0.0023	0.00	0.00
0.20	74	0.0047	1.09	1.47
0.30	277	0.0070	6.10	8.27
0.40	453	0.0093	10.45	14.16
0.50	702	0.0116	16.60	22.50
0.60	981	0.0140	23.49	31.84
0.70	1354	0.0163	32.70	44.33
0.80	2064	0.0186	50.23	68.11
0.90	2519	0.0209	61.47	83.34
1.00	3163	0.0233	77.37	104.90
1.10	3807	0.0256	93.28	126.47
1.20	4314	0.0279	105.80	143.44
1.30	4674	0.0302	114.69	155.50
1.40	4881	0.0326	119.80	162.43
1.50	4915	0.0349	120.64	163.57
1.60	4775	0.0372	117.18	158.88
1.70	4565	0.0396	112.00	151.85
1.80	4313	0.0419	105.77	143.41
1.90	4082	0.0442	100.07	135.67
2.00	3863	0.0465	94.66	128.34
2.10	3741	0.0489	91.65	124.26
2.20	3676	0.0512	90.04	122.08
2.30	3603	0.0535	88.24	119.64
2.40	3547	0.0558	86.86	117.76
2.50	3507	0.0582	85.87	116.42
2.60	3471	0.0605	84.98	115.22
2.70	3442	0.0628	84.26	114.25
	3378			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_10

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24018
Calibration - R_{min}	-29
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r_o (cm)	15.5
r_i (cm)	14.0
h_r (cm)	1.5

Maximum Torque (N.m.)	168.53
X-axis Intercept	0.48
Angle at Failure (rad)	0.0169
Initial Shear Stiffness (Mpa)	9.60
Secant Shear Stiffness (Mpa)	7.68

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	0	0.0000	0.72	0.97
0.10	68	0.0023	2.39	3.24
0.20	110	0.0047	3.43	4.65
0.30	226	0.0070	6.29	8.53
0.40	485	0.0093	12.68	17.19
0.50	809	0.0116	20.68	28.03
0.60	1201	0.0140	30.35	41.15
0.70	1958	0.0163	49.02	66.47
0.80	2886	0.0186	71.92	97.51
0.90	3722	0.0209	92.55	125.48
1.00	4392	0.0233	109.08	147.89
1.10	4831	0.0256	119.91	162.57
1.20	5009	0.0279	124.30	168.53
1.30	4936	0.0302	122.50	166.09
1.40	4689	0.0326	116.40	157.82
1.50	4422	0.0349	109.82	148.89
1.60	4170	0.0372	103.60	140.46
1.70	3895	0.0396	96.81	131.26
1.80	3664	0.0419	91.12	123.54
1.90	3506	0.0442	87.22	118.25
2.00	3422	0.0465	85.14	115.44
2.10	3366	0.0489	83.76	113.57
2.20	3321	0.0512	82.65	112.06
2.30	3274	0.0535	81.49	110.49
2.40	3228	0.0558	80.36	108.95
2.50	3178	0.0582	79.12	107.28
2.60	3136	0.0605	78.09	105.87
2.70	3103	0.0628	77.27	104.77
	3108			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_11

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24012
Calibration - R_{min}	-36
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r_o (cm)	15.0
r_i (cm)	14.0
h_i (cm)	1.5

Maximum Torque (N.m.)	230.91
X-axis Intercept	0.41
Angle at Failure (rad)	0.0209
Initial Shear Stiffness (Mpa)	9.34
Secant Shear Stiffness (Mpa)	8.48

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-29.00	0.0000	0.17	0.23
0.10	35.00	0.0023	1.75	2.37
0.20	92.00	0.0047	3.16	4.28
0.30	193.00	0.0070	5.65	7.66
0.40	431.00	0.0093	11.52	15.62
0.50	924.00	0.0116	23.68	32.11
0.60	1649.00	0.0140	41.57	56.36
0.70	2503.00	0.0163	62.64	84.93
0.80	3490.00	0.0186	86.99	117.94
0.90	4431.00	0.0209	110.21	149.42
1.00	5309.00	0.0233	131.87	178.79
1.10	6068.00	0.0256	150.59	204.18
1.20	6610.00	0.0279	163.97	222.31
1.30	6867.00	0.0302	170.31	230.91
1.40	6853.00	0.0326	169.96	230.44
1.50	6660.00	0.0349	165.20	223.98
1.60	6393.00	0.0372	158.61	215.05
1.70	6092.00	0.0396	151.19	204.98
1.80	5823.00	0.0419	144.55	195.98
1.90	5578.00	0.0442	138.51	187.79
2.00	5429.00	0.0465	134.83	182.80
2.10	5327.00	0.0489	132.31	179.39
2.20	5209.00	0.0512	129.40	175.45
2.30	5144.00	0.0535	127.80	173.27
2.40	5134.00	0.0558	127.55	172.94
2.50	5099.00	0.0582	126.69	171.77
2.60	5034.00	0.0605	125.08	169.59
2.70	4971.00	0.0628	123.53	167.48
	4926.00			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_12

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24010
Calibration - R_{min}	-36
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions		
r_o (cm)	15.0	Maximum Torque (N.m.)
r_i (cm)	13.5	X-axis Intercept
h_r (cm)	1.3	Angle at Failure (rad)
		Initial Shear Stiffness (Mpa)
		Secant Shear Stiffness (Mpa)

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-29	0.0000	0.17	0.23
0.10	37	0.0023	1.80	2.44
0.20	75	0.0047	2.74	3.71
0.30	116	0.0070	3.75	5.08
0.40	219	0.0093	6.29	8.53
0.50	407	0.0116	10.93	14.82
0.60	798	0.0140	20.58	27.90
0.70	1285	0.0163	32.59	44.19
0.80	1823	0.0186	45.87	62.19
0.90	2433	0.0209	60.92	82.60
1.00	3163	0.0233	78.93	107.02
1.10	3838	0.0256	95.59	129.60
1.20	4379	0.0279	108.93	147.69
1.30	4823	0.0302	119.89	162.55
1.40	4998	0.0326	124.21	168.40
1.50	5040	0.0349	125.24	169.81
1.60	4943	0.0372	122.85	166.56
1.70	4774	0.0396	118.68	160.91
1.80	4666	0.0419	116.01	157.30
1.90	4593	0.0442	114.21	154.85
2.00	4567	0.0465	113.57	153.98
2.10	4542	0.0489	112.96	153.15
2.20	4507	0.0512	112.09	151.98
2.30	4496	0.0535	111.82	151.61
2.40	4495	0.0558	111.80	151.57
2.50	4488	0.0582	111.62	151.34
2.60	4473	0.0605	111.25	150.84
2.70	4467	0.0628	111.10	150.64
	4367			

Carleton-2 Section

(22oC)

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
New May-20-01 9	125	163.57	0.0219	5.85	5.73
New May-20-01 10	125	168.53	0.0169	9.60	7.68
New May-20-01 11	125	230.91	0.0209	9.34	8.48
New May-20-01 12	125	169.81	0.0229	7.25	5.70
Mean		183.20	0.0206	8.01	6.90
St. Dev		31.92	0.0026	1.78	1.40
CoV		17.42	12.82	22.23	20.33

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_13

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	24004
Calibration - R _{min}	-23
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r _o (cm)	16.0
r _i (cm)	15.0
h _i (cm)	1.4

Maximum Torque (N.m.)	354.88
X-axis Intercept	0.46
Angle at Failure (rad)	0.0243
Initial Shear Stiffness (Mpa)	8.08
Secant Shear Stiffness (Mpa)	6.48

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.57	0.77
0.10	58	0.0023	2.00	2.71
0.20	87	0.0047	2.72	3.68
0.30	124	0.0070	3.63	4.92
0.40	378	0.0093	9.90	13.43
0.50	882	0.0116	22.35	30.30
0.60	1867	0.0140	46.67	63.28
0.70	2986	0.0163	74.30	100.74
0.80	4219	0.0186	104.75	142.02
0.90	5590	0.0209	138.60	187.92
1.00	6916	0.0233	171.35	232.31
1.10	8145	0.0256	201.69	273.46
1.20	9182	0.0279	227.30	308.18
1.30	9951	0.0302	246.29	333.92
1.40	10420	0.0326	257.87	349.62
1.50	10577	0.0349	261.75	354.88
1.60	10411	0.0372	257.65	349.32
1.70	9985	0.0396	247.13	335.06
1.80	9400	0.0419	232.68	315.48
1.90	8663	0.0442	214.48	290.80
2.00	7962	0.0465	197.17	267.33
2.10	7341	0.0489	181.84	246.54
2.20	6843	0.0512	169.54	229.87
2.30	6345	0.0535	157.25	213.20
2.40	5947	0.0558	147.42	199.87
2.50	5671	0.0582	140.60	190.63
2.60	5475	0.0605	135.76	184.07
2.70	5305	0.0628	131.56	178.38
	5140			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_14

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R_{max}	24112
Calibration - R_{min}	94
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r_o (cm)	18.0
r_i (cm)	16.5
h_i (cm)	2.0

Maximum Torque (N.m.)	451.64
X-axis Intercept	0.27
Angle at Failure (rad)	0.0288
Initial Shear Stiffness (Mpa)	8.17
Secant Shear Stiffness (Mpa)	6.98

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	86	0.0000	-0.20	-0.27
0.10	90	0.0023	-0.10	-0.13
0.20	456	0.0047	8.94	12.12
0.30	1165	0.0070	26.46	35.87
0.40	2053	0.0093	48.39	65.61
0.50	3106	0.0116	74.40	100.88
0.60	4273	0.0140	103.23	139.96
0.70	5616	0.0163	136.41	184.94
0.80	7031	0.0186	171.36	232.33
0.90	8205	0.0209	200.36	271.65
1.00	9636	0.0233	235.71	319.58
1.10	10907	0.0256	267.11	362.15
1.20	12000	0.0279	294.11	398.75
1.30	12857	0.0302	315.28	427.46
1.40	13414	0.0326	329.03	446.11
1.50	13579	0.0349	333.11	451.64
1.60	13278	0.0372	325.68	441.56
1.70	12472	0.0396	305.77	414.56
1.80	11349	0.0419	278.02	376.95
1.90	10379	0.0442	254.06	344.46
2.00	9574	0.0465	234.18	317.50
2.10	9017	0.0489	220.42	298.85
2.20	8686	0.0512	212.24	287.76
2.30	8456	0.0535	206.56	280.06
2.40	8235	0.0558	201.10	272.66
2.50	8042	0.0582	196.33	266.19
2.60	7866	0.0605	191.99	260.30
2.70	7687	0.0628	187.56	254.30
	7568			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_15

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	24041
Calibration - R _{min}	-32
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r _o (cm)	18.0
r _i (cm)	16.5
h _t (cm)	2.0

Maximum Torque (N.m.)	423.91
X-axis Intercept	0.56
Angle at Failure (rad)	0.0266
Initial Shear Stiffness (Mpa)	9.25
Secant Shear Stiffness (Mpa)	7.09

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-31.00	0.0000	0.02	0.03
0.10	47.00	0.0023	1.95	2.64
0.20	48.00	0.0047	1.97	2.67
0.30	62.00	0.0070	2.32	3.14
0.40	167.00	0.0093	4.90	6.65
0.50	407.00	0.0116	10.82	14.67
0.60	1063.00	0.0140	26.99	36.59
0.70	2065.00	0.0163	51.68	70.07
0.80	3287.00	0.0186	81.80	110.91
0.90	4732.00	0.0209	117.41	159.19
1.00	6297.00	0.0233	155.98	211.49
1.10	7760.00	0.0256	192.04	260.37
1.20	9220.00	0.0279	228.02	309.16
1.30	10574.00	0.0302	261.39	354.40
1.40	11646.00	0.0326	287.81	390.22
1.50	12350.00	0.0349	305.17	413.75
1.60	12654.00	0.0372	312.66	423.91
1.70	12627.00	0.0396	311.99	423.00
1.80	12313.00	0.0419	304.25	412.51
1.90	11841.00	0.0442	292.62	396.74
2.00	11291.00	0.0465	279.07	378.36
2.10	10678.00	0.0489	263.96	357.88
2.20	10065.00	0.0512	248.85	337.39
2.30	9541.00	0.0535	235.93	319.88
2.40	9182.00	0.0558	227.09	307.89
2.50	8899.00	0.0582	220.11	298.43
2.60	8679.00	0.0605	214.69	291.08
2.70	8520.00	0.0628	210.77	285.77
	8355.00			

Section ID	Carleton-2 Section (22°C)
Sample ID	New_May-20-01_16

Data Discarded

Date	20-May-01
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.1
Calibration - R _{max}	24010
Calibration - R _{min}	0
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	22
Air Temp (°C)	20

Failure Dimensions	
r _o (cm)	18.0
r _i (cm)	16.5
h _i (cm)	1.0
Maximum Torque (N.m.)	153.31
X-axis Intercept	0.59
Angle at Failure (rad)	0.0330
Initial Shear Stiffness (Mpa)	3.86
Secant Shear Stiffness (Mpa)	2.06

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.00	0.00
0.10	84	0.0023	2.08	2.81
0.20	178	0.0047	4.40	5.96
0.30	327	0.0070	8.08	10.96
0.40	569	0.0093	14.06	19.06
0.50	815	0.0116	20.14	27.30
0.60	818	0.0140	20.21	27.41
0.70	901	0.0163	22.26	30.19
0.80	1324	0.0186	32.72	44.36
0.90	1963	0.0209	48.51	65.77
1.00	2577	0.0233	63.68	86.34
1.10	3100	0.0256	76.60	103.86
1.20	3528	0.0279	87.18	118.20
1.30	3910	0.0302	96.62	131.00
1.40	4141	0.0326	102.33	138.74
1.50	4190	0.0349	103.54	140.38
1.60	4347	0.0372	107.42	145.64
1.70	4440	0.0396	109.71	148.75
1.80	4493	0.0419	111.02	150.53
1.90	4544	0.0442	112.28	152.24
2.00	4576	0.0465	113.08	153.31
2.10	4573	0.0489	113.00	153.21
2.20	4538	0.0512	112.14	152.04
2.30	4507	0.0535	111.37	151.00
2.40	4496	0.0558	111.10	150.63
2.50	4461	0.0582	110.23	149.46
2.60	4419	0.0605	109.20	148.05
2.70	4368	0.0628	107.94	146.34
	4284			

Carleton-2 Section**(22oC)**

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	G_i	G_s
		Nm	Rad	MPa	MPa
New May-20-01 13	150	354.88	0.0243	8.08	6.48
New May-20-01 14	150	451.64	0.0288	8.17	6.98
New May-20-01 15	150	423.91	0.0266	9.25	7.09
New May-20-01 16	150	-	-	-	-
Mean		410.14	0.0266	8.50	6.85
St. Dev		49.83	0.0022	0.65	0.33
CoV		12.15	8.32	7.64	4.76

Section ID	Carleton-2 Section (44°C)
Sample ID	New_Aug-05-02_1

Date	05-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R_{max}	24024
Calibration - R_{min}	-24
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	45
Air Temp (°C)	28

Data recorded @0.1 and presented @0.2

Failure Dimensions	
r_o (cm)	17.5
r_i (cm)	10.0
h_f (cm)	1.8

Maximum Torque (N.m.)	141.29
X-axis Intercept	1.43
Angle at Failure (rad)	0.0556
Initial Shear Stiffness (Mpa)	2.65
Secant Shear Stiffness (Mpa)	1.95

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-24	0.0000	0.00	0.00
0.20	65	0.0047	2.20	2.98
0.40	99	0.0093	3.03	4.11
0.60	115	0.0140	3.43	4.65
0.80	136	0.0186	3.95	5.35
1.00	188	0.0233	5.23	7.09
1.20	249	0.0279	6.74	9.13
1.40	392	0.0326	10.26	13.92
1.60	685	0.0372	17.49	23.72
1.80	1055	0.0419	26.62	36.09
2.00	1553	0.0465	38.91	52.75
2.20	2107	0.0512	52.57	71.28
2.40	2629	0.0558	65.45	88.74
2.60	3069	0.0605	76.31	103.46
2.80	3278	0.0652	81.47	110.45
3.00	3519	0.0698	87.41	118.51
3.20	3786	0.0745	94.00	127.44
3.40	3989	0.0791	99.01	134.24
3.60	4120	0.0838	102.24	138.62
3.80	4200	0.0884	104.21	141.29
4.00	4194	0.0931	104.06	141.09
4.20	4151	0.0977	103.00	139.65
4.40	4079	0.1024	101.23	137.25
4.60	3987	0.1070	98.96	134.17
4.80	3866	0.1117	95.97	130.12
5.00	3724	0.1163	92.47	125.37
5.20	3592	0.1210	89.21	120.96
5.40	3466	0.1256	86.10	116.74
	3289			

Section ID	Carleton-2 Section (44°C)
Sample ID	New_Aug-05-02_2

Date	05-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	24052
Calibration - R _{min}	27
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Data recorded @0.1 and presented @0.2

Failure Dimensions	
r _o (cm)	17.0
r _i (cm)	10.0
r _f (cm)	2.0

Maximum Torque (N.m.)	178.86
X-axis Intercept	0.90
Angle at Failure (rad)	0.0445
Initial Shear Stiffness (Mpa)	4.28
Secant Shear Stiffness (Mpa)	3.09

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	55	0.0000	0.69	0.94
0.20	182	0.0047	3.83	5.19
0.40	232	0.0093	5.06	6.86
0.60	321	0.0140	7.26	9.84
0.80	494	0.0186	11.53	15.64
1.00	821	0.0233	19.61	26.58
1.20	1322	0.0279	31.98	43.36
1.40	2015	0.0326	49.09	66.56
1.60	2820	0.0372	68.97	93.52
1.80	3588	0.0419	87.94	119.23
2.00	4228	0.0465	103.74	140.66
2.20	4729	0.0512	116.12	157.43
2.40	5076	0.0558	124.69	169.05
2.60	5281	0.0605	129.75	175.91
2.80	5369	0.0652	131.92	178.86
3.00	5343	0.0698	131.28	177.99
3.20	5225	0.0745	128.37	174.04
3.40	5069	0.0791	124.51	168.82
3.60	4876	0.0838	119.75	162.35
3.80	4688	0.0884	115.10	156.06
4.00	4500	0.0931	110.46	149.77
4.20	4315	0.0977	105.89	143.57
4.40	4138	0.1024	101.52	137.64
4.60	3959	0.1070	97.10	131.65
4.80	3794	0.1117	93.03	126.13
5.00	3632	0.1163	89.03	120.70
5.20	3478	0.1210	85.22	115.55
5.40	3352	0.1256	82.11	111.33
	3235			

Section ID	Carleton-2 Section (44°C)
Sample ID	New_Aug-05-02_3

Date	05-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	24058
Calibration - R _{min}	27
Steel Plate Diameter (mm)	125
Pavement Temp (°C)	22
Air Temp (°C)	20

Data recorded @0.1 and presented @0.2

Failure Dimensions	
r ₀ (cm)	17.0
r _i (cm)	13.0
h _r (cm)	2.5

Maximum Torque (N.m.)	285.83
X-axis Intercept	0.73
Angle at Failure (rad)	0.0483
Initial Shear Stiffness (Mpa)	6.33
Secant Shear Stiffness (Mpa)	4.54

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	48	0.0000	0.52	0.70
0.20	135	0.0047	2.67	3.62
0.40	191	0.0093	4.05	5.49
0.60	321	0.0140	7.26	9.84
0.80	663	0.0186	15.70	21.29
1.00	1698	0.0233	41.26	55.93
1.20	2960	0.0279	72.41	98.18
1.40	4192	0.0326	102.83	139.42
1.60	5288	0.0372	129.89	176.11
1.80	6094	0.0419	149.79	203.08
2.00	6863	0.0465	168.77	228.83
2.20	7560	0.0512	185.98	252.16
2.40	8083	0.0558	198.89	269.66
2.60	8435	0.0605	207.58	281.45
2.80	8566	0.0652	210.82	285.83
3.00	8507	0.0698	209.36	283.86
3.20	8188	0.0745	201.49	273.18
3.40	7754	0.0791	190.77	258.65
3.60	7278	0.0838	179.02	242.72
3.80	6835	0.0884	168.08	227.89
4.00	6344	0.0931	155.96	211.45
4.20	5559	0.0977	136.58	185.18
4.40	4511	0.1024	110.71	150.10
4.60	4003	0.1070	98.16	133.09
4.80	3737	0.1117	91.60	124.19
5.00	3561	0.1163	87.25	118.30
5.20	3425	0.1210	83.89	113.74
5.40	3316	0.1256	81.20	110.10
	3220			

Carleton-2 Section**(44oC)**

Sample ID	Steel Plate Diameter	T_{max}	Φ_{max}	Gi	Gs
		Nm	Rad	MPa	MPa
New_Aug-05-02_1	125	141.29	0.0556	2.65	1.95
New_Aug-05-02_2	125	178.86	0.0445	4.28	3.09
New_Aug-05-02_3	125	285.83	0.0483	6.33	4.54
Mean		202.00	0.0495	4.42	3.20
St. Dev		75.00	0.0057	1.84	1.30
CoV		37.13	11.45	41.69	40.66

Section ID	Carleton-2 Section (44°C)
Sample ID	New_Aug-05-02_1

Date	05-Aug-02
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	0.2
Calibration - R _{max}	24024
Calibration - R _{min}	-24
Steel Plate Diameter (mm)	150
Pavement Temp (°C)	45
Air Temp (°C)	28

Data recorded @0.1 and presented @0.2

Failure Dimensions	
r _o (cm)	22.0
r _i (cm)	13.0
h _i (cm)	2.5

Maximum Torque (N.m.)	288.21
X-axis Intercept	1.81
Angle at Failure (rad)	0.0561
Initial Shear Stiffness (Mpa)	2.84
Secant Shear Stiffness (Mpa)	2.28

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.59	0.80
0.20	71	0.0047	2.34	3.18
0.40	133	0.0093	3.87	5.25
0.60	165	0.0140	4.66	6.32
0.80	195	0.0186	5.40	7.33
1.00	248	0.0233	6.71	9.10
1.20	367	0.0279	9.65	13.08
1.40	519	0.0326	13.40	18.16
1.60	712	0.0372	18.16	24.62
1.80	1180	0.0419	29.70	40.27
2.00	1661	0.0465	41.57	56.36
2.20	2168	0.0512	54.08	73.32
2.40	2772	0.0558	68.98	93.53
2.60	3545	0.0605	88.05	119.38
2.80	4459	0.0652	110.60	149.96
3.00	5338	0.0698	132.29	179.36
3.20	6146	0.0745	152.22	206.39
3.40	6914	0.0791	171.17	232.08
3.60	7654	0.0838	189.43	256.83
3.80	8189	0.0884	202.63	274.73
4.00	8506	0.0931	210.45	285.33
4.20	8592	0.0977	212.57	288.21
4.40	8412	0.1024	208.13	282.18
4.60	8022	0.1070	198.51	269.14
4.80	7561	0.1117	187.13	253.72
5.00	6894	0.1163	170.68	231.41
5.20	6341	0.1210	157.03	212.91
5.40	6016	0.1256	149.02	202.04
	5716			

APPENDIX C

Field Testing Results for Test Samples at 870900 SPS-9A Test Section

Section ID	LTPP - 870901
Sample ID	870901-2

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23975
Calibration - R _{min}	-39
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	33
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	10.6
r _i (cm)	6.0
h _i (cm)	1.4

Maximum Torque (N.m.)	919.47
X-axis Intercept	3.55
Angle at Failure (rad)	0.0802
Initial Shear Stiffness (Mpa)	19.46
Secant Shear Stiffness (Mpa)	17.20

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-30	0.0000	0.22	0.30
1.00	0	0.0233	0.96	1.31
2.00	138	0.0465	4.37	5.93
3.00	1325	0.0698	33.70	45.69
4.00	5300	0.0931	131.91	178.84
5.00	13048	0.1163	323.33	438.38
6.00	22061	0.1396	546.01	740.29
7.00	27410	0.1629	678.17	919.47
8.00	11575	0.1861	286.94	389.04
9.00	9291	0.2094	230.51	312.53
10.00	8255	0.2327	204.92	277.83
11.00	7758	0.2560	192.64	261.18
12.00	7243	0.2792	179.91	243.93
13.00	6831	0.3025	169.73	230.13
14.00	6451	0.3258	160.34	217.40
15.00	5888	0.3490	146.43	198.54
16.00	5745	0.3723	142.90	193.75
17.00	5672	0.3956	141.10	191.30
18.00	5559	0.4188	138.31	187.52
19.00	5656	0.4421	140.70	190.77
20.00	5578	0.4654	138.78	188.15
21.00	5418	0.4886	134.82	182.80
22.00	5276	0.5119	131.31	178.04

Section ID	LTPP - 870901
Sample ID	870901-3

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	27154
Calibration - R_{min}	3384
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	33
Air Temp (°C)	25

Failure Dimensions	
r_o (cm)	9.7
r_i (cm)	5.5
h_i (cm)	1.2

Maximum Torque (N.m.)	771.92
X-axis Intercept	0.22
Angle at Failure (rad)	0.0880
Initial Shear Stiffness (Mpa)	14.60
Secant Shear Stiffness (Mpa)	13.16

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	3361	0.0000	-0.57	-0.78
1.00	8575	0.0233	129.57	175.67
2.00	15373	0.0465	299.25	405.72
3.00	21879	0.0698	461.64	625.89
4.00	26194	0.0931	569.34	771.92
5.00	16450	0.1163	326.13	442.17
6.00	10591	0.1396	179.89	243.89
7.00	8808	0.1629	135.38	183.55
8.00	7442	0.1861	101.29	137.33
9.00	6688	0.2094	82.47	111.81
10.00	5667	0.2327	56.98	77.26
11.00	4007	0.2560	15.55	21.08
12.00	3002	0.2792	-9.53	-12.93
13.00	2501	0.3025	-22.04	-29.88
14.00	2392	0.3258	-24.76	-33.57
15.00	2444	0.3490	-23.46	-31.81
16.00	2410	0.3723	-24.31	-32.96
17.00	2167	0.3956	-30.38	-41.18
18.00	2082	0.4188	-32.50	-44.06
19.00	2177	0.4421	-30.13	-40.85
20.00	2226	0.4654	-28.90	-39.19
21.00	2319	0.4886	-26.58	-36.04
22.00	2380	0.5119	-25.06	-33.98

Section ID	LTPP - 870901
Sample ID	870901-4

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23987
Calibration - R _{min}	-29
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Maximum Torque (N.m.)	689.35
X-axis Intercept	1.49
Angle at Failure (rad)	0.0817
Initial Shear Stiffness (Mpa)	16.65
Secant Shear Stiffness (Mpa)	12.66

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	5.5
h _r (cm)	0.8

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.72	0.97
1.00	204	0.0233	5.76	7.80
2.00	3955	0.0465	98.42	133.44
3.00	11446	0.0698	283.48	384.35
4.00	19497	0.0931	482.38	654.02
5.00	20552	0.1163	508.44	689.35
6.00	8642	0.1396	214.21	290.43
7.00	7657	0.1629	189.88	257.44
8.00	7081	0.1861	175.65	238.15
9.00	6871	0.2094	170.46	231.11
10.00	6605	0.2327	163.89	222.20
11.00	6377	0.2560	158.26	214.57
12.00	5547	0.2792	137.75	186.77
13.00	4977	0.3025	123.67	167.67
14.00	4500	0.3258	111.89	151.70
15.00	4421	0.3490	109.93	149.05
16.00	4330	0.3723	107.69	146.00
17.00	4300	0.3956	106.95	145.00
18.00	4200	0.4188	104.47	141.65
19.00	4135	0.4421	102.87	139.47
20.00	4171	0.4654	103.76	140.68
21.00	4376	0.4886	108.82	147.54
22.00	4300	0.5119	106.95	145.00

Section ID	LTPP - 870901
Sample ID	870901-5

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	24012
Calibration - R _{min}	0
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	9.7
r _t (cm)	5.5
h _t (cm)	1.1

Maximum Torque (N.m.)	751.11
X-axis Intercept	2.89
Angle at Failure (rad)	0.0722
Initial Shear Stiffness (Mpa)	16.33
Secant Shear Stiffness (Mpa)	15.60

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.00	0.00
1.00	26	0.0233	0.64	0.87
2.00	525	0.0465	12.97	17.59
3.00	2816	0.0698	69.58	94.34
4.00	8375	0.0931	206.93	280.56
5.00	15935	0.1163	393.73	533.83
6.00	22421	0.1396	553.99	751.11
7.00	11952	0.1629	295.32	400.39
8.00	8892	0.1861	219.71	297.88
9.00	8151	0.2094	201.40	273.06
10.00	7315	0.2327	180.74	245.05
11.00	6522	0.2560	161.15	218.49
12.00	6198	0.2792	153.14	207.63
13.00	5871	0.3025	145.06	196.68
14.00	5600	0.3258	138.37	187.60
15.00	5487	0.3490	135.58	183.82
16.00	5337	0.3723	131.87	178.79
17.00	5349	0.3956	132.17	179.19
18.00	5090	0.4188	125.77	170.52
19.00	5018	0.4421	123.99	168.10
20.00	4858	0.4654	120.03	162.74
21.00	4859	0.4886	120.06	162.78
22.00	4697	0.5119	116.06	157.35

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23984
Calibration - R_{min}	-27
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Time (s)	Torque (Nm)
0.00	0.00
1.00	10.00
2.00	20.00
3.00	30.00
4.00	410.00
4.50	420.00
5.00	410.00
6.00	400.00
7.00	390.00
8.00	380.00
9.00	370.00
10.00	360.00
11.00	350.00
12.00	340.00
13.00	330.00
14.00	320.00
15.00	310.00

Maximum Torque (N.m.)	-
X-axis Intercept	2.80
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	15.05
Secant Shear Stiffness (Mpa)	-

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LTPP - 870901

Sample ID	T_{max}	Φ_{max}	Gi	Gs
	Nm	Rad	MPa	MPa
870901-1	897.38	0.0969	15.03	13.90
870901-2	919.47	0.0802	19.46	17.20
870901-3	771.92	0.0880	14.60	13.16
870901-4	689.35	0.0817	16.65	12.66
870901-5	751.11	0.0722	16.33	15.60
Mean	805.85	0.0838	16.66	14.50
St. Dev	98.75	0.0092	1.48	1.87
CoV	12.25	10.99	8.90	12.91
870901-6 - Shoulder	-	-	15.05	-
870901-7 - Shoulder	-	-	12.17	-

Section ID	LTPP - 870902
Sample ID	870902-1

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23995
Calibration - R _{min}	-27
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	36
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	13.0
r _i (cm)	8.0
h _i (cm)	2.0

Maximum Torque (N.m.)	396.75
X-axis Intercept	1.61
Angle at Failure (rad)	0.0556
Initial Shear Stiffness (Mpa)	12.45
Secant Shear Stiffness (Mpa)	10.71

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-27	0.0000	0.00	0.00
1.00	117	0.0233	3.56	4.82
2.00	2367	0.0465	59.13	80.17
3.00	8535	0.0698	211.47	286.71
4.00	11821	0.0931	292.62	396.75
5.00	9634	0.1163	238.61	323.51
6.00	8328	0.1396	206.35	279.78
7.00	7714	0.1629	191.19	259.22
8.00	7422	0.1861	183.98	249.44
9.00	7017	0.2094	173.97	235.88
10.00	6187	0.2327	153.47	208.08
11.00	5931	0.2560	147.15	199.51
12.00	5701	0.2792	141.47	191.81
13.00	5467	0.3025	135.69	183.97
14.00	5346	0.3258	132.70	179.92
15.00	5204	0.3490	129.20	175.17
16.00	5062	0.3723	125.69	170.41
17.00	5021	0.3956	124.68	169.04
18.00	4938	0.4188	122.63	166.26
19.00	4873	0.4421	121.02	164.08
20.00	4808	0.4654	119.42	161.91
21.00	4868	0.4886	120.90	163.92
22.00	4818	0.5119	119.66	162.24

Section ID	LTPP - 870902
Sample ID	870902-4

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23987
Calibration - R _{min}	-36
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	14.0
r _t (cm)	8.0
h _t (cm)	1.7

Maximum Torque (N.m.)	509.07
X-axis Intercept	1.84
Angle at Failure (rad)	0.0735
Initial Shear Stiffness (Mpa)	11.94
Secant Shear Stiffness (Mpa)	10.39

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-37	0.0000	-0.02	-0.03
1.00	108	0.0233	3.56	4.82
2.00	951	0.0465	24.38	33.05
3.00	5936	0.0698	147.49	199.97
4.00	13127	0.0931	325.09	440.76
5.00	15167	0.1163	375.47	509.07
6.00	8757	0.1396	217.16	294.43
7.00	6912	0.1629	171.60	232.65
8.00	6112	0.1861	151.84	205.86
9.00	5704	0.2094	141.76	192.20
10.00	5278	0.2327	131.24	177.94
11.00	5020	0.2560	124.87	169.30
12.00	4716	0.2792	117.36	159.12
13.00	4497	0.3025	111.95	151.79
14.00	4447	0.3258	110.72	150.11
15.00	4347	0.3490	108.25	146.76
16.00	4233	0.3723	105.43	142.95
17.00	4201	0.3956	104.64	141.88
18.00	4039	0.4188	100.64	136.45
19.00	3904	0.4421	97.31	131.93
20.00	3753	0.4654	93.58	126.87
21.00	3626	0.4886	90.44	122.62
22.00	3451	0.5119	86.12	116.76

Section ID	LTPP - 870902
Sample ID	870902-6 - Shoulder

Epoxy Failure

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23997
Calibration - R _{min}	-30
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	-
r _i (cm)	-
h _r (cm)	-

Maximum Torque (N.m.)	-
X-axis Intercept	1.72
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	16.53
Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-29	0.0000	0.02	0.03
1.00	120	0.0233	3.70	5.02
2.00	2123	0.0465	53.16	72.08
3.00	9784	0.0698	242.34	328.57
4.00	910	0.0931	23.21	31.47
5.00	707	0.1163	18.20	24.67
6.00	630	0.1396	16.30	22.10
7.00	581	0.1629	15.09	20.46
8.00	462	0.1861	12.15	16.47
9.00	417	0.2094	11.04	14.97
10.00	397	0.2327	10.54	14.30
11.00	382	0.2560	10.17	13.79
12.00	371	0.2792	9.90	13.43
13.00	362	0.3025	9.68	13.12
14.00	351	0.3258	9.41	12.76
15.00	345	0.3490	9.26	12.55
16.00	339	0.3723	9.11	12.35
17.00	331	0.3956	8.91	12.09
18.00	325	0.4188	8.77	11.89
19.00	322	0.4421	8.69	11.78

Section ID	LTPP - 870902
Sample ID	870902-7 - Shoulder

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	24004
Calibration - R_{min}	-25
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Failure Dimensions	
r_o (cm)	12.5
r_i (cm)	8.0
h_i (cm)	1.7

Maximum Torque (N.m.)	397.50
X-axis Intercept	1.44
Angle at Failure (rad)	0.0595
Initial Shear Stiffness (Mpa)	10.37
Secant Shear Stiffness (Mpa)	10.02

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-26	0.0000	-0.02	-0.03
1.00	313	0.0233	8.35	11.32
2.00	2568	0.0465	64.02	86.80
3.00	7981	0.0698	197.68	268.01
4.00	11849	0.0931	293.18	397.50
5.00	9612	0.1163	237.95	322.61
6.00	8129	0.1396	201.33	272.97
7.00	7248	0.1629	179.58	243.47
8.00	6375	0.1861	158.02	214.25
9.00	5665	0.2094	140.49	190.48
10.00	5240	0.2327	130.00	176.25
11.00	4880	0.2560	121.11	164.20
12.00	4632	0.2792	114.99	155.90
13.00	4296	0.3025	106.69	144.65
14.00	3759	0.3258	93.43	126.68
15.00	3522	0.3490	87.58	118.74
16.00	3383	0.3723	84.15	114.09
17.00	3323	0.3956	82.67	112.08
18.00	3334	0.4188	82.94	112.45
19.00	2860	0.4421	71.23	96.58
20.00	2362	0.4654	58.94	79.91
21.00	2171	0.4886	54.22	73.51
22.00	2056	0.5119	51.38	69.66

LTPP - 870902

Sample ID	T_{max}	Φ_{max}	G_i	G_s
	Nm	Rad	MPa	MPa
870902-1	396.75	0.0556	12.45	10.71
870902-2	639.88	0.0858	12.93	11.18
870902-3	547.48	0.0585	16.02	14.04
870902-4	509.07	0.0735	11.94	10.39
870902-5	-	-	14.20	-
Mean	523.29	0.0684	13.51	11.58
St. Dev	100.66	0.0140	1.64	1.67
CoV	19.23	20.55	12.12	14.42
870902-6 - Shoulder	-	-	16.53	-
870902-7 - Shoulder	397.50	0.0595	10.37	10.02

Section ID	LTPP - 870903
Sample ID	870903-2

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23981
Calibration - R _{min}	-44
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	36
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	6.0
h _i (cm)	1.2

Maximum Torque (N.m.)	704.23
X-axis Intercept	1.70
Angle at Failure (rad)	0.0768
Initial Shear Stiffness (Mpa)	18.45
Secant Shear Stiffness (Mpa)	13.76

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-46	0.0000	-0.05	-0.07
1.00	67	0.0233	2.74	3.72
2.00	2522	0.0465	63.37	85.91
3.00	11174	0.0698	277.03	375.60
4.00	19542	0.0931	483.68	655.78
5.00	20989	0.1163	519.41	704.23
6.00	7956	0.1396	197.56	267.86
7.00	6954	0.1629	172.82	234.31
8.00	6403	0.1861	159.21	215.86
9.00	5728	0.2094	142.54	193.26
10.00	5394	0.2327	134.29	182.08
11.00	5121	0.2560	127.55	172.93
12.00	5185	0.2792	129.13	175.08
13.00	5051	0.3025	125.82	170.59
14.00	4779	0.3258	119.10	161.48
15.00	4755	0.3490	118.51	160.68
16.00	4780	0.3723	119.13	161.52
17.00	4733	0.3956	117.97	159.94
18.00	4650	0.4188	115.92	157.16
19.00	4558	0.4421	113.65	154.08
20.00	4461	0.4654	111.25	150.84
21.00	4483	0.4886	111.79	151.57
22.00	4452	0.5119	111.03	150.54

Section ID	LTPP - 870903
Sample ID	870903-3

Data not correctly recorded

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23981
Calibration - R_{min}	-44
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	35
Air Temp (°C)	25

Failure Dimensions		Torque (N.m.)	
r_o (cm)	-	Maximum Torque	-
r_i (cm)	-	X-axis Intercept	-
h_i (cm)	-	Angle at Failure (rad)	-
		Initial Shear Stiffness (Mpa)	-
		Secant Shear Stiffness (Mpa)	-

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00		0.0000	1.09	1.47
1.00		0.0233	1.09	1.47
2.00		0.0465	1.09	1.47
3.00		0.0698	1.09	1.47
4.00		0.0931	1.09	1.47
5.00		0.1163	1.09	1.47
6.00		0.1396	1.09	1.47
7.00		0.1629	1.09	1.47
8.00		0.1861	1.09	1.47
9.00		0.2094	1.09	1.47
10.00		0.2327	1.09	1.47
11.00		0.2560	1.09	1.47
12.00		0.2792	1.09	1.47
13.00		0.3025	1.09	1.47
14.00		0.3258	1.09	1.47
15.00		0.3490	1.09	1.47
16.00		0.3723	1.09	1.47
17.00		0.3956	1.09	1.47
18.00		0.4188	1.09	1.47
19.00		0.4421	1.09	1.47
20.00		0.4654	1.09	1.47
21.00		0.4886	1.09	1.47
22.00		0.5119	1.09	1.47

Section ID	LTPP - 870903
Sample ID	870903-4

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23746
Calibration - R_{min}	0
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r_o (cm)	10.0
r_i (cm)	6.0
h_i (cm)	1.0

Maximum Torque (N.m.)	634.86
X-axis Intercept	0.94
Angle at Failure (rad)	0.0712
Initial Shear Stiffness (Mpa)	13.84
Secant Shear Stiffness (Mpa)	13.38

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.00	0.00
1.00	1036	0.0233	25.88	35.09
2.00	6489	0.0465	162.13	219.82
3.00	13912	0.0698	347.59	471.28
4.00	18741	0.0931	468.25	634.86
5.00	12334	0.1163	308.17	417.82
6.00	8292	0.1396	207.18	280.90
7.00	6760	0.1629	168.90	229.00
8.00	6112	0.1861	152.71	207.05
9.00	5611	0.2094	140.19	190.08
10.00	4508	0.2327	112.63	152.71
11.00	3379	0.2560	84.43	114.47
12.00	2851	0.2792	71.23	96.58
13.00	2658	0.3025	66.41	90.04
14.00	2667	0.3258	66.64	90.35
15.00	2517	0.3490	62.89	85.26
16.00	2437	0.3723	60.89	82.55
17.00	2190	0.3956	54.72	74.19
18.00	1814	0.4188	45.32	61.45
19.00	3904	0.4421	97.54	132.25
20.00	3753	0.4654	93.77	127.13
21.00	3626	0.4886	90.60	122.83
22.00	3451	0.5119	86.22	116.90

Section ID	LTPP - 870903
Sample ID	870903-5

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	24014
Calibration - R _{min}	0
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	6.0
h _i (cm)	1.0

Maximum Torque (N.m.)	657.69
X-axis Intercept	0.77
Angle at Failure (rad)	0.0751
Initial Shear Stiffness (Mpa)	14.08
Secant Shear Stiffness (Mpa)	13.14

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	0	0.0000	0.00	0.00
1.00	1501	0.0233	37.08	50.28
2.00	7466	0.0465	184.46	250.09
3.00	16477	0.0698	407.09	551.94
4.00	19634	0.0931	485.09	657.69
5.00	9063	0.1163	223.91	303.59
6.00	5402	0.1396	133.46	180.95
7.00	4240	0.1629	104.76	142.03
8.00	3532	0.1861	87.26	118.31
9.00	3014	0.2094	74.47	100.96
10.00	2638	0.2327	65.18	88.37
11.00	2443	0.2560	60.36	81.83
12.00	2253	0.2792	55.66	75.47
13.00	2138	0.3025	52.82	71.62
14.00	2036	0.3258	50.30	68.20
15.00	1962	0.3490	48.47	65.72
16.00	1808	0.3723	44.67	60.56
17.00	1787	0.3956	44.15	59.86
18.00	1774	0.4188	43.83	59.42
19.00	1462	0.4421	36.12	48.97
20.00	1194	0.4654	29.50	40.00

Section ID	LTPP - 870903
Sample ID	870903-7 - Shoulder

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23985
Calibration - R _{min}	-39
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	34
Air Temp (°C)	25

Failure Dimensions	
r _o (cm)	13.0
r _i (cm)	10.0
h _i (cm)	1.0

Maximum Torque (N.m.)	429.12
X-axis Intercept	0.94
Angle at Failure (rad)	0.0480
Initial Shear Stiffness (Mpa)	12.78
Secant Shear Stiffness (Mpa)	13.41

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-25	0.0000	0.35	0.47
1.00	334	0.0233	9.21	12.49
2.00	6109	0.0465	151.83	205.86
3.00	12777	0.0698	316.51	429.12
4.00	10266	0.0931	254.49	345.05
5.00	7335	0.1163	182.11	246.91
6.00	6727	0.1396	167.09	226.55
7.00	6215	0.1629	154.45	209.41
8.00	5773	0.1861	143.53	194.61
9.00	5410	0.2094	134.57	182.45
10.00	5074	0.2327	126.27	171.20
11.00	4916	0.2560	122.37	165.91
12.00	4846	0.2792	120.64	163.57
13.00	4781	0.3025	119.04	161.39
14.00	4761	0.3258	118.54	160.72
15.00	4716	0.3490	117.43	159.21
16.00	4632	0.3723	115.36	156.40
17.00	4496	0.3956	112.00	151.85
18.00	4413	0.4188	109.95	149.07
19.00	4297	0.4421	107.08	145.18
20.00	4328	0.4654	107.85	146.22
21.00	4175	0.4886	104.07	141.10
22.00	4101	0.5119	102.24	138.62

LTPP - 870903

Sample ID	T_{max}	ϕ_{max}	Gi	Gs
	Nm	Rad	MPa	MPa
870903-1	-	-	17.30	-
870903-2	704.23	0.0768	18.45	13.76
870903-3	-	-	-	-
870903-4	634.86	0.0712	13.84	13.38
870903-5	657.69	0.0751	14.08	13.14
Mean	665.59	0.0743	15.92	13.43
St. Dev	35.35	0.0029	2.31	0.31
CoV	5.31	3.87	14.51	2.32
870902-6 - Shoulder	-	-	13.36	-
870903-7 - Shoulder	429.12	0.0480	12.78	13.41

Section ID	LTPP - 870960
Sample ID	870960-1

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23995
Calibration - R _{min}	-29
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	39
Air Temp (°C)	28

Failure Dimensions	
r _o (cm)	13.0
r _i (cm)	7.5
h _i (cm)	1.6

Maximum Torque (N.m.)	479.25
X-axis Intercept	1.78
Angle at Failure (rad)	0.0749
Initial Shear Stiffness (Mpa)	14.37
Secant Shear Stiffness (Mpa)	9.60

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-32.00	0.0000	-0.07	-0.10
1.00	0.00	0.0233	0.72	0.97
2.00	1475.00	0.0465	37.14	50.36
3.00	8251.00	0.0698	204.48	277.24
4.00	14232.00	0.0931	352.19	477.51
5.00	14284.00	0.1163	353.48	479.25
6.00	11131.00	0.1396	275.61	373.68
7.00	8313.00	0.1629	206.02	279.32
8.00	6596.00	0.1861	163.61	221.83
9.00	5800.00	0.2094	143.95	195.18
10.00	5399.00	0.2327	134.05	181.75
11.00	5088.00	0.2560	126.37	171.33
12.00	4737.00	0.2792	117.70	159.58
13.00	4557.00	0.3025	113.26	153.56
14.00	4466.00	0.3258	111.01	150.51
15.00	4431.00	0.3490	110.14	149.34
16.00	4282.00	0.3723	106.47	144.35
17.00	4145.00	0.3956	103.08	139.76
18.00	3944.00	0.4188	98.12	133.03
19.00	3958.00	0.4421	98.46	133.50
20.00	3989.00	0.4654	99.23	134.54
21.00	3939.00	0.4886	97.99	132.86
22.00	3830.00	0.5119	95.30	129.21

Section ID	LTPP - 870960
Sample ID	870960-3

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	24000
Calibration - R _{min}	-23
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	39
Air Temp (°C)	28

Failure Dimensions	
r _o (cm)	11.5
r _i (cm)	7.0
h _i (cm)	1.8

Maximum Torque (N.m.)	489.25
X-axis Intercept	1.43
Angle at Failure (rad)	0.0597
Initial Shear Stiffness (Mpa)	12.90
Secant Shear Stiffness (Mpa)	12.29

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-23	0.0000	0.00	0.00
1.00	191	0.0233	5.29	7.17
2.00	3210	0.0465	79.85	108.26
3.00	9796	0.0698	242.50	328.79
4.00	14588	0.0931	360.85	489.25
5.00	13581	0.1163	335.98	455.53
6.00	11017	0.1396	272.66	369.67
7.00	9075	0.1629	224.69	304.65
8.00	7955	0.1861	197.03	267.14
9.00	7384	0.2094	182.93	248.02
10.00	6948	0.2327	172.16	233.42
11.00	6587	0.2560	163.25	221.33
12.00	6348	0.2792	157.35	213.33
13.00	6062	0.3025	150.28	203.76
14.00	5758	0.3258	142.77	193.58
15.00	5466	0.3490	135.56	183.80
16.00	5341	0.3723	132.48	179.61
17.00	5268	0.3956	130.67	177.17
18.00	5109	0.4188	126.75	171.84
19.00	4965	0.4421	123.19	167.02
20.00	4718	0.4654	117.09	158.75
21.00	4032	0.4886	100.15	135.78

Section ID	LTPP - 870960
Sample ID	870960-4

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23973
Calibration - R _{min}	-49
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	39
Air Temp (°C)	28

Failure Dimensions	
r _o (cm)	12.0
r _i (cm)	6.0
h _r (cm)	1.0

Maximum Torque (N.m.)	543.85
X-axis Intercept	1.90
Angle at Failure (rad)	0.0721
Initial Shear Stiffness (Mpa)	12.54
Secant Shear Stiffness (Mpa)	11.31

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-50	0.0000	-0.02	-0.03
1.00	26	0.0233	1.85	2.51
2.00	602	0.0465	16.08	21.80
3.00	5132	0.0698	127.96	173.49
4.00	13335	0.0931	330.56	448.18
5.00	16192	0.1163	401.12	543.85
6.00	14260	0.1396	353.41	479.15
7.00	12339	0.1629	305.96	414.83
8.00	11004	0.1861	272.99	370.12
9.00	9405	0.2094	233.50	316.58
10.00	8291	0.2327	205.98	279.28
11.00	7411	0.2560	184.25	249.81
12.00	6845	0.2792	170.27	230.85
13.00	6153	0.3025	153.18	207.68
14.00	5936	0.3258	147.82	200.42
15.00	5742	0.3490	143.03	193.92
16.00	5536	0.3723	137.94	187.02
17.00	5329	0.3956	132.83	180.09
18.00	5327	0.4188	132.78	180.02
19.00	5232	0.4421	130.43	176.84
20.00	5070	0.4654	126.43	171.42
21.00	4769	0.4886	119.00	161.34
22.00	4628	0.5119	115.51	156.62

Section ID	LTPP - 870960
Sample ID	870960-6 - Shoulder

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23975
Calibration - R _{min}	-53
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	39
Air Temp (°C)	28

Failure Dimensions	
r _o (cm)	12.5
r _i (cm)	8.0
h _i (cm)	1.4

Maximum Torque (N.m.)	446.36
X-axis Intercept	2.25
Angle at Failure (rad)	0.0407
Initial Shear Stiffness (Mpa)	16.40
Secant Shear Stiffness (Mpa)	16.43

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-32	0.0000	0.52	0.70
1.00	69	0.0233	3.01	4.08
2.00	972	0.0465	25.31	34.31
3.00	5680	0.0698	141.56	191.93
4.00	13280	0.0931	329.22	446.36
5.00	12846	0.1163	318.50	431.83
6.00	5430	0.1396	135.39	183.56
7.00	4220	0.1629	105.51	143.05
8.00	3592	0.1861	90.00	122.03
9.00	3137	0.2094	78.77	106.79
10.00	2859	0.2327	71.90	97.49
11.00	2578	0.2560	64.96	88.08
12.00	2437	0.2792	61.48	83.36
13.00	2300	0.3025	58.10	78.77
14.00	2290	0.3258	57.85	78.44
15.00	2080	0.3490	52.67	71.41
16.00	1838	0.3723	46.69	63.31
17.00	1761	0.3956	44.79	60.73
18.00	1689	0.4188	43.01	58.32
19.00	1558	0.4421	39.78	53.93
20.00	1541	0.4654	39.36	53.36
21.00	1528	0.4886	39.04	52.93
22.00	1528	0.5119	39.04	52.93

LTPP - 870960

Sample ID	T_{max}	Φ_{max}	Gi	Gs
	Nm	Rad	MPa	MPa
870960-1	479.25	0.0749	14.37	9.60
870960-2	594.16	0.0721	16.32	12.36
870960-3	489.25	0.0597	12.90	12.29
870960-4	543.85	0.0721	12.54	11.31
870960-5	509.45	0.0632	14.09	12.10
Mean	523.19	0.0684	14.04	11.53
St. Dev	46.73	0.0066	1.49	1.16
CoV	8.93	9.61	10.58	10.05
870960-6 - Shoulder	446.36	0.0407	16.40	16.43
870960-7 - Shoulder	-	-	-	-

Section ID	LTPP - 870961
Sample ID	870961-1

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23993
Calibration - R _{min}	-34
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	36
Air Temp (°C)	26

Failure Dimensions		
r _o (cm)	11.0	
r _i (cm)	7.0	
h _i (cm)	0.8	
Maximum Torque (N.m.)		503.70
X-axis Intercept		1.92
Angle at Failure (rad)		0.0715
Initial Shear Stiffness (Mpa)		12.72
Secant Shear Stiffness (Mpa)		10.56

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-32.00	0.0000	0.05	0.07
1.00	24.00	0.0233	1.43	1.94
2.00	1803.00	0.0465	45.36	61.50
3.00	6860.00	0.0698	170.23	230.81
4.00	13259.00	0.0931	328.24	445.04
5.00	15011.00	0.1163	371.51	503.70
6.00	12259.00	0.1396	303.55	411.56
7.00	10850.00	0.1629	268.76	364.39
8.00	9678.00	0.1861	239.82	325.15
9.00	8579.00	0.2094	212.68	288.36
10.00	7660.00	0.2327	189.99	257.59
11.00	6946.00	0.2560	172.36	233.69
12.00	6297.00	0.2792	156.33	211.96
13.00	5805.00	0.3025	144.18	195.49
14.00	5422.00	0.3258	134.73	182.66
15.00	5233.00	0.3490	130.06	176.34
16.00	5018.00	0.3723	124.75	169.14
17.00	4852.00	0.3956	120.65	163.58
18.00	4793.00	0.4188	119.19	161.60
19.00	4600.00	0.4421	114.43	155.14
20.00	4415.00	0.4654	109.86	148.95
21.00	4234.00	0.4886	105.39	142.89
22.00	4186.00	0.5119	104.20	141.28

[illegible]

The graph plots Torque (Nm) on the y-axis (0.00 to 450.00) against Time (s) on the x-axis (0.00 to 20.00). The data points show a sharp rise to a peak torque of about 400 Nm at 4.5 seconds, followed by a steady decline to zero torque at 20 seconds.

Time (s)	Torque (Nm)
0.00	0.00
1.00	30.00
2.00	100.00
3.00	250.00
4.00	380.00
4.50	400.00
5.00	380.00
6.00	320.00
7.00	280.00
8.00	250.00
9.00	220.00
10.00	200.00
11.00	180.00
12.00	160.00
13.00	140.00
14.00	120.00
15.00	100.00
16.00	80.00
17.00	60.00
18.00	40.00
19.00	20.00
20.00	0.00

Maximum Torque (N.m.)	393.76
X-axis Intercept	1.75
Angle at Failure (rad)	0.0523
Initial Shear Stiffness (Mpa)	11.35
Secant Shear Stiffness (Mpa)	11.30

Section ID	LTPP - 870961
Sample ID	870961-3

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23995
Calibration - R _{min}	-27
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	10.0
r _t (cm)	6.0
h _t (cm)	1.0

Maximum Torque (N.m.)	407.29
X-axis Intercept	0.78
Angle at Failure (rad)	0.0749
Initial Shear Stiffness (Mpa)	11.48
Secant Shear Stiffness (Mpa)	8.15

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-23	0.0000	0.10	0.13
1.00	1167	0.0233	29.49	39.98
2.00	6367	0.0465	157.92	214.11
3.00	11972	0.0698	296.35	401.80
4.00	12136	0.0931	300.40	407.29
5.00	9269	0.1163	229.59	311.29
6.00	7688	0.1396	190.55	258.35
7.00	6513	0.1629	161.53	219.00
8.00	5729	0.1861	142.16	192.75
9.00	5396	0.2094	133.94	181.60
10.00	5012	0.2327	124.45	168.74
11.00	4279	0.2560	106.35	144.19
12.00	3910	0.2792	97.24	131.84
13.00	3553	0.3025	88.42	119.88
14.00	3306	0.3258	82.32	111.61
15.00	2985	0.3490	74.39	100.86
16.00	2703	0.3723	67.43	91.42
17.00	1959	0.3956	49.05	66.50
18.00	1840	0.4188	46.11	62.52
19.00	1771	0.4421	44.41	60.21
20.00	1718	0.4654	43.10	58.43
21.00	1675	0.4886	42.04	56.99
22.00	1640	0.5119	41.17	55.82

Section ID	LTPP - 870961
Sample ID	870961-4

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23974
Calibration - R _{min}	-50
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	13.0
r _i (cm)	8.5
h _f (cm)	0.7

Maximum Torque (N.m.)	398.25
X-axis Intercept	1.88
Angle at Failure (rad)	0.0493
Initial Shear Stiffness (Mpa)	12.04
Secant Shear Stiffness (Mpa)	12.11

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-51	0.0000	-0.02	-0.03
1.00	0	0.0233	1.23	1.67
2.00	638	0.0465	16.99	23.04
3.00	6160	0.0698	153.36	207.93
4.00	11844	0.0931	293.74	398.25
5.00	11266	0.1163	279.46	378.90
6.00	8508	0.1396	211.35	286.55
7.00	6763	0.1629	168.25	228.12
8.00	5423	0.1861	135.16	183.25
9.00	4486	0.2094	112.02	151.88
10.00	3746	0.2327	93.75	127.10
11.00	3322	0.2560	83.28	112.91
12.00	2975	0.2792	74.71	101.29
13.00	2259	0.3025	57.02	77.31
14.00	1858	0.3258	47.12	63.89
15.00	1807	0.3490	45.86	62.18
16.00	1760	0.3723	44.70	60.61
17.00	1737	0.3956	44.13	59.83
18.00	1617	0.4188	41.17	55.82
19.00	1521	0.4421	38.80	52.60
20.00	1412	0.4654	36.11	48.95
21.00	1141	0.4886	29.41	39.88
22.00	4628	0.5119	115.53	156.64

Section ID	LTPP - 870961
Sample ID	870961-5

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23988
Calibration - R_{min}	-35
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r_o (cm)	12.5
r_i (cm)	7.5
h_i (cm)	0.7

Maximum Torque (N.m.)	407.04
X-axis Intercept	1.87
Angle at Failure (rad)	0.0496
Initial Shear Stiffness (Mpa)	13.02
Secant Shear Stiffness (Mpa)	12.32

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-22	0.0000	0.32	0.44
1.00	0	0.0233	0.86	1.17
2.00	787	0.0465	20.30	27.52
3.00	6985	0.0698	173.37	235.06
4.00	12121	0.0931	300.22	407.04
5.00	9992	0.1163	247.64	335.75
6.00	7991	0.1396	198.22	268.75
7.00	6523	0.1629	161.96	219.59
8.00	5499	0.1861	136.67	185.31
9.00	4628	0.2094	115.16	156.14
10.00	4188	0.2327	104.30	141.41
11.00	3658	0.2560	91.21	123.66
12.00	3316	0.2792	82.76	112.21
13.00	2930	0.3025	73.23	99.28
14.00	2643	0.3258	66.14	89.67
15.00	2398	0.3490	60.09	81.47
16.00	2119	0.3723	53.20	72.13
17.00	1900	0.3956	47.79	64.79
18.00	1763	0.4188	44.41	60.21
19.00	1726	0.4421	43.49	58.97
20.00	1666	0.4654	42.01	56.96
21.00	1533	0.4886	38.73	52.50
22.00	1365	0.5119	34.58	46.88

Section ID	LTPP - 870961
Sample ID	870961-7 - Shoulder

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	24011
Calibration - R _{min}	-22
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	12.0
r _i (cm)	7.5
h _f (cm)	1.0

Maximum Torque (N.m.)	487.34
X-axis Intercept	2.74
Angle at Failure (rad)	0.0525
Initial Shear Stiffness (Mpa)	14.08
Secant Shear Stiffness (Mpa)	13.93

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-24	0.0000	-0.05	-0.07
1.00	0	0.0233	0.54	0.74
2.00	132	0.0465	3.80	5.15
3.00	1648	0.0698	41.23	55.90
4.00	8400	0.0931	207.91	281.89
5.00	14538	0.1163	359.44	487.34
6.00	7736	0.1396	191.52	259.67
7.00	4641	0.1629	115.11	156.07
8.00	3633	0.1861	90.23	122.34
9.00	3027	0.2094	75.27	102.05
10.00	2587	0.2327	64.41	87.33
11.00	2300	0.2560	57.32	77.72
12.00	2081	0.2792	51.92	70.39
13.00	2039	0.3025	50.88	68.98
14.00	1864	0.3258	46.56	63.13
15.00	1870	0.3490	46.71	63.33
16.00	1684	0.3723	42.12	57.10
17.00	1643	0.3956	41.10	55.73
18.00	1561	0.4188	39.08	52.98
19.00	1549	0.4421	38.78	52.58
20.00	1603	0.4654	40.12	54.39
21.00	1650	0.4886	41.28	55.96
22.00	1620	0.5119	40.54	54.96

LTPP - 870961

Sample ID	T_{max}	Φ_{max}	G_i	G_s
	Nm	Rad	MPa	MPa
870961-1	503.70	0.0715	12.72	10.56
870961-2	393.76	0.0523	11.35	11.30
870961-3	407.29	0.0749	11.48	8.15
870961-4	398.25	0.0493	12.04	12.11
870961-5	407.04	0.0496	13.02	12.32
Mean	422.01	0.0595	12.12	10.89
St. Dev	46.03	0.0126	0.74	1.68
CoV	10.91	21.20	6.09	15.43
870961-6 - Shoulder	-	-	22.58	-
870961-7 - Shoulder	487.34	0.0525	14.08	13.93

Section ID	LTPP - 870962
Sample ID	870962-1

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23987
Calibration - R _{min}	-45
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	9.5
r _i (cm)	6.0
h _i (cm)	1.0

Maximum Torque (N.m.)	619.91
X-axis Intercept	2.55
Angle at Failure (rad)	0.0570
Initial Shear Stiffness (Mpa)	15.66
Secant Shear Stiffness (Mpa)	16.31

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-31.00	0.0000	0.35	0.47
1.00	0.00	0.0233	1.11	1.51
2.00	312.00	0.0465	8.81	11.95
3.00	3182.00	0.0698	79.67	108.02
4.00	10294.00	0.0931	255.25	346.07
5.00	18475.00	0.1163	457.22	619.91
6.00	12800.00	0.1396	317.12	429.95
7.00	7904.00	0.1629	196.24	266.07
8.00	6474.00	0.1861	160.94	218.21
9.00	5486.00	0.2094	136.55	185.14
10.00	5147.00	0.2327	128.18	173.79
11.00	4785.00	0.2560	119.24	161.67
12.00	4371.00	0.2792	109.02	147.81
13.00	3878.00	0.3025	96.85	131.31
14.00	3664.00	0.3258	91.57	124.15
15.00	3403.00	0.3490	85.12	115.41
16.00	3257.00	0.3723	81.52	110.53
17.00	3252.00	0.3956	81.40	110.36
18.00	2984.00	0.4188	74.78	101.39
19.00	2822.00	0.4421	70.78	95.97
20.00	2494.00	0.4654	62.68	84.99
21.00	2157.00	0.4886	54.36	73.71
22.00	1904.00	0.5119	48.12	65.24

Section ID	LTPP - 870962
Sample ID	870962-2

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1
Calibration - R _{max}	23993
Calibration - R _{min}	-35
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	12.0
r _i (cm)	7.0
h _i (cm)	0.9

Maximum Torque (N.m.)	638.42
X-axis Intercept	1.68
Angle at Failure (rad)	0.0773
Initial Shear Stiffness (Mpa)	13.60
Secant Shear Stiffness (Mpa)	12.39

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-24	0.0000	0.27	0.37
1.00	187	0.0233	5.48	7.43
2.00	2086	0.0465	52.37	71.01
3.00	7971	0.0698	197.68	268.02
4.00	15198	0.0931	376.13	509.97
5.00	19035	0.1163	470.88	638.42
6.00	6750	0.1396	167.54	227.15
7.00	4054	0.1629	100.97	136.89
8.00	3012	0.1861	75.24	102.01
9.00	2514	0.2094	62.94	85.34
10.00	2248	0.2327	56.37	76.43
11.00	2070	0.2560	51.98	70.47
12.00	1936	0.2792	48.67	65.98
13.00	1814	0.3025	45.66	61.90
14.00	1725	0.3258	43.46	58.92
15.00	1609	0.3490	40.59	55.04
16.00	1531	0.3723	38.67	52.43
17.00	1451	0.3956	36.69	49.75
18.00	1364	0.4188	34.54	46.84
19.00	1268	0.4421	32.17	43.62
20.00	1106	0.4654	28.17	38.20
21.00	977	0.4886	24.99	33.88

Section ID	LTPP - 870962
Sample ID	870962-3

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R _{max}	23996
Calibration - R _{min}	-33
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	40
Air Temp (°C)	26

Failure Dimensions	
r _o (cm)	13.5
r _i (cm)	9.0
h _i (cm)	0.8

Maximum Torque (N.m.)	459.93
X-axis Intercept	1.94
Angle at Failure (rad)	0.0712
Initial Shear Stiffness (Mpa)	13.85
Secant Shear Stiffness (Mpa)	9.69

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb.ft)	Torque (N.m.)
0.00	-32.00	0.0000	0.02	0.03
1.00	0.00	0.0233	0.81	1.10
2.00	367.00	0.0465	9.88	13.39
3.00	6663.00	0.0698	165.33	224.16
4.00	13699.00	0.0931	339.06	459.70
5.00	13706.00	0.1163	339.23	459.93
6.00	6273.00	0.1396	155.70	211.10
7.00	4411.00	0.1629	109.73	148.77
8.00	3466.00	0.1861	86.39	117.13
9.00	2965.00	0.2094	74.02	100.36
10.00	2755.00	0.2327	68.84	93.33
11.00	2475.00	0.2560	61.93	83.96
12.00	2315.00	0.2792	57.97	78.60
13.00	2236.00	0.3025	56.02	75.96
14.00	2103.00	0.3258	52.74	71.51
15.00	2012.00	0.3490	50.49	68.46
16.00	1836.00	0.3723	46.15	62.57
17.00	1688.00	0.3956	42.49	57.61
18.00	1598.00	0.4188	40.27	54.60
19.00	1517.00	0.4421	38.27	51.89
20.00	1347.00	0.4654	34.07	46.20
21.00	1191.00	0.4886	30.22	40.98
22.00	1640.00	0.5119	41.31	56.01

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23982
Calibration - R_{min}	-46
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Epoxy Failure

[illegible]

Failure Dimensions	
r_o (cm)	-
r_i (cm)	-
h_i (cm)	-

Maximum Torque (N.m.)	-
X-axis Intercept	1.92
Angle at Failure (rad)	-
Initial Shear Stiffness (Mpa)	11.08
Secant Shear Stiffness (Mpa)	-

Section ID	LTPP - 870961
Sample ID	870962-7 - Shoulder

Date	31-Aug-00
Weather	Sunny
Test Speed (rpm)	1800
Data Recording (sec)	1.0
Calibration - R_{max}	23987
Calibration - R_{min}	-42
Steel Plate Diameter (mm)	100
Pavement Temp (°C)	38
Air Temp (°C)	26

Failure Dimensions	
r_o (cm)	14.0
r_i (cm)	9.0
h_f (cm)	1.4

Maximum Torque (N.m.)	448.92
X-axis Intercept	2.27
Angle at Failure (rad)	0.0401
Initial Shear Stiffness (Mpa)	16.74
Secant Shear Stiffness (Mpa)	16.77

Time Step (sec)	Torque Cell Output	Angle (rad)	Torque (lb. ft)	Torque (N.m.)
0.00	-31.00	0.0000	0.27	0.37
1.00	0.00	0.0233	1.04	1.41
2.00	541.00	0.0465	14.39	19.52
3.00	5609.00	0.0698	139.53	189.18
4.00	13368.00	0.0931	331.11	448.92
5.00	12229.00	0.1163	302.98	410.79
6.00	5853.00	0.1396	145.55	197.34
7.00	4612.00	0.1629	114.91	155.80
8.00	3924.00	0.1861	97.92	132.77
9.00	3458.00	0.2094	86.42	117.17
10.00	2975.00	0.2327	74.49	101.00
11.00	2724.00	0.2560	68.30	92.60
12.00	3719.00	0.2792	92.86	125.91
13.00	1179.00	0.3025	30.15	40.87
14.00	1143.00	0.3258	29.26	39.67
15.00	2349.00	0.3490	59.04	80.04
16.00	2156.00	0.3723	54.27	73.58
17.00	2017.00	0.3956	50.84	68.93
18.00	1954.00	0.4188	49.28	66.82
19.00	1878.00	0.4421	47.41	64.27
20.00	1689.00	0.4654	42.74	57.95
21.00	1605.00	0.4886	40.67	55.14
22.00	1501.00	0.5119	38.10	51.65

LTPP - 870962

Sample ID	T_{max}	Φ_{max}	G_i	G_s
	Nm	Rad	MPa	MPa
870962-1	619.91	0.0570	15.66	16.31
870962-2	638.42	0.0773	13.60	12.39
870962-3	459.93	0.0712	13.85	9.69
870962-4	571.42	0.0563	15.91	15.22
870962-5	496.19	0.0505	14.72	14.75
Mean	557.18	0.0625	14.75	13.67
St. Dev	77.32	0.0113	1.04	2.65
CoV	13.88	18.04	7.05	19.37
870962-6 - Shoulder	-	-	11.08	-
870962-7 - Shoulder	448.92	0.0401	16.74	16.77