DEVELOPMENT OF THE DUPLICATE SHEAR TEST FOR ASPHALT MIXTURES

by

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Abstract

THE DEVELOPMENT OF THE DUPLICATE SHEAR TEST FOR ASPHALT MIXTURES

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Permanent shear deformation is the main cause of rutting in asphalt concrete layers. Therefore, the determination of the shear properties of asphalt mixtures is helpful for predicting the rutting in asphalt pavement structures and for the identification of poor performing asphalt mixtures. The objective of this study was to develop a new test device to replicate similar loading conditions and constraints of the Superpave Shear Tester (SST). The new device, named the Duplicate Shear Tester (DST), determines the mechanical average of the shear properties and responses of two specimens instead of that of a single specimen as in the SST tests. The DST device is simple and inexpensive and can be used with any universal testing machine that can provide repeated dynamic and static axial loads in a temperature-controlled environment. The two most used SST tests, the Frequency Sweep Test at Constant Height (FSCH) and the Repeated Shear Test at Constant Height (RSCH) were performed with the DST device mounted inside of a UTM-25 test system.

To evaluate the effectiveness of the DST, four asphalt surface mixtures were subjected to FSCH and RSCH tests. For each mixture, three pairs of specimens were tested. The FSCH tests were performed at 30°C to measure the shear dynamic modulus and phase angle of the mixtures at ten loading frequencies between 0.01 to 10 Hz. As the FSCH is theoretically performed in the linear viscoelastic behavior domain, the FSCH

test was performed twice on some sets of the specimens. The RSCH tests were performed at 50°C and the permanent shear deformation of the specimens were reported at 5,000 loading cycles.

From the data analysis of the FSCH test results, it has been concluded that the DST test is highly repetitive and reliable in measuring the shear dynamic modulus and phase angle at high load frequencies between 0.5 Hz to 10 Hz, for which a variability of less than 10% was observed. A variability higher than 10 percent was recorded for the FSCH tests done at frequencies lower than 0.5 Hz.

The RSCH test results demonstrated the capability of the DST in evaluating the permanent shear deformation of asphalt concrete mixtures. A variability slightly higher than 10 percent was observed for the shear permanent deformation of two of the asphalt mixtures.

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Chapter 1

Introduction

Rutting is a common distress in flexible pavements. It exhibits as a channelized depression along the wheel path, sometimes accompanied by upheavals along the sides of the wheel path. This distress has a considerable effect on the safety and driving comfort of road users since water accumulates in the ruts causing hydroplaning. The water can freeze in the winter making the pavement surface very slippery. When the depressions are very deep, the steering of the vehicles is affected (Sousa, Craus, & Monismith, 1991). Rutting gradually develops under the repetition of traffic loads and heavy vehicles, due to a combination of densification and shear deformation in any of the pavement layers including the subgrade (Sousa, et al., 1991). In cold regions, rutting can develop as surface wearing due to the continuous loss of coated aggregates caused by environmental and traffic loads or the use of studded tires (White, Haddock, Hand, & Fang, 2002).

For the properly constructed pavements with stiff supporting materials or with thick asphalt layers, rutting may occur in the upper two inches of the asphalt concrete layers (Sousa, et al., 1991) (Brown & Cross, 1992). In this case, it develops as a combination of two mechanisms: mixture densification and permanent shear deformation of the asphalt. The densification can occur as a result of post compaction under traffic load as well as vertical creep deformation. Under the densification, the volume of the mixture is decreased and the air voids reduce. The creep deformation usually develops under long duration of loading at high temperatures when the stiffness of the asphalt mixture is low.

The permanent shear deformation involves lateral, shear movement of asphalt mixture from beneath the wheel load, normally in the top two to four inches from the pavement surface. This movement is a plastic flow and is not recoverable after the traffic load is removed. Under the shear deformation, the volume of mixture remains constant, while some of the mixture is moved to the sides of wheel path and forming upheavals. Both of these mechanisms happen over the progressive traffic load. However the shear deformation is considered to be the dominant source of rutting in properly constructed pavements, responsible for about 90% of the rutting in asphalt layers. (Sousa, et al., 1991) (Brown & Cross, 1992)

All components of the asphalt mixture including bituminous materials, aggregates, additives, and their properties and proportions can affect the rut resistance of the mixture. No single variable can be used to predict the rutting in mixture; however the interactions between different components of the mixture affect the rut resistance. As a result, a laboratory test system which can evaluate at the mix design stage the rut susceptibility of mixture and predict its field performance is needed.

Currently, there are two categories of test systems developed to evaluate the susceptibility of asphalt mixtures to rutting. The empirical laboratory tests are used for screening the poor and good rut resistance mixtures. Examples such test systems include the French Rutting Tester (FRT), the Hamburg Wheel-Tracking Test, and the Asphalt Pavement Analyzer (APA). They generally consist of a small loaded steel or rubber wheel that rolls repeatedly over an asphalt concrete specimen. The depression caused by the repeated wheel loading to the asphalt concrete samples has been considered as correlated to field rut performance of the mix and, therefore, has been used as indicator of the rut resistance of the tested asphalt mix.

The second category includes test systems that measure the fundamental mechanical properties of mixtures; these properties can be used in mechanical models to predict the deformation in asphalt concrete layers due to the action of wheel loads.

Examples of these test systems include the dynamic triaxial test, static creep triaxial test, and the Superpave Shear Tester (SST). Some of the mechanical properties and responses measured by these test systems were the top-selected for the Simple Performance Test (SPT) for the Superpave mix design for permanent deformation (Witczak, Kaloush, Pellinen, El-Basyouny, & Quintus, 2002). Although the measurements of these test systems have been found to be highly correlated to the observed permanent deformation, the SST is the only one that provides direct measurement of shear properties and responses.

The Superpave Shear Tester (SST) is one of the successful outcomes of the SHRP program funded by the U.S Congress in the late 1980s. It was later found that two of the six SST tests, the Frequency Sweep Shear Test at Constant Height (FSCH), and the Repeated Shear Test at Constant Height (RSCH) are successful in characterizing the shear properties and predicting the rut resistance of asphalt mixtures. However, the SST equipment is quite expensive, complex and hard to operate. Therefore, it has not been widely adopted as a simple performance test for predicting the permanent deformation. Consequently, it would be beneficial to have a simpler device that can evaluate the mechanical shear properties of asphalt mixtures at a lower cost.

This study proposes a new test device that can measure mechanical properties and responses of asphalt mixtures under shear loads. The loading conditions and constraints of the proposed device are similar to those in the SST tests. However this device is much simpler and less expensive and can be used with a conventional material load testing frame that can apply dynamic forces of up to 25kN at frequencies up to 25 Hz, and it is fitted with a temperature control chamber.

Chapter 2

Background

Over the past decades researchers have tried to introduce new test equipment and devices that can accurately measure the fundamental shear properties and responses of asphalt mixtures. Such a test equipment can be beneficial and widely used in industry if it is simple, quick, repeatable, accurate, and at a reasonable cost.

Four different shear test systems are introduced in this chapter. These test systems measure the fundamental properties and responses of asphalt mixtures under shear load considering the viscoelastic behavior of asphalt mixtures. Two of them are developed for field verification and quality control or quality assurance purposes: the Field Shear Test (FST), and the In-Situ Shear Stiffness Tester (InSiSST™). The other two are laboratory test equipment: the Dynamic Shear Rheometer (DSR) and the Superpave Shear Tester (SST). Since the objective of this thesis is to develop a new test device to replicate similar loading conditions and constraints of the SST, this equipment is discussed in more details.

2.1 Field Shear Test (FST)

2.1.1 Background

The Field Shear Test (FST) was first developed under the NCHRP project 9-7 as a possible quality control and quality assurance test for the Superpave mix designs. EnduraTEC Systems of Eden Prairie delivered the first prototype FST device in 1996. This device was expected to perform two of the Superpave Shear Test (SST) procedures: the SSCH and the FSCH. The major differences between the first FST device and the SST were the specimen orientation and the loading condition, as shown in

Figure 2-1. The positioning of the specimen was more like an indirect tensile test, producing shear stresses across the specimen diameter in vertical direction. These differences made the FST to perform tests with least specimen preparation. (Cominsky, Killingsworth, Anderson, Anderson, Crockford, 1998)

Limited initial results from comparing the FST and SST tests concluded that the first FST might be a potential quality control and quality assurance tool (Cominsky, et al., 1998). However, further study and evaluation found that the first FST device was inaccurate in measuring the complex modulus and maximum permanent strain. This inaccuracy was due to bad performance of the servo-pneumatic loading system and the low-resolution measurement of deflection (Christensen, Bonaquist, & Handojo, 2002).

The FST device was evaluated during the NCHRP 9-18 and one of the major findings of the evaluation was the need to change the FST test geometry to be able to shear the parallel ends of the specimen just like in the SST tests. In order to make the FST simpler and less expensive than the SST, NCHRP 9-18 suggested to use shear stresses of up to 100 kPa and shear strains of up to 0.1 percent, which are much higher than the 35 kPa maximum shear stresses used in the Simple Shear Test and 0.01 percent maximum shear strains used in the Shear Frequency Sweep test by the SST. This was based on the findings that the hot mixed asphalt behaves linearly up to stresses of 100 kPa and strains of 0.1 percent, and the SST limits were highly conservative. Increasing the stress and strain limits helped develop a device that was simpler and provided better data quality at the same time. A new FST device was developed by the EnduraTEC System addressing the needs in addition to the shortcomings in the loading system, resolution of the measuring system, and the specimen clamping. The modified FST device shears a specimen in a similar way as the SST does. (Christensen, et al., 2002)

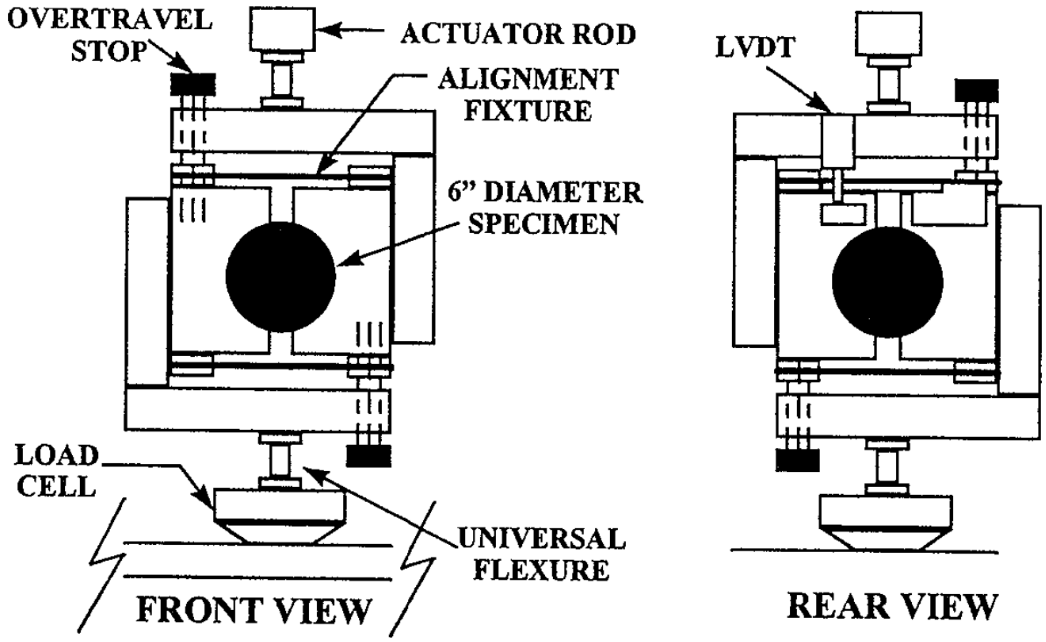

Figure 2-1 First FST Test Device (Christensen, et al., 2002)

2.1.2 FST Device Description

Figure 2-2 illustrates the FST device. The FST device compromises the following components:

- Servo-pneumatic loading device
- Hydraulic clamps
- Environmental chamber
- Computer system

The loading system is capable of applying different load waves and it executes shear loads up to 1,260 kPa. The hydraulic clamps hold the specimen in position minimizing the specimen preparation. The environmental chamber enables testing at a specified testing temperature. The computer system is used to perform and control the test procedure. (Cominsky, et al., 1998)

Figure 2-2 Modified FST Test Device (Christensen, et al., 2002)

2.1.3 FST Specimen Preparation

The specimen for the FST test is a gyratory compacted asphalt concrete specimen with a diameter of 150 mm and height between 50 mm to 122 mm. The FST device has the capability of performing shear tests directly on the specimen without any prior sawing or gluing.

2.1.4 FST Test Procedure

A gyratory compacted specimen is conditioned at the testing temperature for at least two hours. Then the specimen is mounted between the hydraulic clamps and the clamps are closed with an inside hydraulic pressure of 10.3 MPa. After mounting the specimen, the environmental chamber is closed and the specimen is given at least five minutes to reach thermal equilibrium. Next, the frequency sweep test is performed. To simulate the strain-controlled condition, the load stresses are adjusted with the change in the frequency. After the test completion, the hydraulic clamps are loosened and the specimen is rotated 90 degrees. Once again the hydraulic clamps are closed with the 10.3 MPa hydraulic pressure and the test is executed. This process is repeated four times for each specimen. The shear dynamic modulus calculated for each specimen is the average of the four test determinations. (Christensen, 2003)

2.1.5 Evaluation of the FST Test

The FST device is compact, user-friendly and rugged that makes it suitable for quality control and quality assurance applications. In addition, this device was estimated to cost approximately $30,000, which is relatively low when compared to the SST. This device also does not require any special specimen preparation such as saw cutting or gluing, which significantly reduces the complexity and time for the test procedure. (Christensen, et al., 2002)

A Finite Element analysis was performed to determine the stress and strain distribution through the modified FST and SST devices. It was concluded that the FST stress distribution was complex and not ideal in comparison with the stress distribution in the SST. Therefore, the data collected by the FST should be considered as approximate. In addition, it was found that the difference in the clamping pressure resulted in different measured responses. This difference is due to different level of confinement of material at the clamps. Moreover the variability in the data collected by this device appeared to be high for quality control and quality assurance applications, or for a performance test. (Christensen, et al., 2002) (Witczak, et al., 2002)

Although the FST device satisfied many of the requirements for a quality control or quality assurance test equipment, the data collected by this device is approximate and the variability level of data is high (Witczak, et al., 2002). This has prevented the FST device becoming an adopted quality control and quality assurance test device.

2.2 In-Situ Shear Stiffness Test (InSiSST™)

2.2.1 Background

In early 1990's Abd El Halim and Abd El Nabi developed the concept of testing asphalt concrete pavement in the field using a torsion loading. The Carleton In-Situ Shear Strength Test (CiSSST) device was constructed in Carleton University in Canada to study the practicability of this idea. In this approach, a steel disk was glued to the surface of the pavement. And torsion was applied from a disk with finite dimension onto a surface with infinite dimension. The shear strength of the pavement was determined based on the torque applied when the failure of the asphalt surface occurred. Considering a surface failure shaped as a frustum of a cone, Abd El Naby developed an equation to determine the in-situ shear strength of the asphalt concrete mix.

The results of Abd El Naby's (1995) research proved that the CiSSST was able to discriminate different mixes by determining the actual field shear properties with a high repeatability and low variation. In spite of these advantages, the CiSSST had several mechanical and operational deficiencies, including the lack of convenient portability and tedious stabilization process, limited data collection and control system, and insufficient torque capacity to fail some mixes. (Goodman, 2000)

The noted deficiencies led to development of the In-Situ Shear Stiffness (InSiSST™) test device. The InSiSST™ test device was designed based on the review of the previous works done by other researchers and the critical analysis of the CiSSST deficiencies and optimized new objectives for a portable, safe and single operator that provides in-situ shear strength/stiffness at a reasonable cost and time. This device is able to determine both the shear strength and shear stiffness of the asphalt concrete pavement, as it constantly records the applied torque and angular displacement, one data point every second. Figure 2-3 illustrates the loading conditions of the InSiSST™ test.

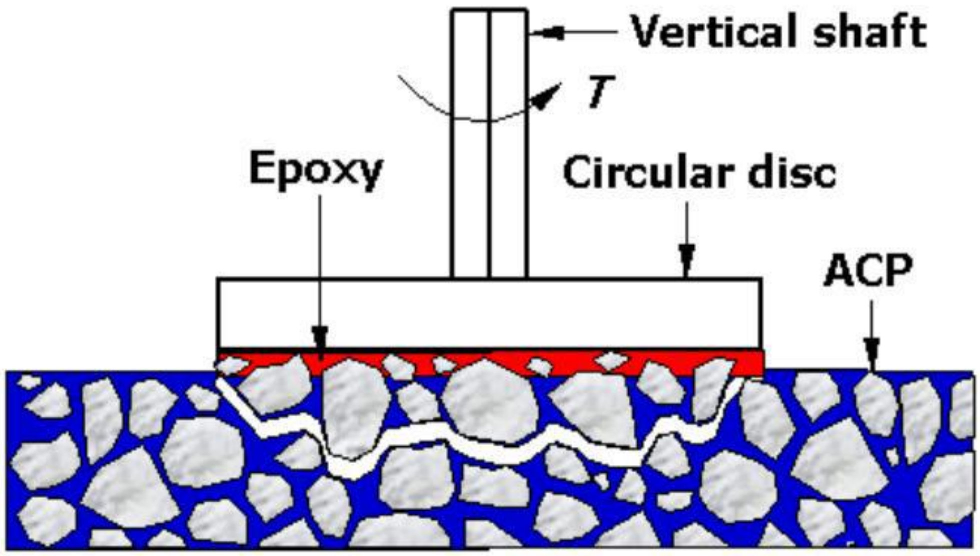

Figure 2-3 Loading Conditions of the InSiSST™ Test (El Halim, 2007)

2.2.1 InSiSST™ Test Device Description

The InSiSST™ is illustrated in Figure 2-4. This test device comprises the following components: (Goodman, 2000)

- Primary force generation system
- Transportation system
- Test frame and positioning system
- Stabilization system, epoxy system
- Test control/data collection system

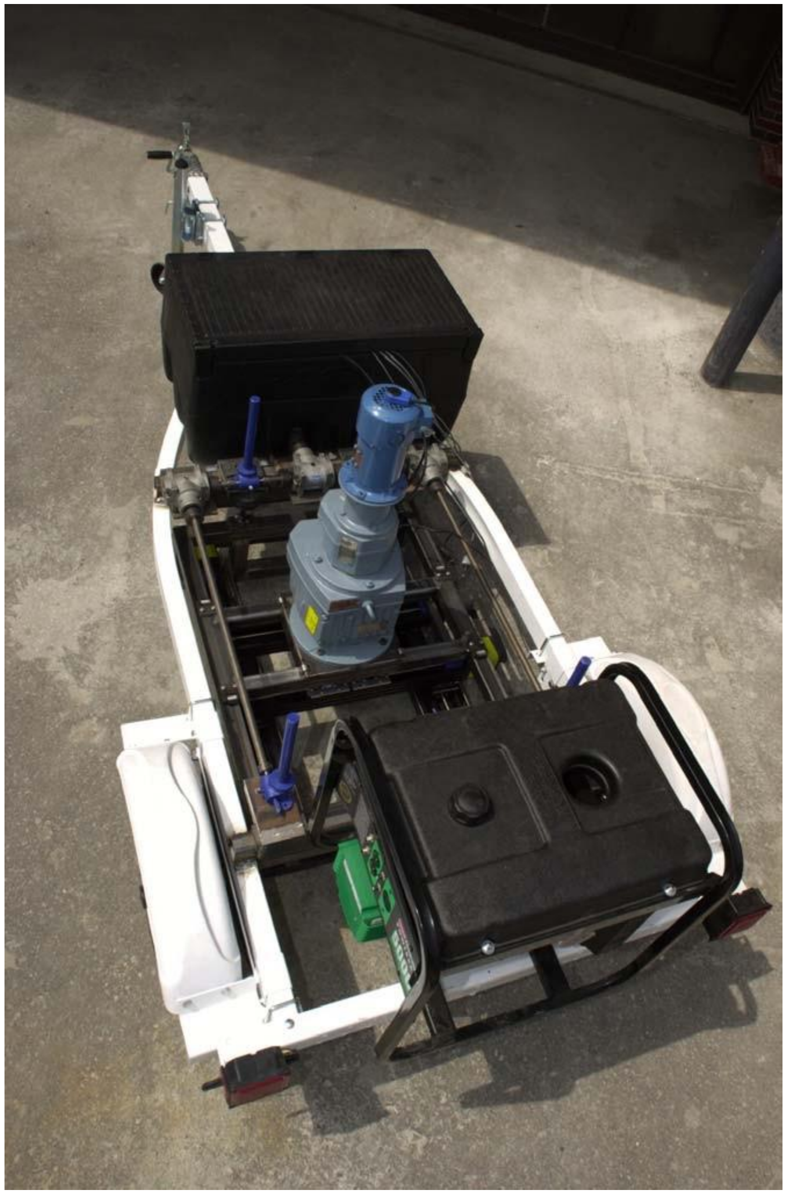

Figure 2-4 Top View of the InSiSST™ Test Device (El Halim, 2007)

The primary force generation system adopted a motor and a gearbox with more overall capacity than the ones for the CiSSST. The new primary force generation system incorporates a lower speed of loading and provides a torque of 1,550 N.m, which is almost twice the power provided by the CiSSST. The new test device addressed the mobility by the trailer-mounted option that allows portability from site to site. The test frame and positioning system support the elements of the InSiSST^{TM}. The test frame provides a testing area of 0.1 m^2 and the motor controlled positioning system allows the device to perform tests over any disk placed in the testing area. The testing area allows placement of four 100 mm diameter disks or three disks of 125 mm to 150 mm diameter. This provides a statistically significant number of tests performed with a single frame. The stabilization system of the InSiSST^{TM} comprises of four jacks that help lowering the test frame and lift the trailer. The trailer weight and friction help stabilizing the frame against rotational forces. The new epoxy system adopted for the InSiSST^{TM} reduced the required time for curing prior to test from 24 hours to two hours. The InSiSST^{TM} also utilizes a laptop computer to control the test procedure and collecting instantaneous torque and angle of twist measurements. A closed loop system controls the rate of displacement to ensure a strain-controlled test. Test results and site relevant data are also saved to the laptop. (Goodman, 2000)

2.2.2 InSiSST^{TM} Site Preparation

The InSiSST^{TM} is an in-situ test equipment, and it involves on site preparation of pavement surface. The test site should be secured through traffic control measures. The test sections, the surface of the pavement on the test sections should be dried, cleaned and free of deleterious materials. A brush or broom could be utilized to remove fine particles off the pavement. And if it is necessary, the surface might be cleaned by water and soap and dried before gluing the plates to it.

2.2.3 InSiSST^{TM} Test Procedure

The InSiSST^{TM} device test is towed to the test site by a vehicle with a trailer hitch. Then the epoxy glue is prepared in accordance to the manufacturer's specifications. The epoxy is applied to the bottom of the loading disks. The loading disks are glued to the pavement in a proper alignment and distance from each other. Meanwhile the epoxy cures other measurements such as density and rutting survey can be performed. After the epoxy cures, the InSiSST^{TM} is moved over the test section and the test frame is placed in such a way that embraces all the loading disks. Then the test frame is lowered and the torque cell and the gearbox are aligned over the first test plate using the slide control pad. After that, the torque cell is aligned in a radial direction with the load plate and connected to it. The torque cell software is activated and the torque cell is calibrated using the calibration button. After calibration, the test may start at a desired selected strain rate from the motor controller software. When the failure happens, the drive motor should be stopped. The failed asphalt and the loading disk are inspected and the failure depth is measured using calipers. Similar process is repeated until all the load plates under the test frame are tested. After the test completion, the remaining holes in the pavement should be sealed with a slurry mix to protect the pavement from moisture infiltration. (Goodman, 2000)

2.2.4 Evaluation of the InSiSST^{TM} Test Device

The InSiSST^{TM} device test provides in-situ the fundamental shear properties of the asphalt concrete. This device is a portable, single operator and a simple in-situ test device that provides fast and repeatable test results. (Goodman, 2000) (El Halim, 2007)

Besides all the mentioned advantages of this in-situ test device, there are several deficiencies including lack of control over the test temperature. The asphalt concrete is a viscoelastic material and its stiffness is highly dependent on the temperature. Consequently the mechanical properties measured by this device should be normalized to a standard temperature before any comparison. Moreover, as an in-situ test device it requires the traffic closure on the test section; the long time required for the curing of the epoxy aggravate that (Goodman, 2000). Overall, this device is an effective in-situ device to measure the shear properties of asphalt concrete pavements.

2.3 Determining the Shear Properties of Asphalt Mixtures Using the Dynamic Shear Rheometer (DSR)

2.3.1 Background

The Dynamic Shear Rheometer (DSR) is used primarily to determine the viscoelastic behavior of asphalt binders. Asphalt binder is a viscoelastic material, and it behaves partly elastic and partly viscous under loading. Under a fully elastic behavior the deformation due to an applied load is recoverable. However under a fully viscous behavior, the deformation due to an applied load is non-recoverable as for a viscous liquid. The viscoelastic characterization helps in the Superpave Performance Grading of the asphalt binders. (Pavement Interactive, 2011)

The DSR measures the complex shear modulus, G*, and the phase angle, δ, of an asphalt specimen. The complex shear modulus is a measure of the total resistance of the asphalt specimen to deformation under repeated shear. The phase angle defines the delay between the applied stress and its resulting strain. The phase angle for a purely elastic material is 0 degrees, while the phase angle is 90 degrees for a purely viscous material. To perform a dynamic shear test, a thin asphalt sample is sandwiched between two circular plates. The DSR shears the specimen by oscillating the upper plate back and forth at a preselected frequency and angular deflection or torque, while the bottom plate is fixed, Figure 2-5. (Pavement Interactive, 2011) (ASTM-D7175-15, 2015)

Being successful at characterizing the viscoelastic behavior of asphalt binders, this device is also used in determining the complex shear modulus and the phase angle of asphalt mixtures. Several modifications are made to the device and to the specimen geometry to make the DSR capable of measuring complex shear modulus. These modifications include using a rectangular prismatic asphalt mixture instead of a cylindrical binder specimen and replacing the circular plates by two fixtures to grab and hold the rectangular prismatic specimen.

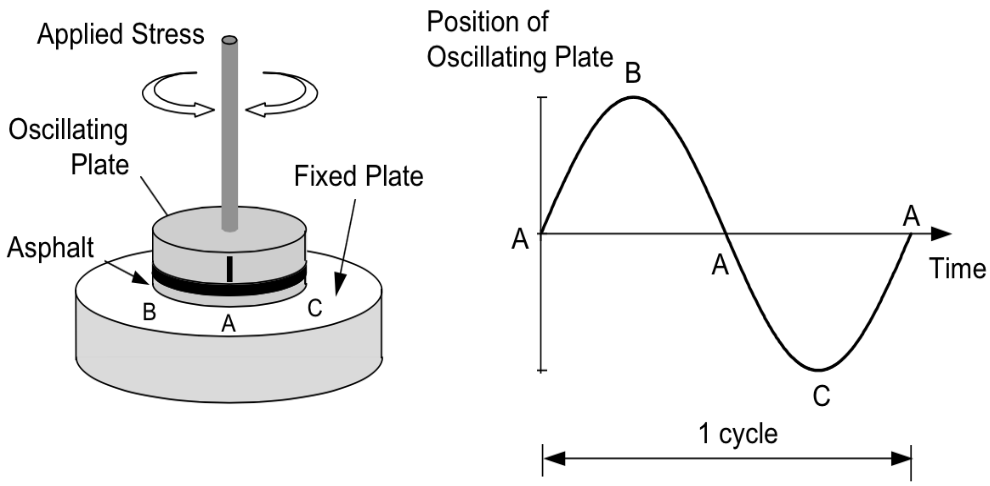

Figure 2-5 Shear Test of an Asphalt Binder Specimen - DSR (NHI, 2000)

The DSR is capable of measuring the viscoelastic behavior of asphalt mixtures with complex shear modulus greater than 10 kPa at frequencies of 0.01 Hz to 25 Hz and strains of 0.001 percent to 0.1 percent at temperatures from 10°C to 70°C. This device can be used for specimen made from either laboratory compacted samples or field cores. (ASTM-D7552-09, 2015)

The DSR can be used to perform other tests in addition to the dynamic shear test. Reinke and Glidden (2004) used this device for static creep and repeated creep tests. Several parameters including time to 5% strain, time to failure, strain at failure, strain at 100 cycles, and mix viscosity at 100 cycles can be determined from those two creep tests. (Reinke & Glidden, 2004)

2.3.2 Description of the Dynamic Shear Rheometer Device

The Dynamic Shear Rheometer (DSR) System for performing tests on asphalt mixtures is illustrated in Figure 2-6. It comprises of the following parts:

- Two test fixtures
- Torque wrench
- Environmental chamber and temperature controller
- Internal DSR thermometer
- Loading device
- Control and data acquisition system
- Digital caliper

The two test fixtures secure the rectangular test specimen along its long dimension in vertical plane. A torqueing wrench capable of applying 0.25 N.m ±0.05 N.m is used to tighten the test specimen in the fixtures without breaking it.

The environmental chamber provides and maintains the required temperature during the test procedure. The environmental chamber can use either laboratory air or commercially bottled air. For test temperatures below 30°C, the environmental chamber can use chilled compressed air or liquid nitrogen. The temperature controller keeps the testing temperature within the ±0.1°C of the designated testing temperature. The internal DSR thermometer is a platinum resistance thermometer (PRT) mounted near the bottom-mounting fixture inside the environmental chamber. It provides constant reading of the temperature during the test with a minimum resolution of 0.1°C.

To determine the shear dynamic modulus and the phase angle, the loading device is suited in a way to apply a strain-controlled sinusoidal oscillatory load to the specimen. The load is applied at different frequencies ranging from 0.01 Hz to 15 Hz with an accuracy of at least 1 percent for strains and the frequencies. If the DSR is used to perform creep tests, the loading device should be capable of applying required static and repeating loads at the required stresses.

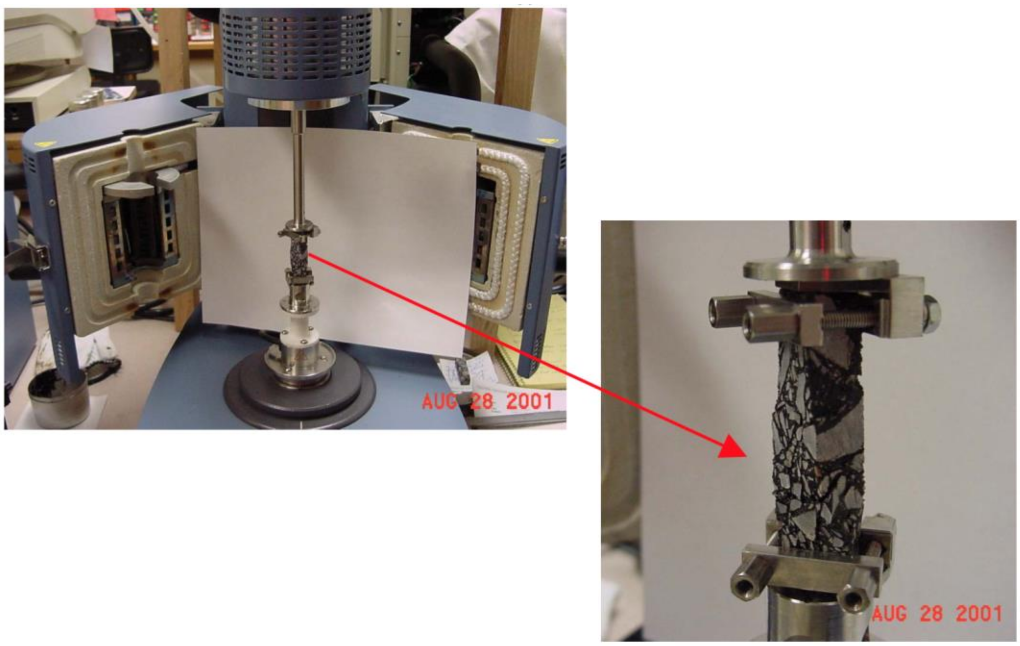

Figure 2-6 DSR Utilized for Asphalt Mixtures (Reinke and Glidden 2004)

The control and data acquisition system records all the measured data including temperature, frequency, deflection angle, percent strain, oscillatory stress and torque with a minimum accuracy of 1.0 percent. Since the calculation of the complex shear modulus is highly dependent on accurate measuring of the specimen dimensions, a digital caliper is used to measure the width and thickness of the test specimen prior to the test with a resolution of ±0.1 mm. (ASTM-D7552-09, 2015)

2.3.3 Specimen Preparation of Asphalt Mixture for the DSR

Test specimens can be prepared from laboratory compacted asphalt mixture samples, field obtained cores, or slabs directly cut from the pavement. The percent air voids in the mixture should be determined as it affects the shear dynamic modulus. Test specimens are sawed to the proper dimensions utilizing a wet cutting saw. To make the test specimens out of the gyratory compacted samples, the first 25 mm of the sample is sawed and discarded to ensure air voids uniformity. A 12 mm thick disk is sawed out of the remaining sample, and then the disk is sawed to a 50 mm wide rectangular prism. The first and the last 25 mm of the 50 mm wide rectangular prism are discarded to prevent air voids variability. Then the 50 mm wide rectangular prismatic is sawed to 10 mm thick rectangular prisms. The dimensions of the prepared specimens should be within the following ranges: 9±1.5 mm wide, 12±2 mm thick and 49±2 mm long. Figure 2-7 demonstrates the preparation of a specimen out of a laboratory compacted sample. (ASTM-D7552-09, 2015)

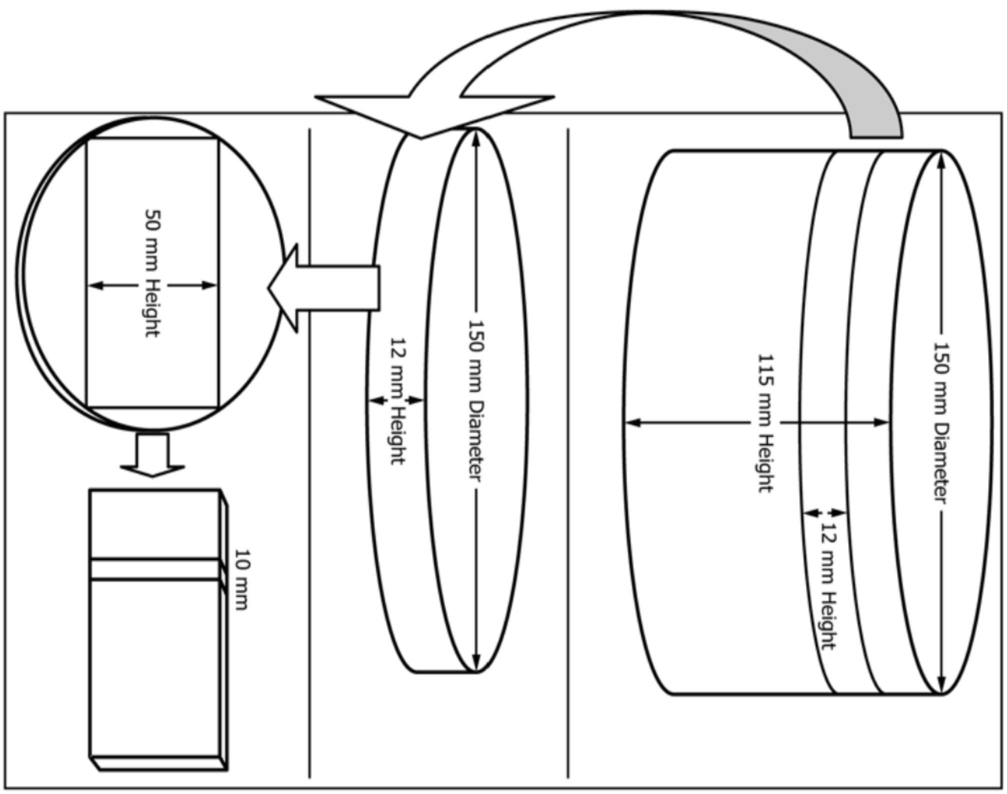

Figure 2-7 Schematic of Preparing Asphalt Mixture Specimen for the DSR Device

(ASTM-D7552-09, 2015)

2.3.4 Test Procedure for Determining the Shear Properties of Asphalt Mixtures Using the DSR

The dynamic shear rheometer device requires zeroing the gap at the testing temperatures or mean of the testing temperatures. The environmental chamber is opened and the specimen is mounted at the center of the test fixtures. The specimen is finger tightened into place and then an approximate 0.200 N.m torque is applied to fasten the tightening screws. The fastening process should be done with care to prevent producing more than 5 N normal forces into the specimen. After tightening the specimen, the environmental chamber is closed and the specimen is conditioned to the testing temperature. When the test is performed at several temperatures, the testing sequence starts from the lowest to the highest temperatures. The test specimen should reach a thermal equilibrium within the ±0.1°C. The test starts in 5 minutes after the thermal equilibrium is reached.

Frequency sweep tests are performed to measure the complex shear modulus and the phase angle. The frequency sweep tests with constant strain of 0.01% are performed from the highest frequency of 15 Hz to the lowest frequency of 0.01 Hz at each temperature. (ASTM-D7552-09, 2015)

The static creep test can be performed by applying a constant rotational stress to an asphalt concrete specimen at a selected temperature while the response strain is recorded till the specimen fails. Reinke and Glidden (2004) performed the static creep tests at 15 kPa stress level. The repeated creep test can be performed by applying a stress to an asphalt concrete specimen for one second followed by 9.0 seconds rest period of zero stress. Part of the deformation due to the stress period recovers during the rest period. The loading and recovering cycles continue up to 2,000 cycles or when the permanent strain in the specimen reaches 5 percent. Reinke and Glidden (2004) adopted a stress level of 68 kPa for the repeated creep test, which is similar to the stress levels for the permanent deformation test in the Superpave shear tests. (Reinke & Glidden, 2004)

2.3.5 Evaluation of Determining Shear Properties of Asphalt Mixtures Using the DSR

The DSR can be used to test specimens made from laboratory or field mixed and laboratory compacted or field cores. This test method is applicable to any type and grade of binder as well as mixture, including Reclaimed Asphalt Pavement (RAP). In addition, the small size of the specimen reduces the required time to reach the testing temperature equilibrium, which significantly reduces testing time when comparing to other tests with bigger specimens. One of the major advantages of this test system is the availability of the DSR device at many asphalt laboratories. This availability makes it opportune for the device to be adopted for shear testing on asphalt mixtures.

The major limitation of this test system is its specimen's geometry. Due to the geometry limitations, the specimen can be only made from dense graded coarse or fine mixtures with nominal maximum aggregate size of 19 mm and lower (ASTM-D7552-09, 2015). As a result the DSR is not appropriate for test of open graded or Stone Matrix Asphalt (SMA) mixtures. Moreover, the specimen preparation requires several saw cuts at a prescribed precision that adds difficulty to the specimen preparation. In addition the smaller size of the specimen affects the uniformity, which affects the test results.

2.4 Superpave Shear Tester (SST)

2.4.1 Background

The U.S. Congress founded the "Strategic Highway Research Program" known as SHRP in 1987 to make the roads of United States safer and durable by improving their performance, saving costs and increasing productivity. In this program the individual projects were placed in several areas: Asphalt, Long-Term Pavement Performance, Concrete and Structures, Winter Maintenance and Highway Operations (Chowdhury & Button, 2002). SHRP was a five year strategically program with $150 million funds, out of which $50 million were used to develop the Asphalt Specification to improve the relationship between laboratory analysis and field performance. (McDonnell, 2002)

The final product of this program was Superpave (Superior Performing Asphalt Pavements), which is a mixture design and analysis system. The Superpave consists of three major parts: asphalt binder specification, mixture design methodology and analysis system. Under the mixture design methodology and analysis system, the Superpave Shear Tester (SST) and the Indirect Tensile Tester (ITT) were the two devices that researchers developed to evaluate the performance of hot mixed asphalt. (Chowdhury & Button, 2002)

The SST, shown in Figure 2-8, measures the nonlinear elastic, Vermeer plastic, viscoelastic and tertiary properties of asphalt mixtures. These are the basic properties for permanent deformation and rut resistance (Chowdhury & Button, 2002). These parameters are the results of different tests conducted by the SST. The six different SST tests include the followings:

- Uniaxial Test
- Volumetric Test
- Frequency Sweep at Constant Height Test (FSCH)
- Simple Shear at Constant Height Test (SSCH)
- Repeated Shear at Constant Height Test (RSCH)
- Repeated Shear at Constant Stress Ratio Test (RSCSR).

Figure 2-8 Superpave Shear Tester (SST) (Chowdhury and Button 2002)

2.4.2 SST System

The SST is a closed loop feedback and servo-hydraulic system. The closed loop feedback maintains the stress or the strain controlled during loading (Brown, Kandhal, & Zhang, 2001). The SST machine consists of four main parts, as illustrated in Figure 2-9:

- Testing apparatus
- Control and data acquisition system
- Environmental control unit
- Hydraulic system

The testing apparatus includes the horizontal and vertical hydraulic actuators that can apply horizontal and vertical loads at the same time. The loading system can apply confining loads as well as shearing and axial loads. These loads can be ramped up or down (increasing or decreasing), maintained statically, or repetitive and dynamic with different wave shapes. The testing apparatus also comprises pressure and temperature controls. In addition, the testing system encompasses Linear Variable Differential Transducers (LVDTs) that are mounted on an asphalt concrete specimen to quantify the specimen's response to applied loads. The signal received from the LVDTs helps the closed-loop feedback system to function. (Chowdhury & Button, 2002) (Brown, et al., 2001)

The control and data acquisition system records and controls the loads' cycle, time and direction, specimen's deformations in horizontal, vertical, and radial directions, and test chamber temperature. This unit encompasses hardware and software systems that automatically record all the information needed. (Chowdhury & Button, 2002)

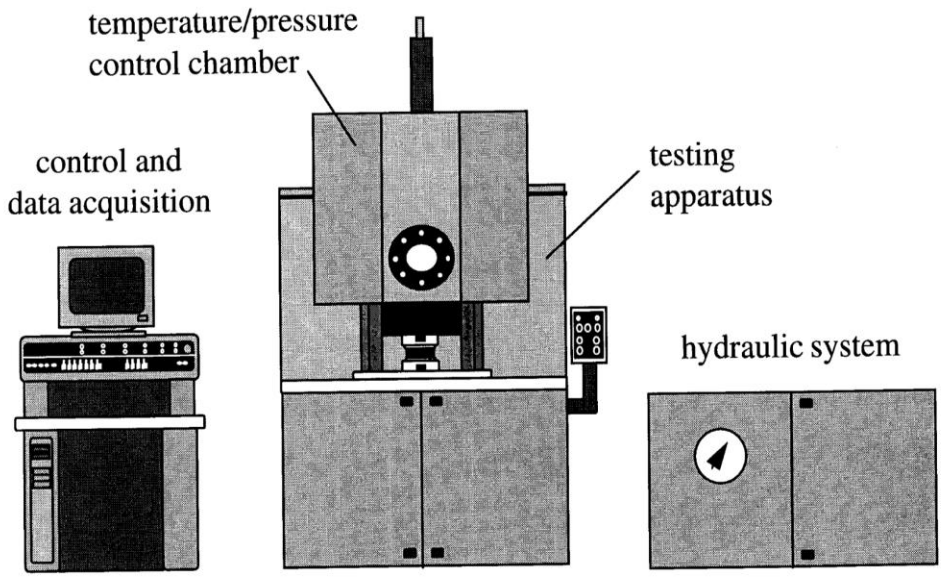

Figure 2-9 Components of the SST Device (Kennedy, et al., 1994)

The environmental unit provides and maintains a specific pressure and temperature inside the test chamber. It can provide temperatures between 1 to 80°C with a ±0.5°C accuracy and it can control and provide an air pressure up to 840 kPa with a rate of 69 kPa per second for tests that require confining pressure, such as the uniaxial and volumetric tests. (Chowdhury & Button, 2002)

The hydraulic system provides axial force and shear load to the specimen through vertical and horizontal actuators as well as confining pressure. Each of the actuators can provide up to 32 kN force with a 2 N resolution. It can also provide a confining pressure of 1,000 kPa. (Chowdhury & Button, 2002)

2.4.3 SST Tests

Volumetric Test

The Volumetric Test (also referred as hydrostatic test) loads an asphalt concrete specimen under a confining pressure at a specific temperature. This test is normally performed at three different temperatures and confining pressures. The confining pressure steadily increases from zero to a certain level depending on the test temperature. The load remains constant for ten seconds, then the confining pressure gradually decreases to zero, as shown in Figure 2-10. Radial LVDTs mounted on the specimen measure its circumferential and axial deformations. The Volumetric Test results help in characterizing the plastic and elastic behavior of the asphalt mixture and predicting its rutting behavior. (Chowdhury & Button, 2002) (NHI, 2000)

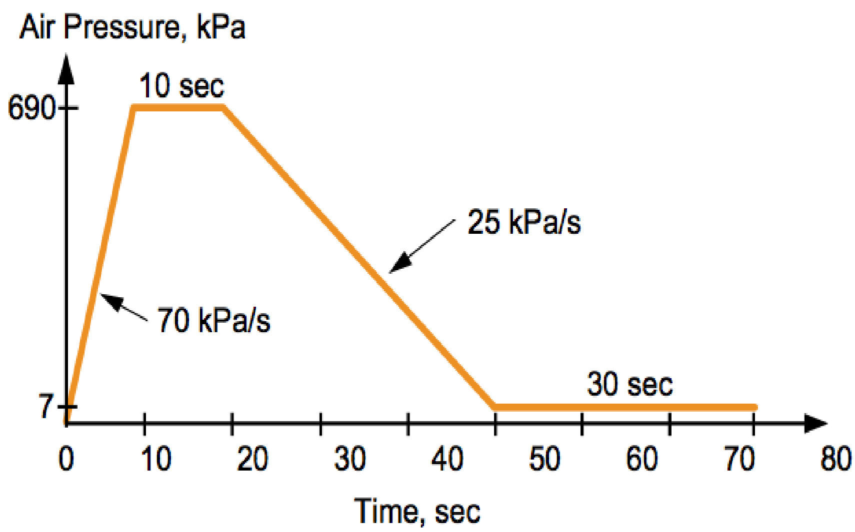

Figure 2-10 Confining Pressure versus Time, Volumetric Test at 20°C - SST (NHI, 2000)

Uniaxial Test

In the Uniaxial Test, an asphalt concrete specimen is subjected to axial and confining pressure loads in a prescribed manner. When the axial load is applied, the specimen tends to increase its circumference. The circumference of the specimen is kept constant with the help of air pressure and the feedback from radial LVDT. Along this test the axial load is increased up to a certain level depending on the test temperature. The axial load remains constant at that level for a while, and then decreases to zero. The schematic axial and confining loadings are illustrated in Figure 2-11. Axial loads and deformation are recorded to describe the elastic and plastic characteristics of the mixture. Similar to the Volumetric Test, the Uniaxial Test is conducted at three different temperatures. (Chowdhury & Button, 2002) (NHI, 2000)

In the Volumetric Test and the Uniaxial Test, the asphalt concrete specimen is subjected to elastic and plastic strains. The recorded loads and deformations are used to describe the elastic and plastic properties of the mixture. Elastic modulus and Poison's ratio of the specimen can be measured from the elastic portion of the graph. From the plastic portion, the volumetric constant, peak angle of friction, factor related to cohesive shear strength and friction angle at constant volume can be calculated. (Chowdhury & Button, 2002)

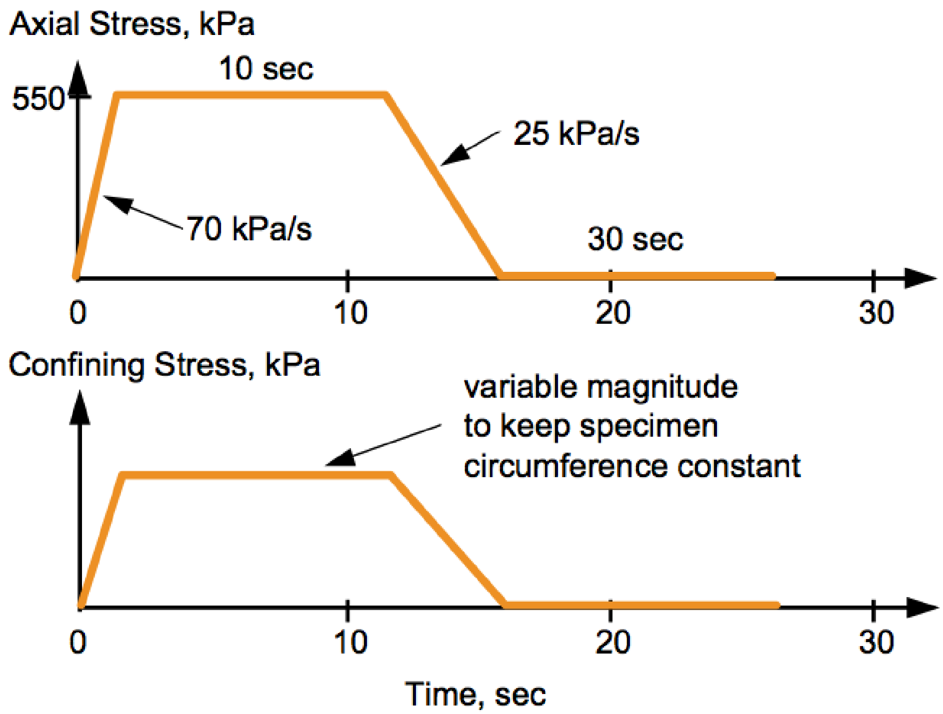

Figure 2-11 Loading stresses versus Time, Uniaxial Test at 20°C - SST (NHI, 2000)

Repeated Shear Test at Constant Height (RSCH)

In the RSCH, an asphalt concrete specimen is loaded repeatedly in shear and axial load. The axial load is applied to keep the specimen at constant height. The loading cycle compromises a load application followed by a rest period. The loading cycles are simply presented in Figure 2-12. Under this repeated shear load, the specimen deforms and part of the deformation is permanent. During the test a cumulative permanent deformation is measured as a function of load cycles. One of the purposes of this test is to check the susceptibility of the HMA mixture to tertiary creep. This kind of creep is a huge amount of plastic deformation in a small number of loads and it is a severe form of rutting. (Brown, et al., 2001) (Chowdhury & Button, 2002)

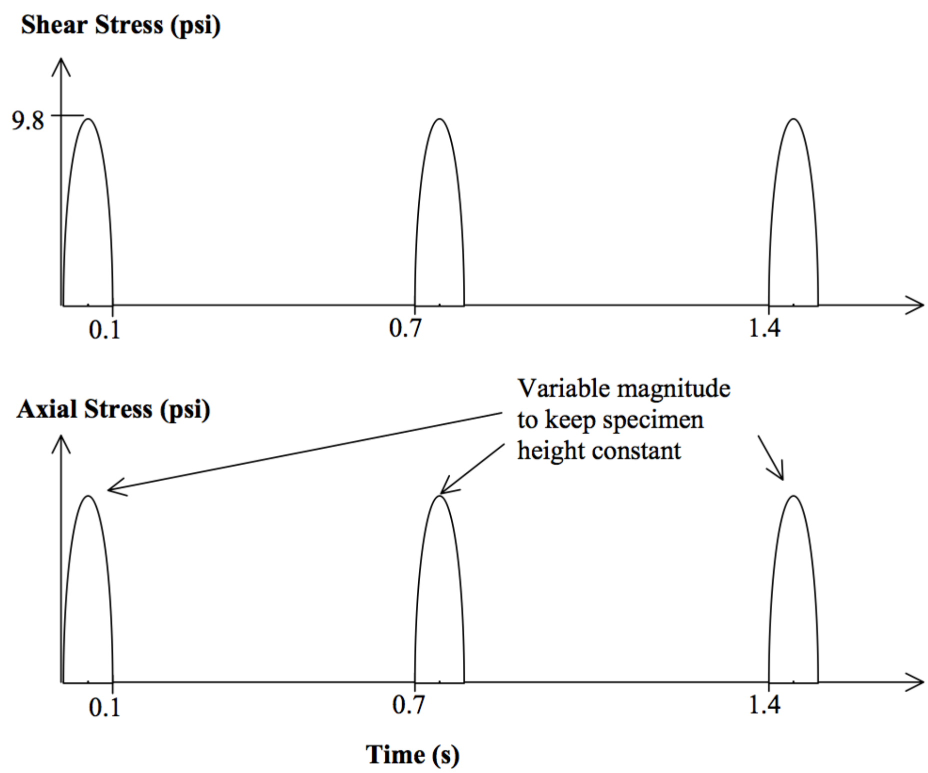

Figure 2-12 Shear and Axial Stresses versus Time, RSCH Test – SST (Chowdhury & Button, 2002)

Figure 2-13 shows a schematic of permanent shear deformation curve as a function of load cycles during RSCH test. The curve can be divided into three major parts: the initial compaction, the linear portion of permanent deformation and the tertiary flow. The initial compaction causes relatively large and rapidly strains; quite steady plastic deformations make the linear portion of the curve. The continuous plastic deformation changes the structure of the mixture and when the air void falls below some certain value, the tertiary flow occurs and leads to failure. (Pavement Interactive, 2008)

During the RSCH test, the shear strain of the specimen under the repetitive load is recorded. The permanent shear strain is calculated at the end of the test. (AASHTO T-320, 2004)

$$\gamma_p = (\delta_{shear,\ initial} - \delta_{shear,\ final}) / h \qquad (2\text{-}1)$$

γ_p: Permanent shear strain

$\delta_{shear,\ initial}$: Initial shear deformation at the start of the test (nominally zero)

$\delta_{shear,\ final}$: Final recorded deformation recorded by the LVDT at the end of the test

h: Specimen height (platen-to-platen height)

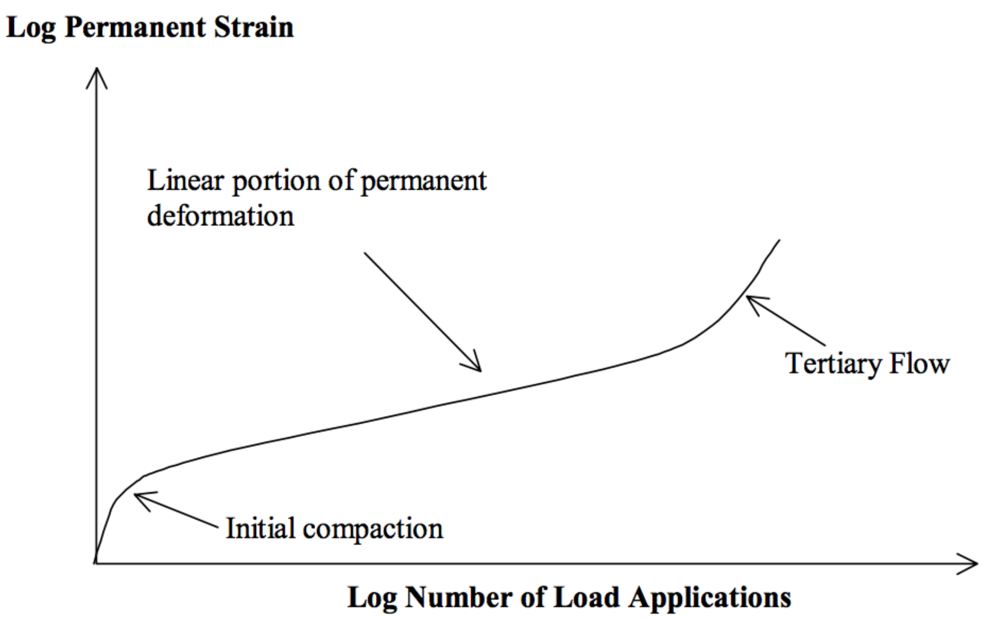

Figure 2-13 Log Permanent Deformation versus Log Number of Load Applications, RSCH Test - SST (Chowdhury & Button, 2002)

Shear Frequency Sweep Test at Constant Height (FSCH)

The FSCH test loads an asphalt concrete specimen under a strain controlled dynamic shear load as well as an axial load that keeps the specimen's height constant. The dynamic shear load is applied at a constant shear strain over a wide range of frequencies at different temperatures. Values of stresses and strains under the shear and axial loads are recorded during the test. The ratio of peak values of shear stress and shear strain are used to calculate the shear dynamic modulus, $|G^*|$. The time lag between the peak shear strain and peak shear stress is used to calculate the phase angle, Φ. The delay between the applied strain and the measured stress is due to the viscoelastic behavior of asphalt mixtures (Chowdhury & Button, 2002) (Anderson, Huber, Steger, & Romero, 2002). The phase angle for a purely elastic material is zero and for a totally viscous fluid is 90 degrees. The shear dynamic modulus and the phase angle are very effective in predicting asphalt mixture's behavior in rutting. High shear dynamic modulus indicates a stiff mixture and a low phase angle indicates an elastic material. Such a material can resist rutting better (Brown, et al., 2001).

Figure 2-14 illustrates the application of dynamic shear strain and stress pulses in the FSCH test. The shear dynamic modulus and phase angle can be calculated as: (Witczak, et al., 2002) (Pavement Interactive, 2008)

$$|G^*| = \tau_0 / \gamma_0 \qquad (2\text{-}2)$$

$$\Phi = t_i / t_p \qquad (2\text{-}3)$$

$$G^* = |G^*| \cos\phi + i\,|G^*| \sin\phi \qquad (2\text{-}4)$$

$|G^*|$: Shear Dynamic Modulus

G^*: Complex Shear Modulus

τ_0: Peak Dynamic Shear Stress

γ_0: Peak Recoverable Shear Strain

t_i: Time Lag between Stress and Strain Cycles

t_p: Time for a Stress Cycle

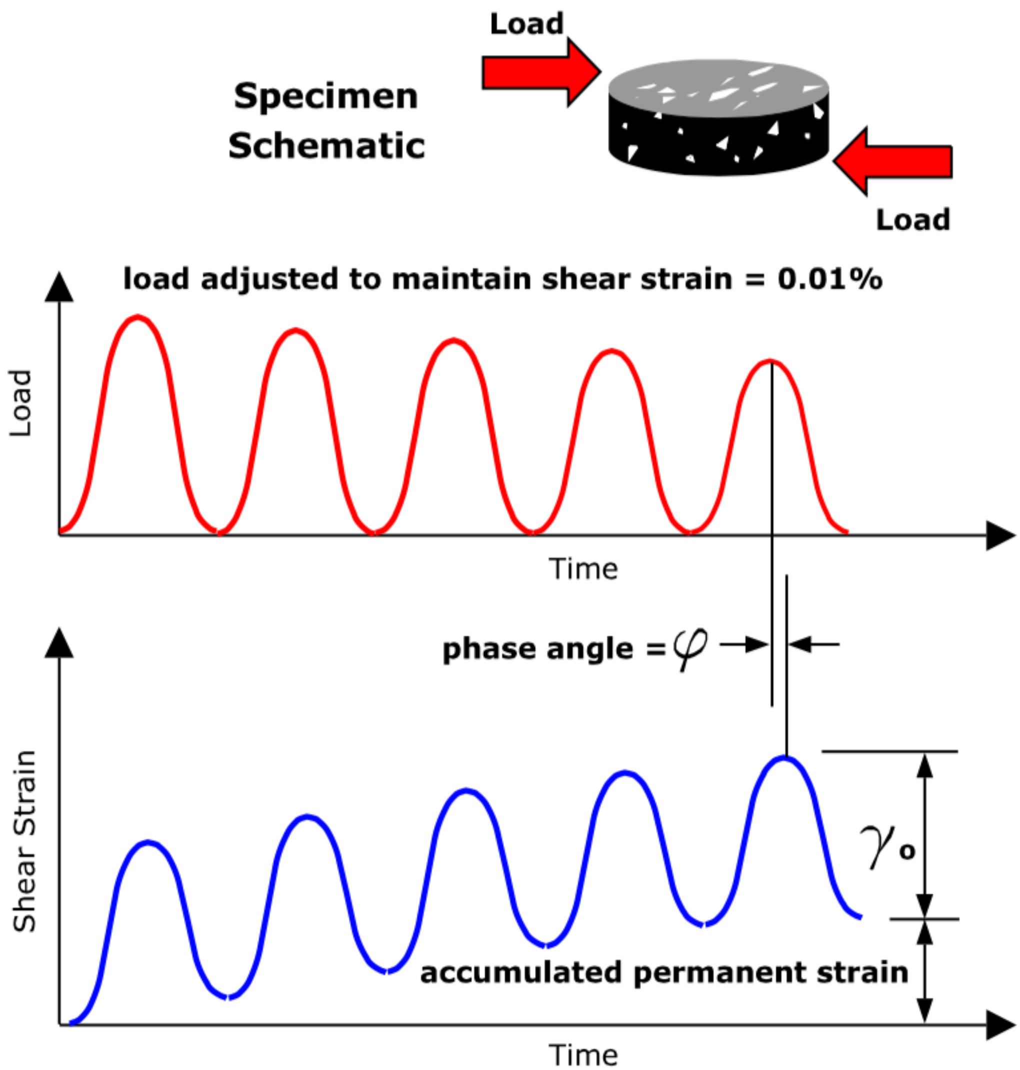

Figure 2-14 Shear Load and Shear Strain versus Time, FSCH Test - SST (Pavement Interactive, 2008)

Simple Shear at Constant Height (SSCH)

In the SSCH test, an asphalt concrete specimen is subjected to a static shear loading and the shear deformation is measured under this load. During this test the shear load raises at a constant rate from zero to a specific level depending on the testing temperatures. The shear load remains steady for ten seconds, then it reduces to zero at a steady rate. All along the test, the height of the specimen is maintained constant by means of the closed loop feedback system. The loading application of this test is simplified in Figure 2-15. (Pavement Interactive, 2008)

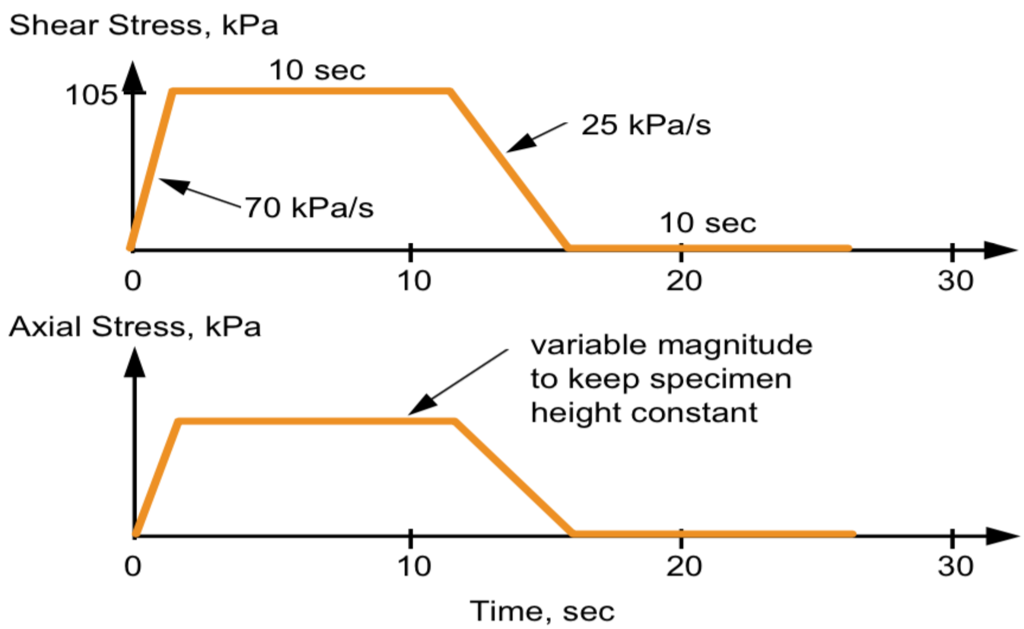

Figure 2-15 Loading Stresses versus Time, SSCH Test at 20°C - SST (NHI, 2000)

The SSCH test can predict the susceptibility of HMA mixtures to permanent deformation and fatigue cracking as it measures the specimen's ability to resist shear strain. At higher temperatures such as 40°C, lower shear strains (creep strains) indicate the ability of the mixture to resist permanent deformation. At lower temperatures like 4°C, higher shear strains (creep strains) are indication of the ability of the mixture to flex and relieve stresses instead of cracking. Shear strains under the loading conditions of the SSCH test are represented in Figure 2-16. (NHI, 2000) (Pavement Interactive, 2008)

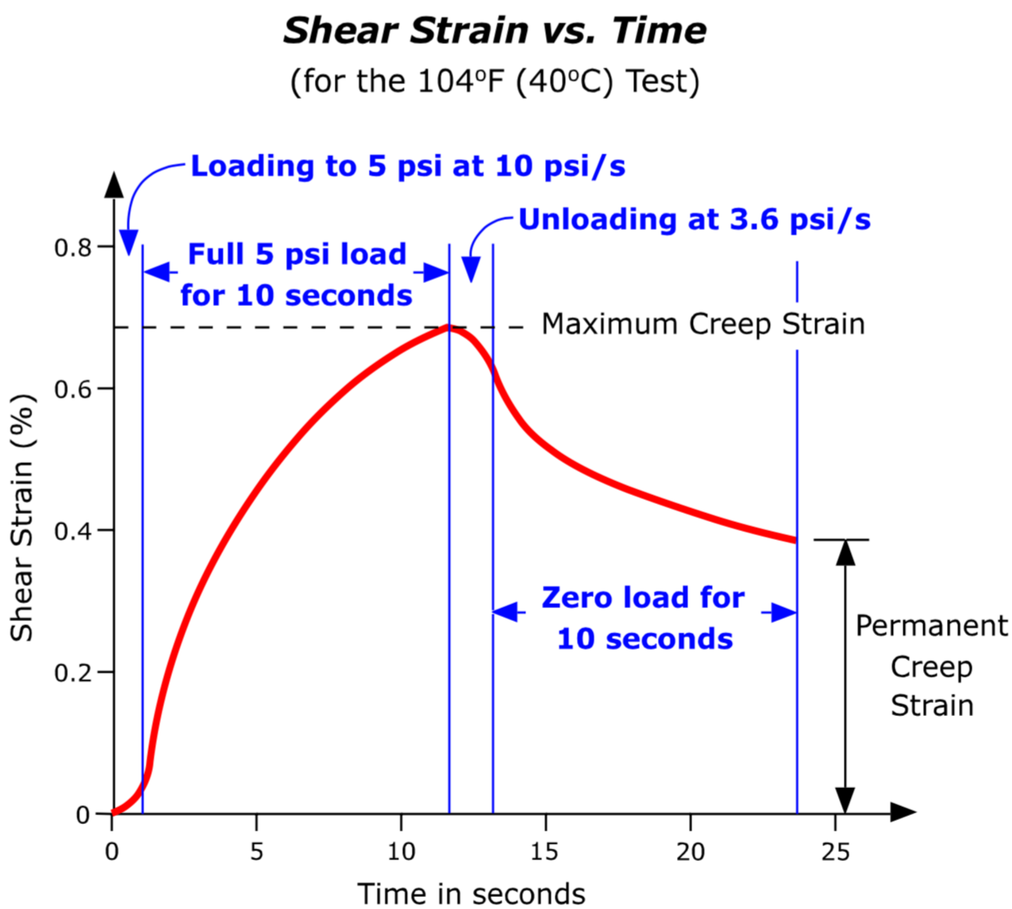

Figure 2-16 Shear Strains versus Time, SSCH Test at 40°C - SST (Pavement Interactive, 2008)

In order to measure the asphalt mixture ability to resist shear strain, the shear load and shear deformation data are used to calculate the maximum deformation, permanent deformation, and elastic recovery as: (AASHTO T-320, 2004)

$$\gamma_{max} = (\delta_{shear,\ maximum} - \delta_{shear,\ initial}) / h \qquad (2\text{-}5)$$

$$Recovery = (\delta_{shear,\ maximum} - \delta_{shear,\ final}) / \delta_{shear,\ maximum} \qquad (2\text{-}6)$$

γ_{max}: Maximum Shear Strain

$\delta_{shear,\ maximum}$: Maximum Recorded Deformation by the Shear LVDT

$\delta_{shear,\ initial}$: Initial Shear Deformation at the Start of the Test (Nominally Zero)

$\delta_{shear,\ final}$: Final Shear Deformation at the end of the Test

h: Specimen Height (Platen-to-Platen Measure only)

*Recovery : C*alculated Recovery of the Specimen

Repeated Shear at Constant Stress Ratio Test (RSCSR)

The RSCSR test is very similar to the RSCH test, except that the axial load is proportional to the shear load. In this test, an asphalt concrete specimen is subjected to a repetitive synchronized haversine shear and axial load pulses, as shown in Figure 2-17. Each load cycle includes a load application followed by a rest period. During the test, the ratio of axial stress to shear stress remains constant. The specimen deforms under the repeated load and part of the deformation is permanent. Cumulative permanent deformation of the specimen is measured over the course of load cycles (Chowdhury & Button, 2002). Similar to the RSCH test, this test evaluates mixture susceptibility to tertiary flow, which is the point where the permanent shear deformation increases rapidly (Kennedy, et al., 1994).

The loads and deformations under both axial and shear forces are recorded. The permanent shear strain is reported and calculated as: (Chowdhury & Button, 2002)

$$\gamma_p = (\delta_{shear,\ initial} - \delta_{shear,\ final}) / h \qquad (2\text{-}7)$$

γ_p: Permanent shear strain,

$\delta_{shear,\ initial}$: Initial shear deformation at the start of the test (nominally zero)

$\delta_{shear,\ final}$: Final recorded deformation recorded by the LVDT at the end of the test

h: Specimen height (platen-to-platen height)

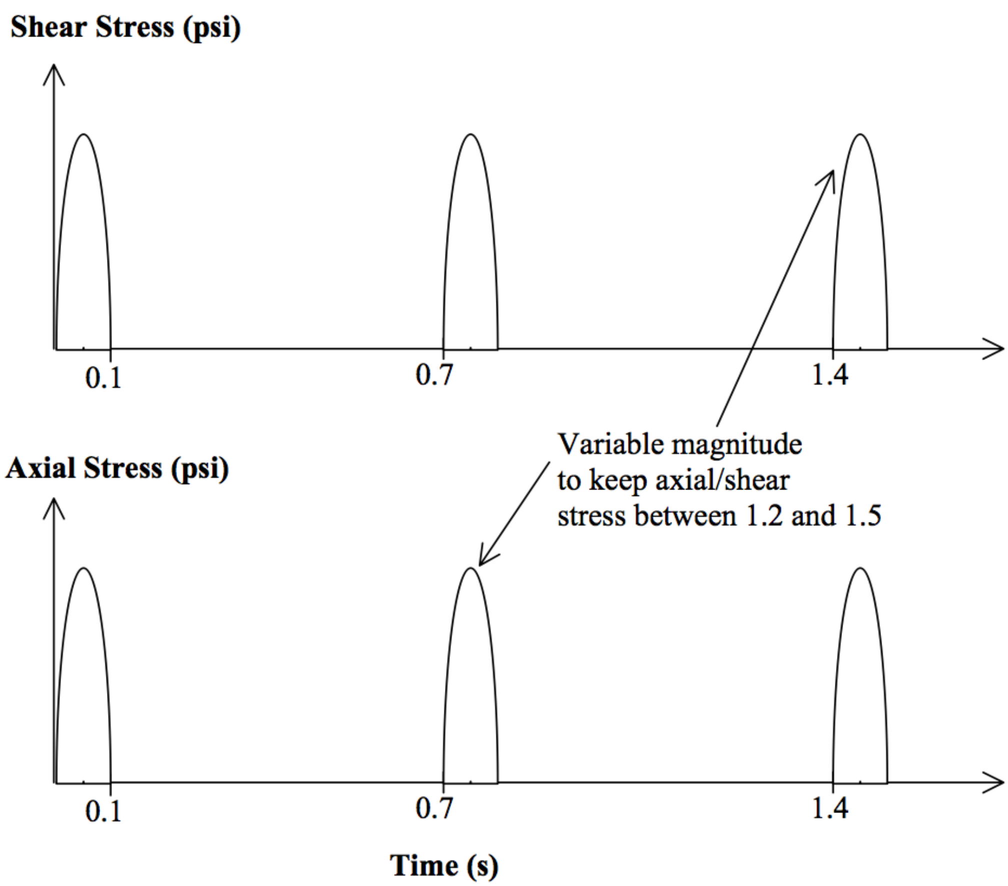

Figure 2-17 Axial and Shear Load Cycles versus Time, RSCSR Test – SST (Chowdhury & Button, 2002)

2.4.4 SST Test Procedures

Specimen Preparation

The diameter of SST specimen is always 150 millimeters and its height controls its size. The SST specimen should be large enough to reflect the characteristics of the mix not its individual constituents, such as the aggregates. As a result, the height of the specimen depends on the nominal maximum size of aggregate (NMA). Minimum specimen height is 50 millimeters for mixtures with NMA equal to 19 millimeters and it can be 38 millimeter for mixtures with smaller NMA. SST can test samples with NMA greater than 19 millimeter, but the larger aggregate size affects test repeatability. (AASHTO T-320, 2004) (Pavement Interactive, 2008)

The specimens can be prepared from laboratory mixed material or field mixed material. Enough loose sample should be produced or obtained considering the size and number of the specimens. Moreover, the laboratory mixed asphalt concrete needs to be conditioned in an oven for 4 ± 0.1 hours at 135 ± 5°C (AASHTO PP2).

The SST specimens can be obtained from laboratory compacted samples or cores from field compacted asphalt concrete. However, the compaction method and amount of air voids in the compacted material affect the test results. Therefore, it is not practical to compare the test results for samples prepared with different compacting method and percentage of air voids. (Pavement Interactive, 2008)

The laboratory compacted specimens are usually compacted with the Superpave Gyratory Compactor (SGC). The specimens are made tall enough so that when both ends are cut off, the remaining sample is 50 or 38 millimeters tall. The laboratory compacted specimens are usually compacted to have an air voids of 3.0 percent for the RSCH test, and 7.0 percent for the FSCH and SSCH tests (AASHTO T-320, 2004). The air voids are not distributed evenly through compacted sample; there are fewer air voids in the middle of the sample. Uneven distribution of the air voids results in 1.0 to 2.0 percent fewer air voids in the specimen when both ends of the sample are cut off. For this reason, the samples are usually compacted to a slightly higher air voids percentage than the targeted value (Pavement Interactive, 2008).

The compacted samples or cores from field should be cut to proper dimensions, 150 millimeters diameter and 50 or 38 millimeters tall, depending on the NMAS of the asphalt mixture. Finally for all the specimens the percentage of air voids and the height should be determined.

Test Preparation

To conduct any of the SST tests, the aluminum platens are completely cleaned and adjusted in their position. The testing specimen is glued to the top and bottom platens using epoxy. The specimen is maintained at the test temperature for two to four hours. (Pavement Interactive, 2008)

Depending on the test procedure, the LVDTs are mounted on the specimen to measure the load response or deformation in the axial, horizontal and radial directions. The LVDTs can be mounted either on the platens or directly on the specimen. If it is connected directly to the specimen, the measured deformations are only depended on the specimen rather than the platens (Chowdhury & Button, 2002).

The glued specimen is centered between the test heads and the platens are secured to the test heads via hydraulic clamps. The environmental chamber is lowered and locked into place. The specimen requires at least 20 to 60 minutes to get stabilized in the environmental chamber (AASHTO T-320, 2004). The test procedure continues according to the type of the test as discussed in the following.

Volumetric Test

In this test procedure the specimen is subjected to a confining pressure, which increases at a constant rate of 70 kPa per second up to a certain level depending on the test temperature, as indicated in Table 2-1. The load remains constant for 10 seconds, then it decreases to zero at a rate of 25 kPa per second. The circumferential and axial deformations of the specimen are recorded during the loading cycle and 30 seconds beyond unloading. This test is conducted at 4, 20 or 40°C (NHI, 2000).

Table 2-1 Volumetric Test Parameters - SST (NHI, 2000)

Temperature	**Pressure**
4°C	830 kPa
20°C	690 kPa
40°C	550 kPa

Uniaxial Test

In this test procedure, the asphalt concrete specimen undergoes axial loads. The axial stress rises from zero at a rate of 70 kPa per second up to a certain stage based on the test temperature, as shown in Table 2-2. The axial stress remains constant for 10 seconds, and then it lowers down to zero at a rate of 25 kPa per second. The axial deformation is recorded up to 30 seconds after load removal. The testing temperatures are the same as for the volumetric test. (NHI, 2000)

Table 2-2 Uniaxial Test Parameters - SST (NHI, 2000)

Temperature	**Pressure**
4°C	655 kPa
20°C	550 kPa
40°C	345 kPa

RSCH Test

In this test procedure, a repeated haversine shear stress of 69 kPa is applied to the specimen for 0.1 second followed by 0.6 second rest period. The height of the specimen is maintained constant with the help of vertical actuator, which moves in relation to the vertical LVDT measurements. Throughout the test, the permanent deformation is measured and the loading continues for 5,000 cycles or until the permanent shear strain reaches 5 percent, or 2.5 millimeters for a 50 millimeters tall specimen. (AASHTO T-320, 2004)

The test temperature is usually the seven-day maximum pavement temperature at the project location. This temperature is measured at a depth of 50 millimeters for thick layers or at actual layer thickness for layers thinner than 50 mm. (AASHTO T-320, 2004)

FSCH Test

In this test procedure, the specimen is preconditioned with a sinusoidal shear strain of peak-to-peak amplitude of 0.01 percent with frequency of 10 Hz for 100 cycles. Then the specimen is loaded with a sinusoidal shear strain of 0.01 percent for 10 more sweeps with various frequencies and number of load cycles, as indicated in Table 2-3. During the loading, the height of the specimen is maintained with the help of vertical actuator moving in response to the vertical LVDT measurements. (AASHTO T-320, 2004)

Multiple specimens can be tested at different temperatures. For different testing temperatures, the specimen should be placed in the conditioning chamber for the new temperature. An intermediate temperature, like 20°C, may be desired for fatigue analysis. Higher temperatures, like 40°C, may be desired to determine the high temperature stiffness. However, the testing should be conducted at temperatures where the mixture stiffness is below 3,000 MPa due to the equipment constraints. The higher testing temperature should be 12 °C below the high-temperature grade of the asphalt binder.

Since the FSCH test theoretically assumed to be conducted in the linear viscoelastic behavior region, the same specimen can be tested at other temperatures or used for other test procedures, such as the RSCH or SSCH tests. (AASHTO T-320, 2004)

Table 2-3 FSCH Test Parameters - SST (AASHTO T-320, 2004)

Frequency	**Number of Cycles**
10	50
5	50
2	20
1	20
0.5	7
0.2	7
0.1	7
0.05	4
0.02	4
0.01	4

SSCH Test

In the SSCH test procedure, the specimen is subjected to shear and axial stresses. The applied shear stresses increase from zero at a constant rate of 70 kPa per second up to a definite stress level depending on the test temperature, as specified in Table 2-4. The shear stress level is maintained constant for 10 seconds and then it is gradually decreased to zero at a rate of 25 kPa per second. Through the test, axial stresses are applied in response to the vertical LVDT measurements to keep the specimen height at constant level. The shear and axial stresses and the deformations are recorded up to 10 seconds after load removal (NHI, 2000) (AASHTO T-320, 2004).

Table 2-4 SSCH Test Parameters - SST

Temperature	Shear Stress
4°C	345 kPa
20°C	105 kPa
40°C	35 kPa

This test induces permanent shear strain. Consequently, the same specimen cannot be tested at different temperatures. However, same specimen may be tested at temperatures below 40°C if the permanent shear strain is sufficiently small (AASHTO T-320, 2004).

RSCST Test

In the RSCSR test procedure, the specimen is subjected to repetitive synchronized haversine shear and axial load pulses. The ratio of haversine shear and axial stresses remains constant within the range of 1.2 to 1.5 along the test. The load is applied for 0.1 second followed by 0.6 second rest period. This test is conducted for 5,000 cycles or when accumulated shear strain reaches 5 percent. However researchers recommend using 10,000 cycles instead, as most of the asphalt mixtures did not show tertiary rutting problems in 5,000 cycles (Chowdhury & Button, 2002). The axial and shear loads and deformations are measured and recorded during this test. The permanent shear strain at the final loading cycle is reported as the test result (NHI, 2000).

For all the SST test procedures, when the testing is finished, the loads are released and the LVDTs are disconnected. To separate the specimen from the aluminum platens, the specimen is placed in the oven for one hour at 135°C. The asphalt mix and the epoxy are removed from the platens and any residue on the platens is cleaned with acetone (AASHTO T-320, 2004).

2.4.5 Evaluation of the SST

The FSCH and the RSCH are the most popular test procedures among the SST tests. The Uniaxial, Volumetric and RSCSR tests were eliminated from the SST tests, as they were complex and poorly correlated with the pavement performance (Chowdhury & Button, 2002) (Pavement Interactive, 2008). Chowdhury and Button (2002) evaluated four of the SST tests and they concluded that the FSCH and RSCH tests are capable of ranking mixtures in the same general order as the conventional wheel testers such as the Asphalt Pavement Analyzer (APA), 1/3-Scale Model Mobile Load Simulator (MMLS3), and Hamburg Wheel Tracking Device. Moreover, Witczak et al (2002) reported that the shear dynamic modulus and the phase angle measured by the FSCH and the permanent deformation measured by the RSCH correlate with observed rut depth in field projects. Although some of the SST Tests found to be effective in predicting and comparing rut resistance of the asphalt mixtures, several deficiencies with the SST, including its high complexity and cost, prevented it from being widely adopted.

Chapter 3

Development of the Duplicate Shear Test

3.1 Development Objectives of the Duplicate Shear Test

In Chapter 2, four different shear test devices were evaluated. Each of those devices had their own advantages and disadvantages. The major deficiency with the FST is the high variability in the results. The InSiSST™ is only effective as an in-situ shear test device and cannot complement the mixture design process. The major deficiency of the DSR is the specimen's geometry, which limits its application to dense graded mixtures. The SST is successful in characterizing the shear properties and predicting the rut resistance of asphalt mixtures. However, the SST is complex, hard to operate, and quite expensive with an approximate cost of $250,000 USD (Goodman, 2000). Consequently, it was decided to develop a simpler and smaller device that can reproduce the SST's test at a substantially lower cost. Considering the advantages and deficiencies of the SST and the other evaluated shear test devices, the new test device should:

1. Provide direct measurement of fundamental shear properties or responses of asphalt mixtures
2. Be simple, relatively inexpensive and adoptable by asphalt laboratories
3. Follow definite test procedures
4. Provide reliable and repeatable measurements

3.2 Development of the Duplicate Shear Tester (DST)

3.2.1 Loading Conditions and Constraints

The loading conditions and constraints of the SST were considered when developing the new test device that can provide measurements similar to those of the SST. The SST applies a dynamic or static shear load to an asphalt concrete specimen in a direction perpendicular to the compaction axis of the mixture. The applied shear load disturbs the mixture skeleton, and the volume and the height of the specimen tend to increase (Figure 3-1). The SST keeps the specimen height constant by means of a closed-loop feedback system. This system measures the axial deformation of the specimen and applies an axial load to neutralize the axial deformation and keeps the specimen height constant. Figure 3-2 illustrates the loading conditions and constraints of the SST.

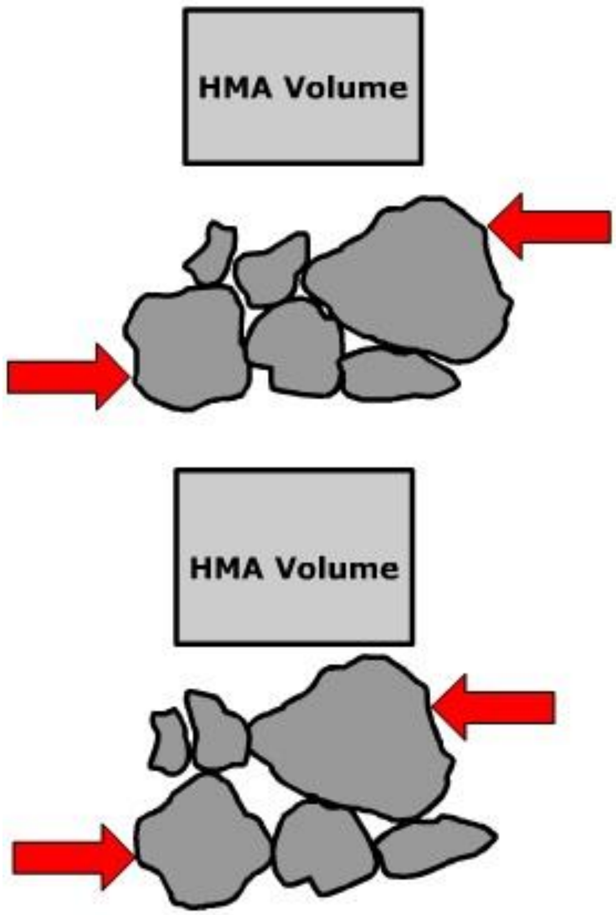

Figure 3-1 Change in the Volume of Compacted Sample Due to Shear Stresses

(Pavement Interactive, 2008)

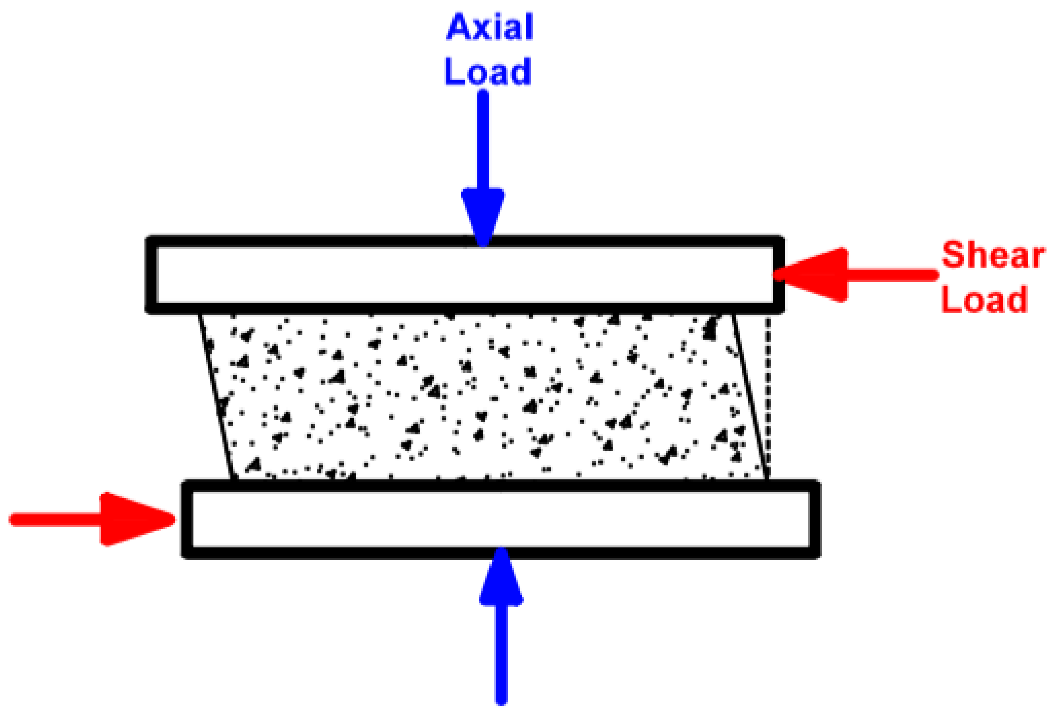

Figure 3-2 Illustration of Superpave Shear Test Loads

A new test device has been developed to replicate similar loading conditions and constraints of the SST but for two specimens tested at the same time. The new device has been named the "Duplicate Shear Tester (DST)", since it measures the average for mechanical shear properties of two cylindrical specimens. Figure 3-3 presents a simple illustration of the DST and how it loads two cylindrical specimens at the same time.

The DST consists of the following parts:

- Two steel platens (10" ×10" × 0.5")
- One aluminum platen (7" × 7" × 0.5")
- Four threaded rods (0.5" standard size and 8.5" long)
- Sixteen nuts (0.5" standard)

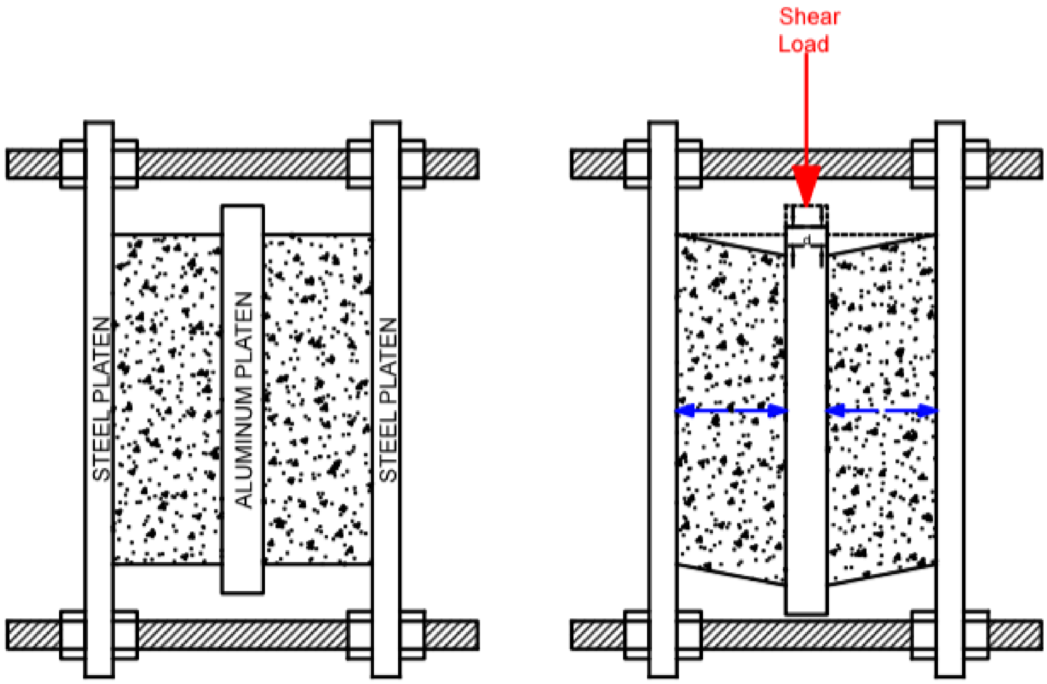

Figure 3-3 Simplified Illustration of the Duplicate Shear Tester (DST)

As indicated in Figure 3-3, to assemble the DST, two similar specimens are glued to the aluminum platen in the middle and to the steel platens on the sides. The steel platens are fixed and kept at a constant distance from each other by the means of the threaded rods and adjustable nuts on each side of the steel platens.

When a vertical force is applied at the top and the center of the aluminum platen, the specimens are subjected to shear stresses. Under these shear stresses, the specimens tend to expand as their skeleton is disturbed. Each specimen induces normal forces to the aluminum and the steel platens. It can be assumed that the specimens confine each other by applying quasi-identical normal forces to the aluminum platen since they are made of the same mix and have almost identical dimension. In addition, the steel platens are fixed and they confine each specimen on the other side. Therefore, it is reasonable to assume that the height of the specimens remains constant. Figure 3-3 illustrates the induced normal forces to the aluminum and steel platens as blue arrows.

The steel and aluminum platens developed for the Duplicate Shear Tester are represented with their typical cross sections in Figure 3-4. The steel platens have a circular depression with a depth of 1/16 inches and an average diameter of 5.9 inches (150 millimeters). The aluminum platen has identical depressions on its both sides. The depressions on the platens contain the epoxy putty used to glue the specimen to the platens and help placing the specimens in the center of the platens.

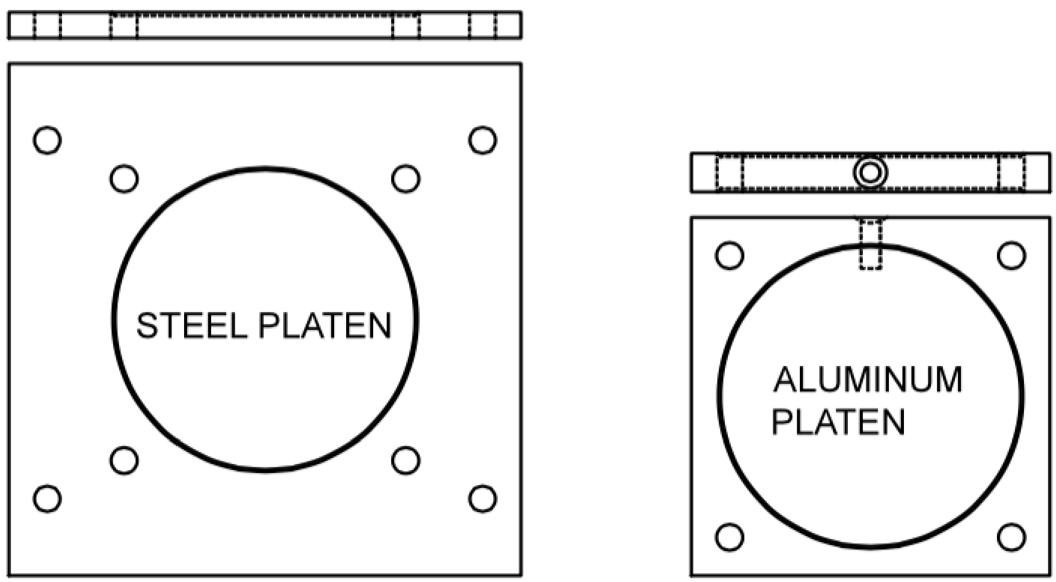

Figure 3-4 Steel and Aluminum Platens of the DST

The diameter of the depressions on the platens increases from 5.85 inches to 5.95 inches at the surface of the platen (the sides are tapered). These depressions are designed to accommodate laboratory compacted cylindrical specimens or cores from field compacted asphalt mix with diameter of 150 millimeters, identical to the specimens used for the SST.

In addition there are eight holes on the steel platens, and four holes on the aluminum platen. Four of the holes on the steel platens are used for the threaded rods, and the remaining holes on the steel and the aluminum platens are used to line up the platens when assembling the device.

3.2.2 Additional System Components Required for the DST

The DST requires several additional components in order to perform the controlled mechanical shear test procedures similar to that of the SST. Additional components include:

1. Loading system
2. Hydraulic system
3. Control and data acquisition system
4. Environmental Unit

The loading apparatus with a loading frame and actuator is required to provide the capability of applying static and dynamic shear loads. The hydraulic system is needed to support the loading system and to provide the source of energy for the actuator. In addition, the data acquisition and control system is needed to control the loading levels, shapes, and frequencies, as well as recording the response of the specimens under the shear loads. The environmental chamber provides the capability of performing the shear tests at desired temperatures.

In order to make the DST simple and inexpensive, it was decided to utilize a universal testing machine that accommodates those components and has the required capabilities. The minimum requirements for the components of the test system are highly dependent on the shear test procedures, and the level of stresses and deformations. The procedures and recommendations of the standard test method of AASHTO-T320 were adopted for the DST. This standard test method recommends that the loading system be capable of applying static, ramped, and repetitive loads of various waveforms. This standard test method requires that the loading system be at minimum capable of applying load pulses in a haversine wave form with load duration of 0.1 second and a rest period of 0.6 second (AASHTO T-320, 2004). In addition the minimum requirements recommended by the AASHTO T-320 for the test system are presented in Table 3-1.

Table 3-1 Recommended Minimum System Requirements for the Shear Tests (AASHTO T-320, 2004)

Measurements and Control System	Range	Resolution	Accuracy
Load (N)	0 to 31,000	2	5
Shear LVDT (mm)	0 to 0.05	0.001	0.002
Temperature (°C)	0 to 80	0.25	0.5

Utilizing a universal testing machine that provides the required additional system components has significantly reduced the cost and complexity of the DST. These advantages can potentially promote the opportunity for the device to be adopted by laboratories that have a universal testing machine with the required capabilities.

3.2.3 Accessories Developed for the DST

Different accessories has been developed for the current DST to provide the capability of adopting the UTM-25, which is a universal testing machine developed by IPC™ Global. These accessories are simple, and they can be modified for other universal testing machines with similar capabilities.

Supporting Mount

A supporting mount for the DST is used to provide the capability for the UTM-25 to accommodate the DST device. The supporting mount compromises a steel base plate with two guide bars and two grippers. The base plate is bolted on the loading table of the UTM-25 and the grippers are connected to the DST. The supporting mount assures that the DST is fixed on the UTM-25 loading frame. This mount is represented in Figure 3-5. Figure 3-6 illustrates how the supporting mount is installed on the UTM-25 loading frame.

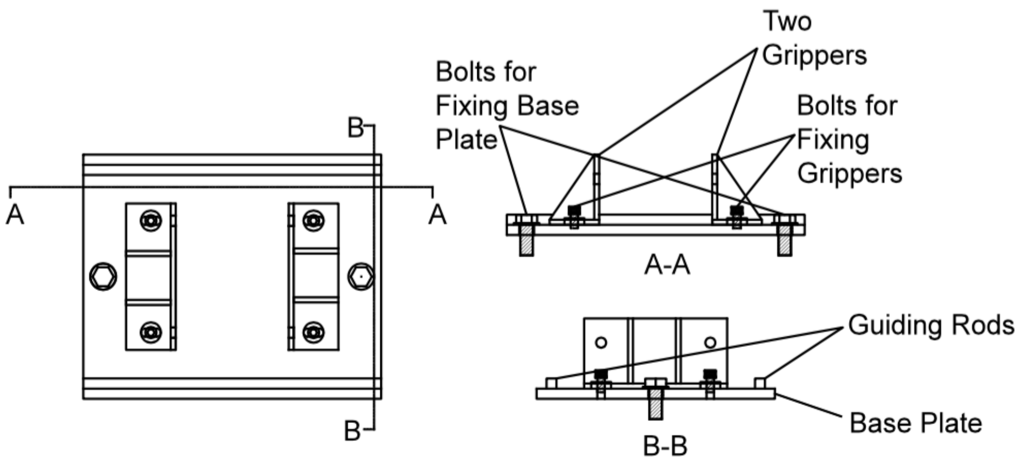

Figure 3-5 Supporting Mount

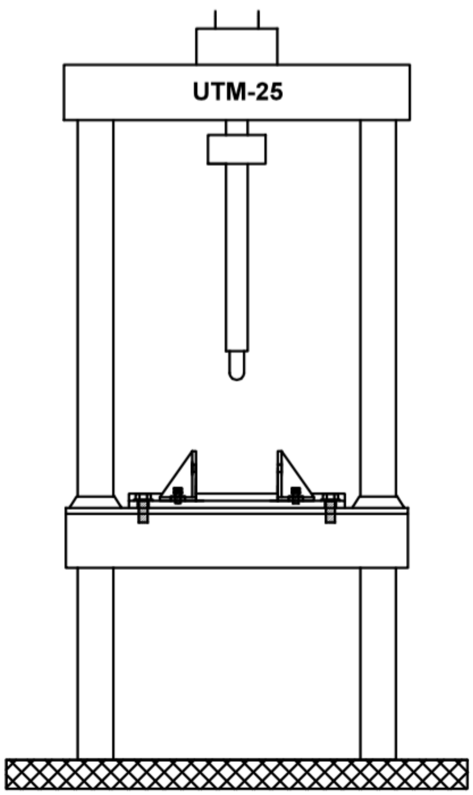

Figure 3-6 Supporting Mount Installed on the UTM-25

Loading Attachments

Depending on the type of the test procedures, one of the two loading attachments presented in Figure 3-7 is mounted on the actuator's ram of the UTM-25. One of these attachments is originally provided by the UTM-25 for the compression tests. However, the same loading attachment can be used for the DST to apply shear loads in one direction (positive). The other attachment is a coupling designed specifically for the DST. This coupling connects the aluminum platen of the DST directly to the loading actuator of the UTM-25. The coupling provides the capability of applying dynamic shear loads in two directions (positive and negative).

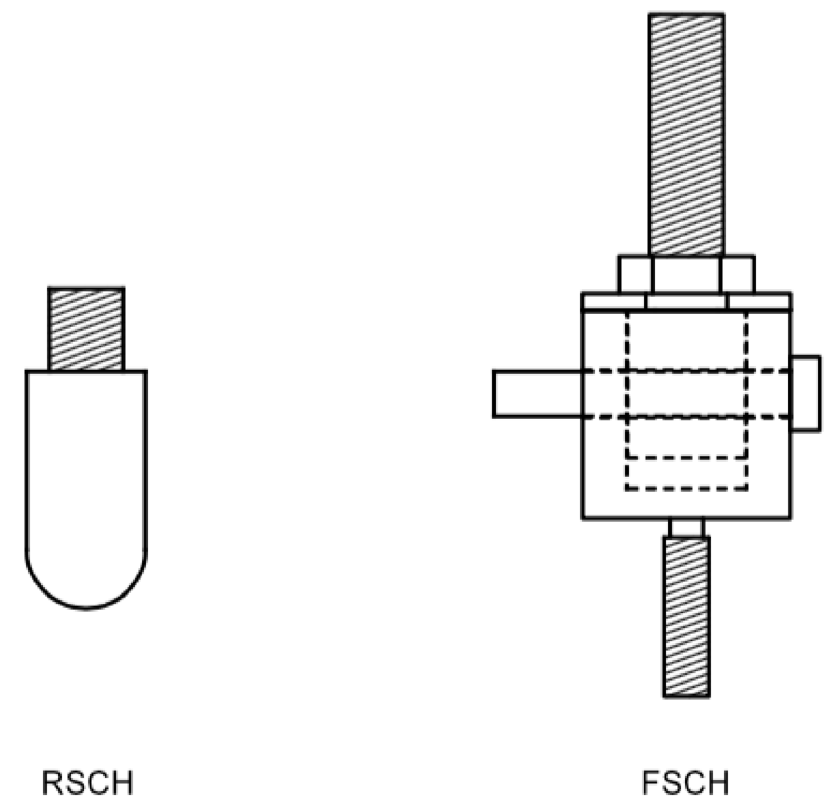

Figure 3-7 Loading Attachments for the DST

The components of the coupling attachment are represented in Figure 3-8. This coupling comprises two metal pieces and one metal pin. One of the metal pieces (Piece 1) is screwed into the actuator’s ram. The other metal piece (Piece 2) is screwed into the aluminum platen of the DST device. When the pin is inserted and the nut on the coupling is tightened, it connects rigidly the aluminum platen to the actuator of the UTM-25.

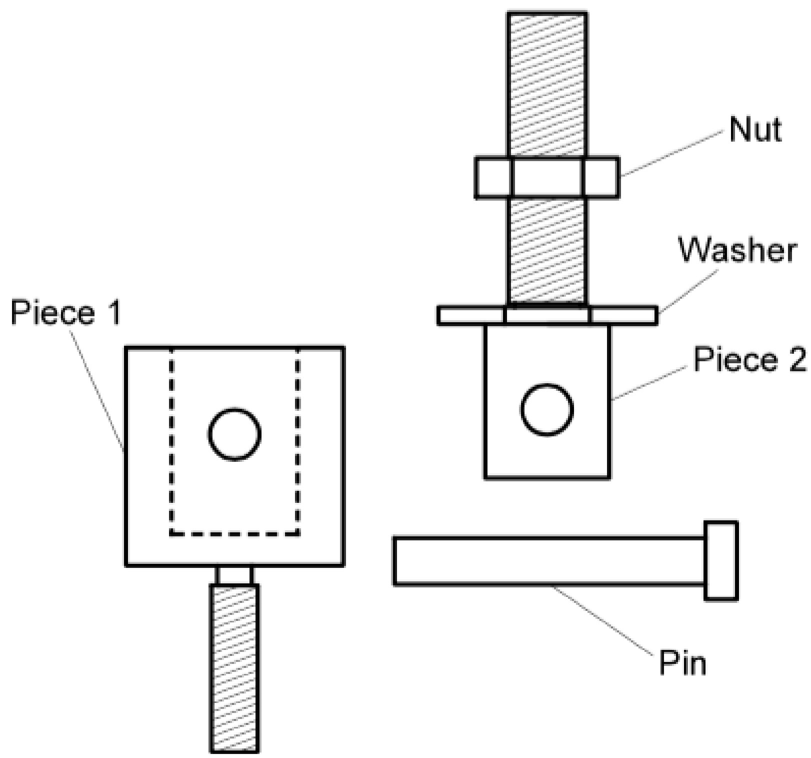

Figure 3-8 Coupling Attachment for the DST

LVDT Mount

Linear Variable Differential Transducers (LVDTs) are utilized to measure the deformation of the specimens under shear loads. The LVDTs are installed on two mounts, and they measure the displacement of the aluminum platen relative to the steel platens. Each LVDT mount includes an aluminum LVDT holder, four steel clamps, a threaded rod, and four nuts. The aluminum holder can hold two different sizes of LVDTs. A bolt on the aluminum holder is used to tighten the LVDT holder and fix the position of the LVDT. An adjusting bolt on top of the holder is used for positioning and fixing the holder on the threaded rod. Each pair of steel clamps is used to grab each of the steel platens. The nuts are used to tie the steel clamps and to fix the LVDT mount's position. Figure 3-9 shows the LVDT mount and its components.

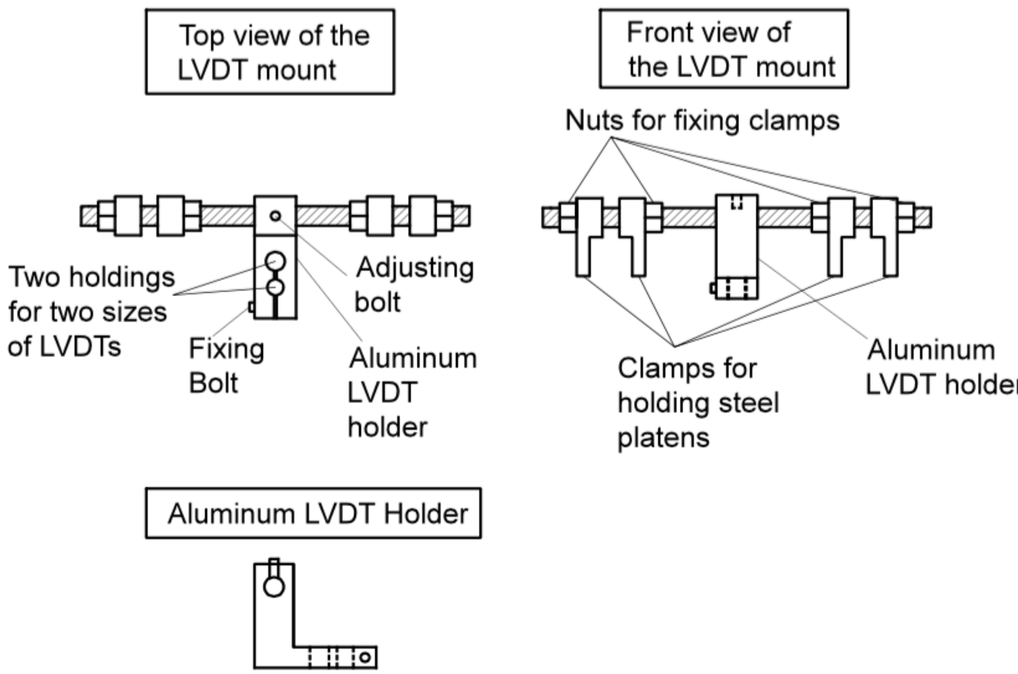

Figure 3-9 LVDT Mount Components

3.3 Selection of the Shear Test Procedures for the DST

As discussed in the Chapter 2, the two most widely used Superpave shear test procedures are the FSCH and RSCH tests. They have been adopted for the DST to measure shear characteristics of asphalt mixtures. The standard test methods recommended by the AASHTO T-320 have been followed for these two shear tests.

3.3.1 FSCH Test

In the standard procedure for the FSCH test, the asphalt concrete specimen is loaded under a strain controlled dynamic shear load over a wide range of frequencies along with an axial load that keeps the specimen's height constant. The DST keeps the height of the specimens constant by means of its fixed frame and the specimens' configuration. In addition, similar to the FST that was discussed in Chapter 2, the DST simulates the strain-controlled condition, by adjusting load stresses with the change in the frequency, and keeping the peak strain level between 75 and 125 micro-strains. This level of strain is within the range of linear behavior of hot mixed asphalt (Christensen, et al., 2002).

To execute the FSCH test procedure with the DST utilizing UTM-25, the specimens are preconditioned first with a sinusoidal shear stress at a frequency of 10 Hz for 100 cycles. Then the specimens are loaded with sinusoidal shear stresses for 10 more sweeps with various frequencies and number of load cycles, as indicated in Table 3-2. The shear stress level changes at each sweep so that the shear deformation remains in the linear viscoelastic region. As expected, the shear stress decreases as the frequency decreases.

During this test, the value of stresses and strains under the sinusoidal shear loads are recorded. The ratio of peak values of shear stress and recoverable shear strain are used to calculate the shear dynamic modulus, $|G^*|$. The time lag between the peak shear strain and peak shear stress is used to calculate the phase angle, Φ. The equations 2-2 and 2-3 provided for the FSCH test in Chapter 2 can be used to calculate the shear dynamic modulus and phase angle. However it should be noted that the properties measured using the DST are the average for the mechanical shear properties of two cylindrical specimens.

Multiple specimens can be tested at different temperatures. However, testing should be conducted at temperatures where the mixture stiffness is below 3,400 MPa, due to equipment constraints. According to the AASHTO T-320, high testing temperature should be 12°C below the high-temperature grade of the asphalt binder. Since the FSCH test is assumed to be conducted in the linear viscoelastic behavior region, the same specimen can be tested at other temperatures or used for other tests, such as the RSCH (AASHTO T-320, 2004).

Table 3-2 FSCH Test Parameters – SST (AASHTO T-320, 2004)

Frequency	**Number of Cycles**
10	50
5	50
2	20
1	20
0.5	7
0.2	7
0.1	7
0.05	4
0.02	4
0.01	4

3.3.2 RSCH Test

In the standard procedure for the RSCH, the specimen is loaded repeatedly under shear load. The DST has adopted a similar procedure, and loads two specimens under the RSCH test procedure. However, the height of the specimens is kept constant by the fixed frame set up.

In this test procedure, each loading cycle consist of a shear stress of 69 kPa for 0.1 second followed by a rest period of 0.6 second. Under this repeated shear load the specimens deform and part of this deformation is permanent. During the test, the cumulative permanent deformation is measured as a function of load cycles and the final permanent deformation at the last cycle is reported. Equation 2-1 provided for the RSCH test in Chapter 2 can be used to calculate the permanent shear deformation. The permanent shear deformation measured using the DST is the average for the permanent shear deformation of two cylindrical specimens.

The RSCH test is usually performed to evaluate the susceptibility of mixtures to rutting at high temperatures. Usually the 7-day maximum pavement temperature at a depth of 50 millimeters is used as the testing temperature.

3.4 Validation of the Design Objectives

In the beginning of this chapter, four objectives were considered in the development of the DST. The first objective was to develop a test device that can measure the fundamental shear properties and responses of asphalt mixtures. This objective was satisfied, as the DST has been designed based on the theoretical background and loading conditions similar to the SST. This device directly measures the mechanical shear properties and responses of two specimens simultaneously. The second design objective was to make a simple, inexpensive device with potential adoptability by the asphalt laboratories. Adopting a universal testing machine to provide the additional system components made the device simple at a relatively low cost. In addition this has provided the opportunity for the DST to be adopted by the pavement laboratories that have an universal testing machine; the universal testing machines are much more common than the SST equipment. The DST adopted the RSCH and the FSCH test procedures in accordance to the standard test methods of the AASHTO T-320. These two definite test procedures in characterizing the shear properties and measuring shear responses of asphalt mixtures. This has satisfied the third objective for the development of the new test device. The fourth objective, evaluation of the reliability and repeatability of the shear test measurements conducted by the DST are discussed in the next chapter.

Chapter 4

Test Methodology, Results and Discussion of the Results

4.1 Overview

This chapter describes the testing and validation of the DST device development. To evaluate the capability of the DST in measuring the shear properties of asphalt mixtures, four asphalt mixtures were tested. The FSCH and RSCH test procedures were followed to determine the shear dynamic modulus, phase angle and permanent shear deformation of the mixtures. Finally, the measured parameters were analyzed to determine validity and repeatability of test results.

4.2 Asphalt Mixtures

Four plant mixed asphalt mixtures were obtained from “Austin Bridge & Road” asphalt concrete plant, located in Fort Worth, Texas. As discussed in Chapter 1, rutting mostly develops in the upper two to four inches of the surface asphalt concrete layer. Therefore, four surface mixtures were selected. All the mixtures were designed according to Texas Department of Transportation (TXDOT) Specification 341.

Three of the mixtures were dense graded hot mixed asphalt, and contained different percentages of fractionated Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS). A dense graded mixture is composed of well-graded aggregates (TXDOT, 2011). Two of the dense graded mixtures were classified as type “C” (Course surface mixture) and one was classified as type “F” (Fine surface mixture).

The fourth mixture was a Stone Matrix Asphalt (SMA) classified as SMA-F (Fine surface mixture). SMA is a gap-graded mixture with high portion of coarse aggregates that forms a stone skeleton. The stone skeleton provides resistance to durability problems, including rutting, by means of a strong stone-to-stone structure (Prowell, Watson, Hurley, & Brown, 2009). The hand working and compacting of SMA mixtures are usually more difficult than those for the dense graded mixtures (TXDOT, 2011).

The summary of the gradation data, type and percentage of different components of the mixtures are presented in Table 4-1 to 4-4. In addition, Figures 4-1 to 4-3 illustrate the mixtures' gradation curves relative to the gradation limits and maximum density lines. These graphs show better how the mixtures were graded; the closer the gradation curve is to the maximum density line, the denser the mixture is.

Table 4-1 Summary of Mixture Design 1

Mixture 1						
Aggregate	Bin No.	1	2	3	8	Total Bin
	Aggregate Source	Limestone-Dolomite	Limestone -Dolomite	Limestone-Dolomite	Fractionated RAP	Total
	Percent of Aggregates (%)	19.1	31	40	9.9	100
	in / #	Cumulative Passing (%)				
	1"	100.0	100	100.0	100.0	**100**
	3/4"	100.0	100	100.0	100.0	**100**
	3/8"	16.0	96	100.0	96.5	**82.4**
	# 4	3.0	37	99.0	66.3	**58.2**
	# 8	2.0	3	85.0	43.6	**39.6**
	# 30	1.0	1.5	40.0	27.7	**19.4**
	# 50	1.0	1.3	27.0	22.8	**13.7**
	# 200	1.0	1.1	5.0	7.0	**3.2**

Asphalt Binder	Origin	Percent (%)	Source & Grade
	New	4	Valero **PG 70-22**
	Recycled	0.5	Unknown
	Total	**4.5**	N/A
Additive	Antistripping Agent	**0.5**	ArrMAZ Ad-Here HP Plus

Table 4-2 Summary of Mixture Design 2

Mixture 2							
Aggregate	Bin No.	1	2	3	8	9	Total Bin
	Aggregate Source	Limestone-Dolomite	Limestone-Dolomite		Fractionated RAP	RAS	Total
	Percent of Aggregates (%)	51.6	26.0	5.0	15.0	2.4	100.0
	in / #	Cumulative Passing (%)					
	3/4"	100.0	100.0	100.0	100.0	100.0	**100.0**
	1/2"	100.0	100.0	100.0	100.0	100.0	**100.0**
	3/8"	99.2	100.0	100.0	96.5	100.0	**99.1**
	# 4	40.0	99.3	100.0	66.3	100.0	**63.8**
	# 8	10.1	83.6	99.0	43.6	98.7	**40.8**
	# 30	6.2	39.1	96.0	27.7	62.0	**23.8**
	# 50	3.1	23.9	73.0	22.8	53.5	**16.2**
	# 200	1.5	4.0	3.0	7.0	21.7	**3.5**
Asphalt Binder	Origin	Percent (%)	Source & Grade				
	New	3.5	Heartland **PG 64-22**				
	Recycled	0.8	RAP				
		0.7	RAS				
	Total	**5.0**	N/A				
Additive	Antistripping Agent	**0.3**	Evotherm 3G/M1				

Table 4-3 Summary of Mixture Design 3

Mixture 3						
Aggregate	Bin No.	1	2	3	8	Total Bin
	Aggregate Source	Igneous	Limestone-Dolomite	Limestone-Dolomite	Mineral Filer	Total
	Percent of Aggregates (%)	48	33	12	7	100
	in / #	Cumulative Passing (%)				
	1/2"	100.0	100	100.0	100.0	**100.0**
	3/8"	90.0	60	100.0	100.0	**82.0**
	# 4	29.0	3	96.5	100.0	**33.5**
	# 8	5.5	2	81.5	100.0	**20.1**
	# 16	4.0	1.8	58.0	100.0	**16.5**
	# 30	3.0	1.7	46.0	99.6	**14.5**
	# 50	2.0	1	35.2	99.2	**12.5**
	# 200	1.2	1	18.0	71.0	**8.0**
Asphalt Binder	Origin	Percent (%)	Source & Grade			
	New	**6.1**	Valero Houston **PG 76-22**			
Additive	Fiber	**0.3**				

Table 4-4 Summary of Mixture Design 4

Mixture 4							
Aggregate	Bin No.	1	2	3	8	9	Total Bin
	Aggregate Source	Limestone-Dolomite	Limestone-Dolomite	Limestone-Dolomite	Fractionated RAP	RAS	Total
	Percent of Aggregates (%)	51.6	26.0	5.0	15.0	2.4	100.0
	in / #	Cumulative Passing (%)					
	1"	100.0	100.0	100.0	100.0	100.0	**100.0**
	3/4"	100.0	100.0	100.0	100.0	100.0	**100.0**
	3/8"	9.1	99.2	100.0	96.5	100.0	**99.1**
	# 4	2.1	40.0	99.3	66.3	100.0	**63.8**
	# 8	2.0	10.1	77.8	43.6	98.7	**40.8**
	# 30	1.7	6.2	25.8	27.7	62.0	**23.8**
	# 50	1.5	3.1	12.0	22.8	53.6	**16.2**
	# 200	1.5	1.6	5.0	7.0	21.8	**3.5**

Asphalt Binder	Origin	Percent (%)	Source & Grade	Substitute Binder
	New	3.5	Valero (Admore) PG 70-22	**PG 64-22**
	Recycled	0.8	RAP	
		0.7	RAS	
	Total	**5.0**	N/A	

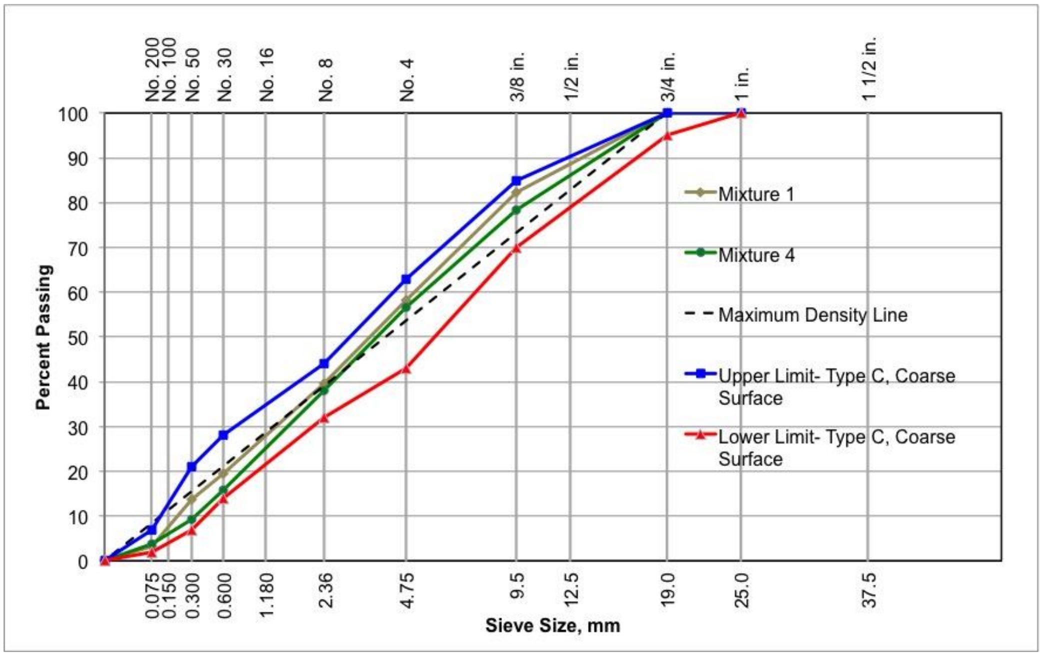

Figure 4-1 Gradation Chart of Mixtures 1 and 4

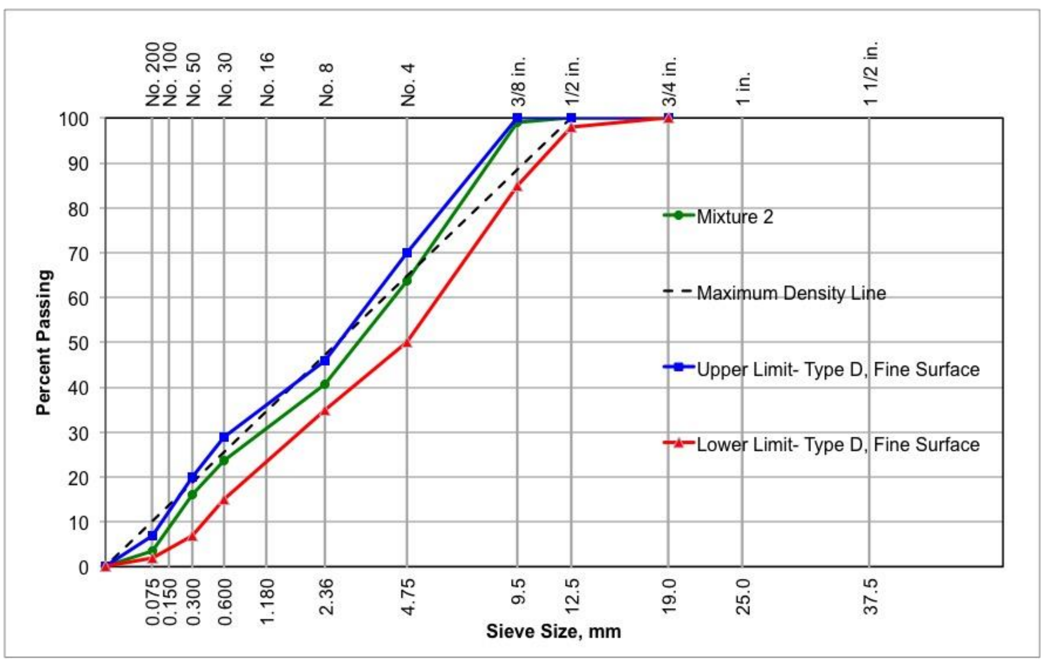

Figure 4-2 Gradation Chart of Mixture 2

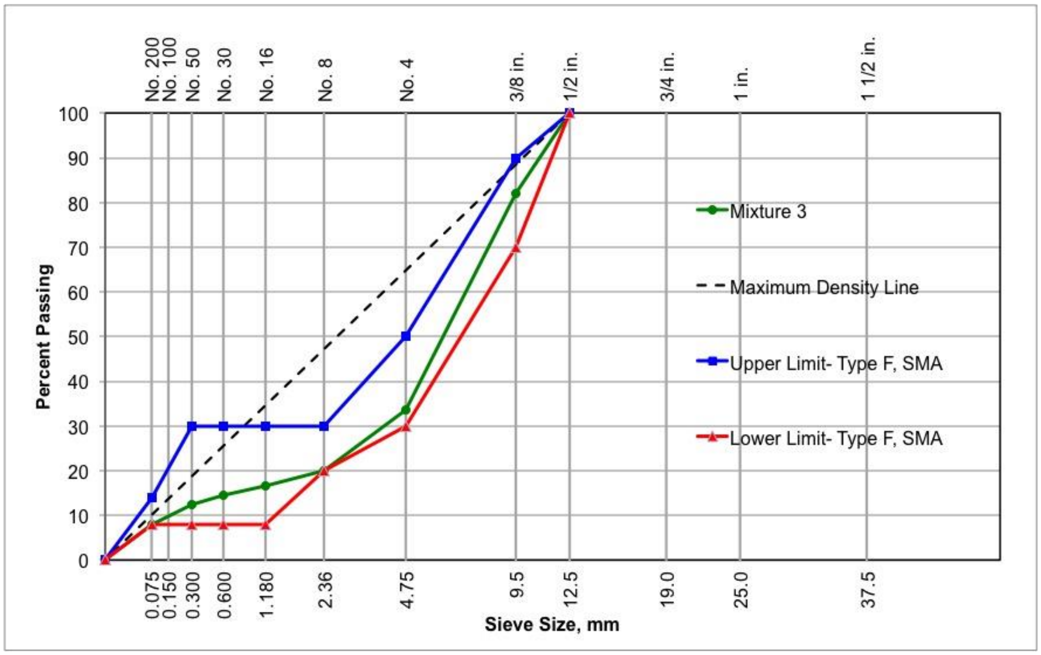

Figure 4-3 Gradation Chart of Mixture 3

4.3 Sampling and Specimen Preparation

The DST accommodates and tests two cylindrical asphalt concrete specimens at the same time. This test device measures a mechanical average for the shear properties of two specimens. Based on the device development assumptions, it is required that the two specimens to be relatively similar. Further study is required to evaluate the allowable level of differences between the two specimens of the DST.

In sampling and test preparation, it was decided for each set of the DST to use a pair of specimens that were made from a uniform mixture such that their air voids percentages and heights did not differ more than one percent and two millimeters respectively. Specimen preparation included compaction of mixture samples at a specific air voids percentage and cutting to proper size and dimensions. Recommendations provided by the AASHTO T-320 standard test method were adopted to prepare the DST specimens.

The four selected asphalt mixtures were plant mixed and each one was collected from one batch of asphalt mixture. Consequently, it was expected that samples from each mixture to be quite uniform.

The Superpave Gyratory Compactor was adopted to compact specimens for the DST. A target air voids of 7.0 percent was selected for both the FSCH and RSCH test procedures. It should be noted that distribution of air voids in a compacted sample is not consistent and after top and bottom removal the remaining will have a lower percentage of air voids. The AASHTO T-320 recommends compacting samples 1 to 2 percent higher than the targeted air voids percentage. Therefore the samples were compacted to 8.0 percent of air voids to achieve the target 7.0 percent after cutting.

Moreover, each compacted sample was needed to be tall enough that after removal of both ends, two specimens with 50 millimeters height could be produced out of it. Therefore it was decided to compact the sample using the Superpave Gyratory Compactor to a height of 165 millimeters, to account for removal of 25.75 millimeters of each end and three saw cuts with an average blade removal thickness of 4.5 millimeters. Figure 4-4 illustrates a compacted sample cut into two small cylindrical specimens with heights of 50 millimeters. This process provided two specimens for each set of the Duplicate Shear Tests.

The AASHTO T-320 recommends Equation 4-1 for calculating the sample weight for field-mixed and laboratory-compacted specimens. This formula was used to calculate the appropriate amount of mixtures required for fabricating a compacted sample with 8.0 percent of air voids and 165 millimeters in height.

$$Mass = 17.671 \times Height \times G_{mm} \times (1\text{-}AV) \qquad (4\text{-}1)$$

Mass: Mixture batch weight (grams)

Height: Target compacted height (millimeters)

G_{mm}: Maximum theoretical specific gravity of the mixture

AV: Percentage of air voids desired in decimals

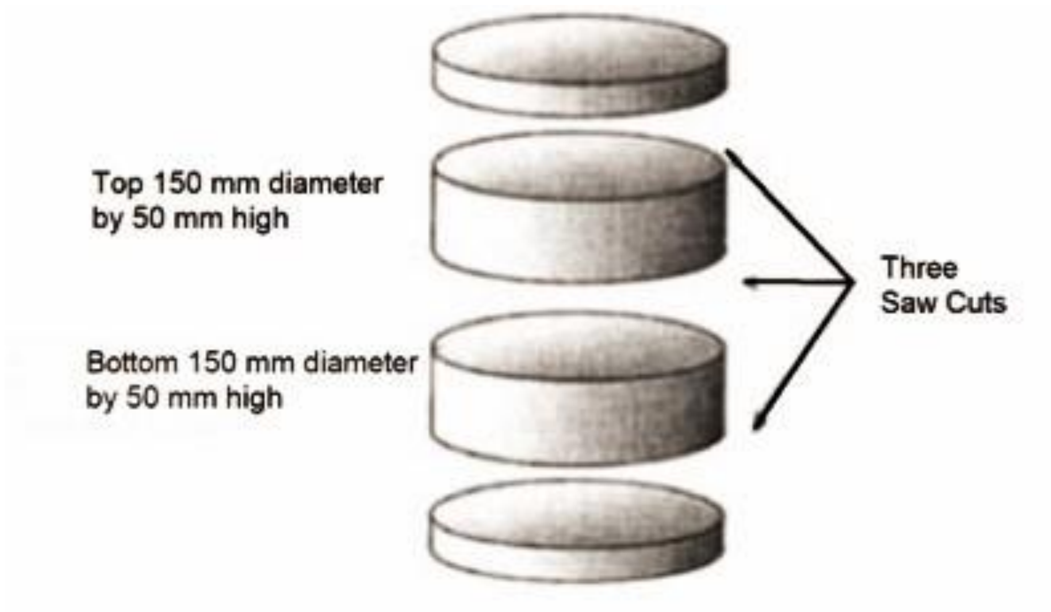

Figure 4-4 Fabricating Two Test Specimens from a Superpave Gyratory Compacted Sample (Witczak, et al., 2002)

The maximum theoretical specific gravity for Mixture 1 was calculated in accordance to the AASHTO T-209 standard test method "Theoretical maximum specific gravity and density of hot-mix asphalt". For the other three mixtures, the maximum theoretical specific gravity values were obtained from the mix design reports, provided by the asphalt mix producer.

The compaction temperature for each mixture was selected based on the PG grade of the binder for each mixture according to the Tex-241-F "Superpave Gyratory

Compacting of Test Specimens of Bituminous Mixtures". The selected compaction temperatures are presented in Table 4-5.

Table 4-5 Compaction Temperatures

Mixture	PG Grade	Compaction Temperature (°C)
1	70-22	135
2	64-22	121
3	76-22	149
4	64-22	121

Samples for all the mixtures were compacted in accordance to the standard test method AASHTO T-312 "Preparing and Determining the Density of the Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor". After compaction, the samples were removed from the mold and left to cool down to room temperatures for one day.

A wet saw with a 20 inch diamond blade for asphalt concrete was utilized to cut the compacted samples into specimens with 50 millimeters height and two parallel faces. For each mixture, the cutting process was done the day after compaction. In case that the cutting process was delayed, the compacted samples were sealed by plastic foil to prevent aging. After cutting, the specimens were left at room temperatures for one day to dry.

The weights and heights of the prepared specimens were determined and recorded. The height measurements were done using a caliper in accordance to the ASTM D 3549 standard test method. Specimens with more than 2 millimeters difference between the smallest and largest height were discarded, as required by the AASHTO T-320. The air voids percentage for each specimen was calculated using Equation 4-1. After measurements, the specimens were stored in pairs in ziplock bags to prevent aging.

Each pair was obtained from one compacted sample. Table 4-6 to 4-9 summarize the dimensions of the specimens.

As shown in these tables, there was variation in percentages of the air voids in the specimens. This indicates that the distribution of the air voids inside the compacted samples by the Superpave Gyratory Compactor was not uniform. However an average percentage of air voids was calculated for each pair of the specimens cut from one compacted sample.

Table 4-6 Specimens' Dimensions, Mixture 1

Mixture 1					
Pair	Top (T)/Bottom (B)	Height (mm)	Weight (g)	% AV	Average % AV
N1	T	49.81	2169.4	6.071	5.923
	B	49.85	2178.0	5.775	
N2	T	49.64	2161.0	6.105	5.937
	B	50.04	2186.2	5.770	
N3	T	49.79	2174.5	5.803	5.439
	B	49.81	2192.4	5.076	
N4	T	49.81	2168.5	6.110	5.926
	B	49.87	2179.4	5.742	

Table 4-7 Specimens' Dimension, Mixture 2

Mixture 2					
Pair	Top (T)/Bottom (B)	Height	Weight	% AV	Average % AV
N1	T	48.80	1984.2	6.570	6.372
	B	48.75	1990.8	6.173	
N2	T	49.93	2029.8	6.587	6.534
	B	49.95	2032.9	6.481	
N3	T	49.67	2019.9	6.555	6.501
	B	49.71	2023.9	6.446	
N4	T	48.79	1976.2	6.938	6.555
	B	49.11	2005.5	6.173	
N5	T	48.91	1979.6	7.006	6.693
	B	49.01	1996.8	6.380	

Table 4-8 Specimens’ Dimension Mixture 3

Mixture 3					
Pair	Top/Bottom	Height (mm)	Weight	% AV	Average % AV
N1	T	50.59	2050.9	6.505	6.262
	B	50.37	2052.6	6.019	
N2	T	50.21	2033.4	6.611	6.303
	B	50.59	2062.3	5.995	
N3	T	50.46	2038.1	6.859	6.648
	B	50.42	2045.7	6.437	
N4	T	51.28	2083.0	6.320	6.646
	B	51.32	2070.3	6.973	
N5	T	50.43	2034.0	6.981	6.451
	B	49.92	2036.4	5.920	

Table 4-9 Specimens’ Dimensions, Mixture 4

Mixture 4					
Pair	Top/Bottom	Height (mm)	Weight	% AV	Average % AV
N1	T	49.74	2029.0	6.314	6.125
	B	49.64	2032.9	5.935	
N2	T	49.83	2031.0	6.382	6.402
	B	49.77	2028.0	6.422	
N3	T	49.96	2036.6	6.377	6.217
	B	49.90	2041.1	6.058	
N4	T	49.82	2028.8	6.464	6.195
	B	49.62	2032.5	5.925	
N5	T	49.91	2025.4	6.789	6.571
	B	49.80	2030.4	6.353	

4.4 Assembling the DST

The AASHTO T-320 recommends testing of three specimens for the FSCH test procedure and requires a minimum of three specimens for the RSCH test procedure. To perform the FSCH and RSCH procedures using the DST, three sets of specimens were used for each mixture. One set of specimens included two specimens produced from one compacted sample. In addition, as the FSCH test is theoretically performed in linear viscoelastic behavior domain, it was decided to test the same sets of specimens for both the FSCH and RSCH tests.

4.4.1 Gluing the Specimens to the Platens

The AASHTO T-320 requires the use of the quickest adhesive with minimum hardened stiffness modulus of 2,000 MPa to glue specimens to platens. Devcon™ Plastic Steel Putty (A) was used for gluing specimens to DST platens. The pot life of this type of epoxy putty is 45 minutes, which provided sufficient time to assemble three sets of DST at the same time.

Prior to gluing, all surfaces of the platens were cleaned. Epoxy putty was prepared by mixing the resin and hardener proportioned in accordance to the manufacturer's instructions. The volumetric method was used to proportion the hardener and the resins: 112.5 cubic centimeter of resin and 45 cubic centimeter of hardener. These provided sufficient amount of epoxy putty without excess waste for three surfaces of specimens, when assembling three sets of DST at the same time.

The sequence of gluing process is illustrated in Figure 4-5 as steps 1 to 4. Step 1 started with gluing the first specimen to the first steel platen. A thin layer of epoxy putty was applied on the circular groove in the middle of the first steel platen, and then the first specimen was placed on the top of it. To ensure uniform bonding between the specimen, the epoxy and the steel platen, the specimen was rotated and, meanwhile, it was pushed into the steel platen until some epoxy came out from the edges of the specimen. Then the steel platen with the specimen was placed on the Platen-Specimen Assembly Stand as indicated in step 1 in Figure 4-5. A level was used to insure that the specimen's surface is parallel to the surface of the steel platen. Then the middle aluminum platen was placed on top of the specimen to check that the specimen was in center of the steel platen; when the specimen is in the center, it gets into the groove of the aluminum platen. After centering and leveling the specimen, the excessive epoxy was removed from the edges of the specimen, and it was left for one hour or until the epoxy hardened.

In step 2, the steel platen and the specimen were removed from the assembly device. A thin layer of epoxy was applied on top of the first specimen and the aluminum platen was put on top of it. To assure uniform bonding, the aluminum platen was rotated on and pushed into the top of the specimen until some epoxy came out from the edges of the specimen. One edge of the aluminum platen was labeled with "B" that indicated the bottom edge of the platen, and this edge was matched with the edge of the steel platen that had the same label. Then the whole device was put back on the assembly device. The guide rods of the assembly device assured that the aluminum platen was in the right position. Then, a level was used to make sure that the aluminum platen was parallel to the first steel platen and the first specimen's surface. Then the excessive epoxy was removed from the edges of the specimen, and the device was left for one hour or until the epoxy hardened.

Step 3 was similar to the step 1, except that the second specimen was glued to the aluminum platen. Also, step 4 was similar to step 2, except that the second steel platen was glued on top of the second specimen. After completing these four steps, the device was left on the assembly device for 24 hours at room temperature or until the epoxy was fully cured.

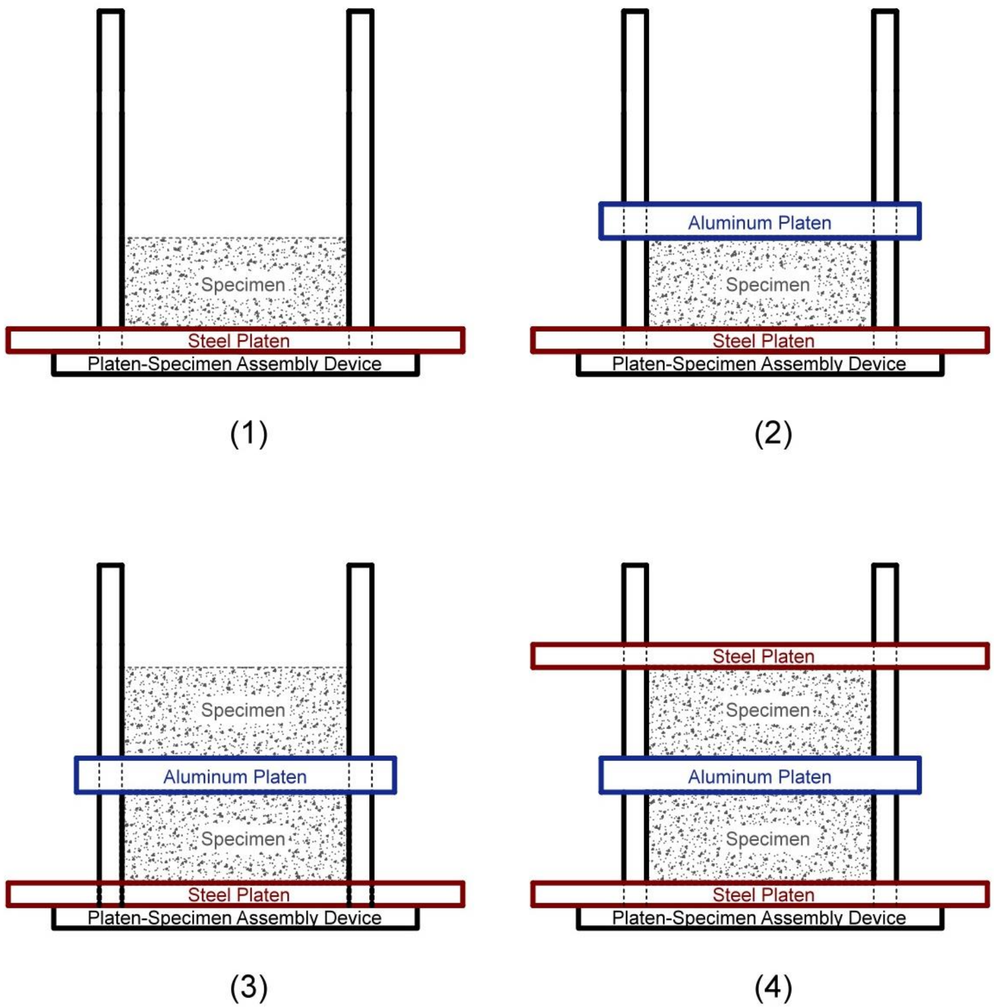

Figure 4-5 Gluing the Specimens and the Platens

4.4.2 Mounting the Threaded Rods and Fixing the LVDT Mounts

When the epoxy was fully cured, the device was removed from the assembly device. To complete the assembly of the DST, four threaded rods with nuts on each side of steel platens were put on the device. All the nuts on both sides of one of the steel platens were tightened while the nuts on the second steel platen were totally loose. Then, the loose nuts on the second steel platen were hand-tightened. After that, each pair of nuts on each rod was tightened with applying the same torque to the nuts at the same time. The purpose of tightening the nuts in this sequence was to prevent generation of axial forces inside the specimens. These steps are represented in Figure 4-6.

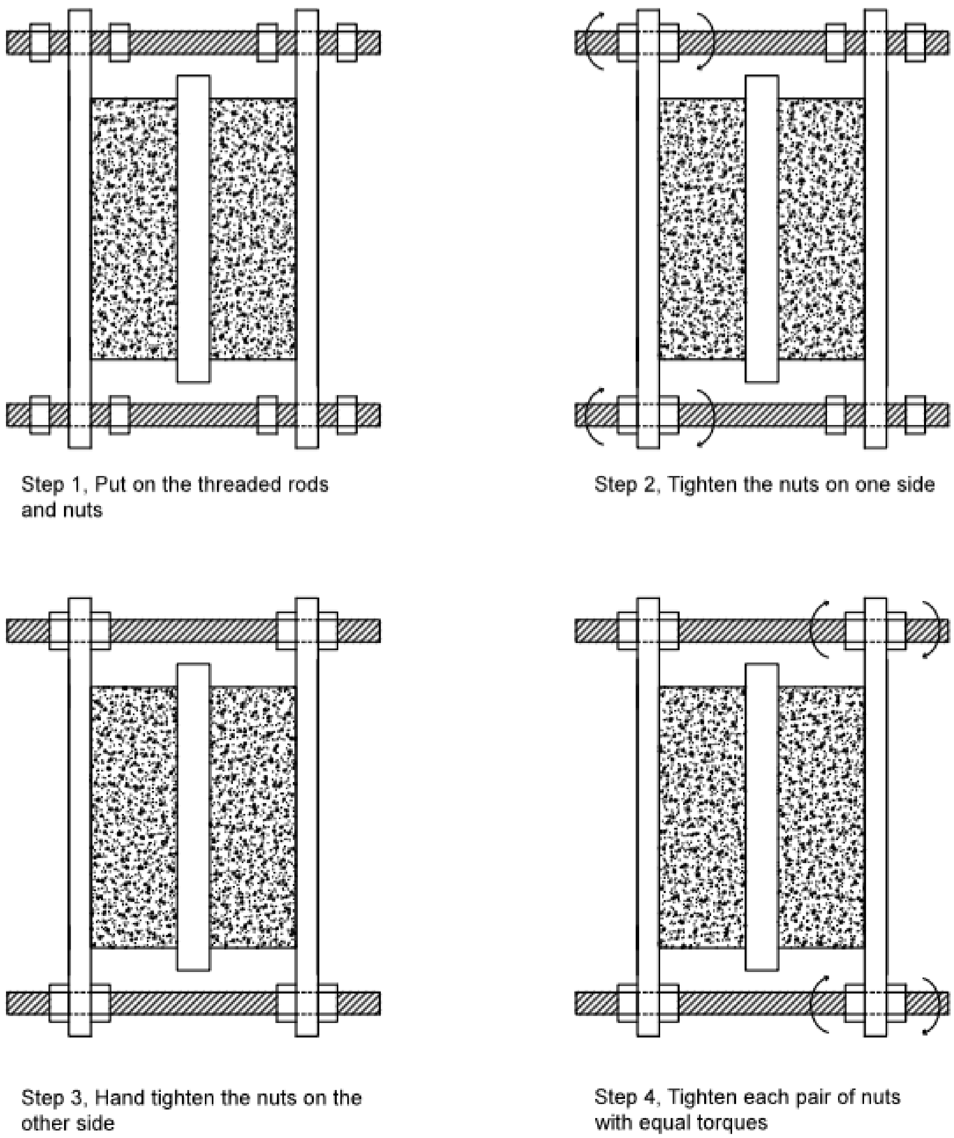

Figure 4-6 Putting Threaded Rods and Nuts on the DST Platens

After mounting the threaded rods and nuts, the LVDT mounts were fixed on top of the DST, as indicated in Figure 4-7. The LVDT mounts were positioned and fixed in a way that the points of the LVDTs touched the marked dots on top of the aluminum platen. The marked dots were placed 2.5 inches away from the center of the aluminum platen on its centerline. Figure 4-8 illustrates the DST device assembling.

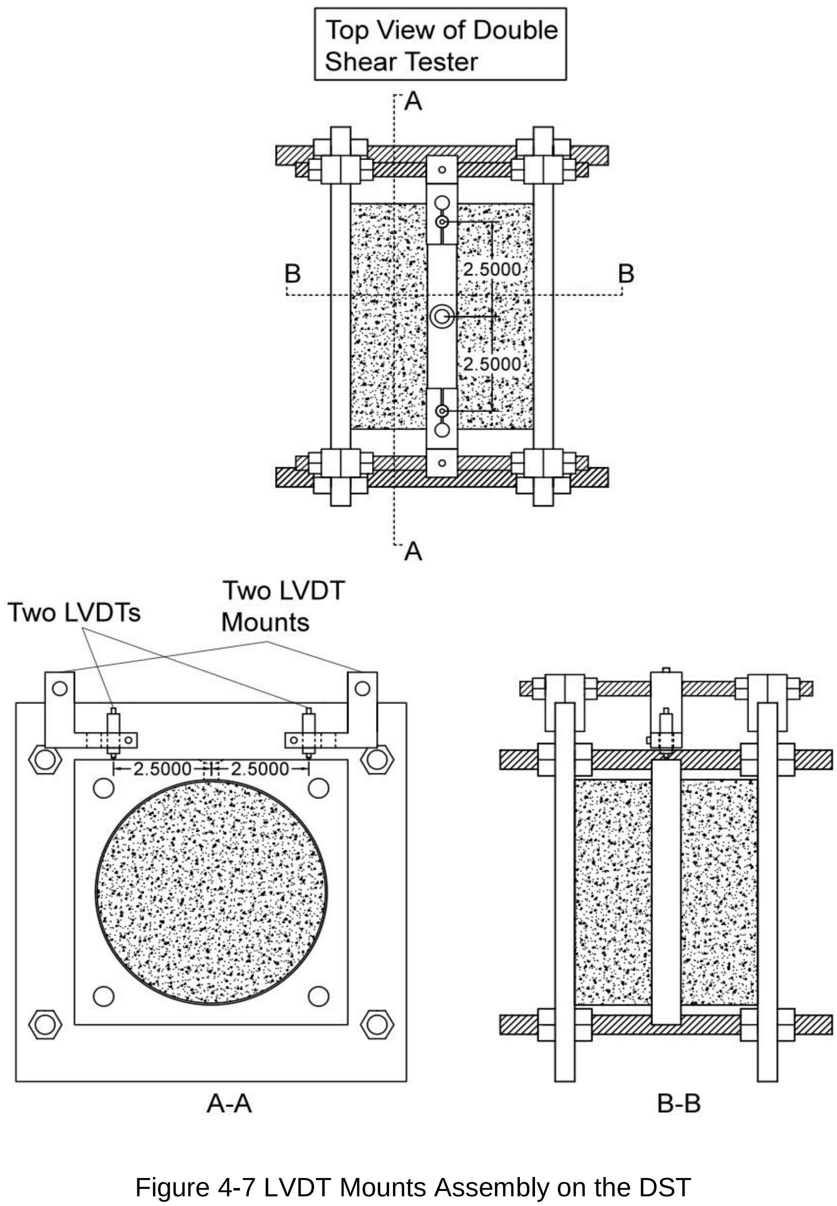

Figure 4-7 LVDT Mounts Assembly on the DST

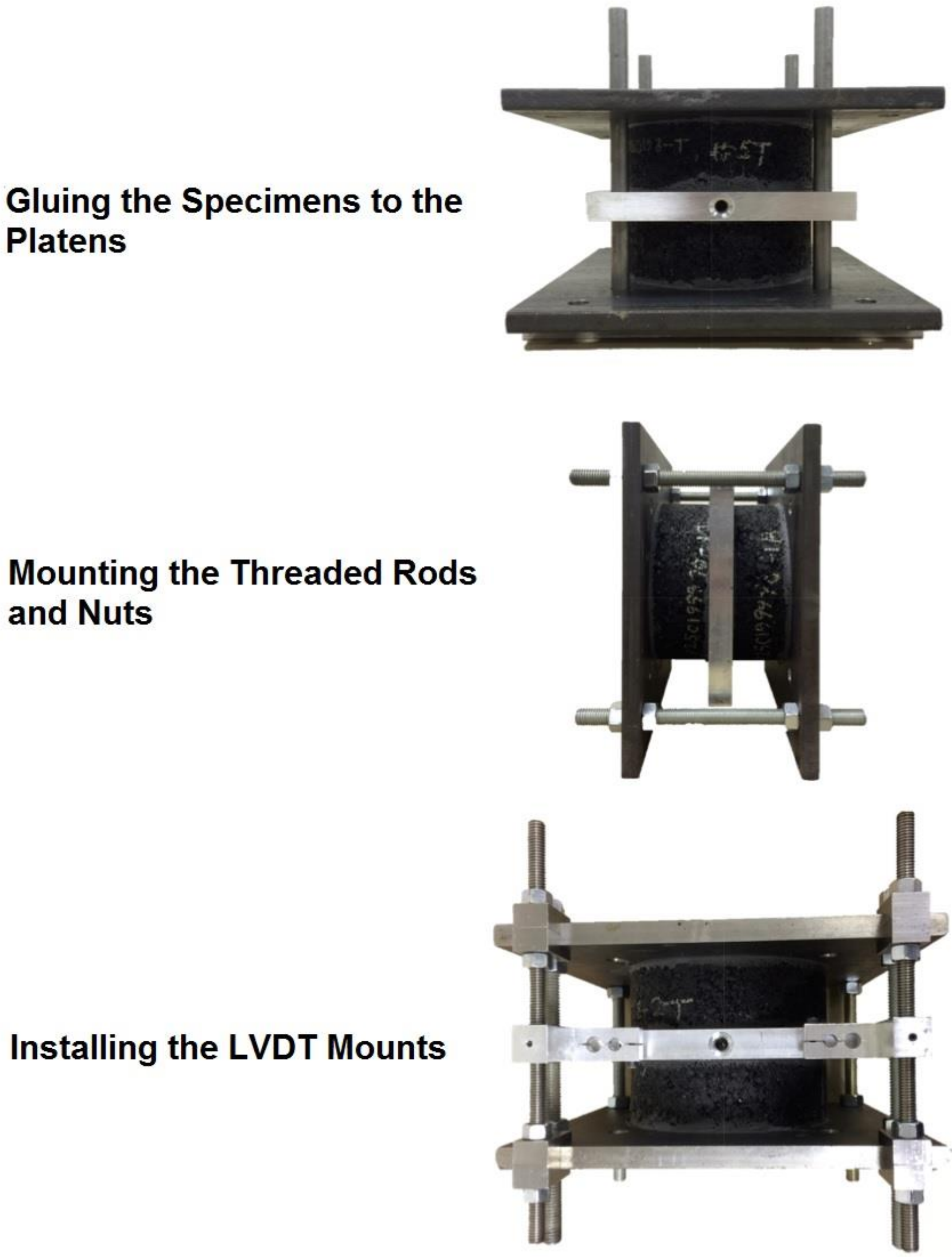

Figure 4-8 The DST Device Assembling

4.5 Testing Temperatures and Conditioning the Specimens

For the FSCH test, a testing temperature of 30°C was selected for all the four mixtures. The AASHTO T-320 recommends limiting the FSCH test temperatures to 12°C below the high-temperature grade of the asphalt binder. The lowest high-temperature grade for all the mixtures was 64°C for Mixtures 2 and 4. Therefore, the selected temperature was way below the 52°C limit for that grade.

For the RSCH test, there is no specified limit on the testing temperature. Usually the 7-day maximum pavement temperature at a depth of 50 millimeters is used as the testing temperature. For all the four mixtures, 50°C was selected as the testing temperature for the RSCH test procedures.

The AASHTO T-320 requires an environmental chamber with the range of 0 to 80°C with resolution of 0.25°C and accuracy of 0.5°C. The environmental chamber for the UTM-25 was used to condition the specimens. This environmental chamber can provide temperatures between -15°C to 60°C with resolution of 0.2°C. Although the higher limit of this environmental chamber does not meet the AASHTO T-320 requirements, it can work well at 50°C. Moreover, this environmental chamber can keep up to three DST sets in addition to the one mounted on the loading frame, thus shortening the conditioning time.

For each mixture, to perform the FSCH test, all three DST sets were conditioned inside the environmental chamber for 6 hours. To minimize the temperature loss, the first set was fixed on the loading frame with the LVDTs in place. However, the coupling connection to the actuator was left loose to prevent any stress development inside the specimens. Whenever the test was finished and a new set was replaced in the loading frame, the specimens were given at least 2 hours for the temperature of the sample to stabilize. For the RSCH tests, the three sets of specimens were conditioned inside the environmental chamber for at least 8 hours. Whenever a new set was replaced in the loading frame, it was given 4 hours for the temperature to stabilize. A thermometer inserted into a dummy specimen with a diameter of 4 inches and a height of 6 inches was used to monitor and record the temperature during testing.

4.6 Installing the DST on the UTM-25 Device

The following steps were considered to install the DST on the UTM-25 testing equipment. These steps are also represented in Figure 4-9 for the RSCH test, and in Figure 4-10 for the FSCH test.

Step 1: The proper loading attachment depending on the test procedure was installed on the actuator's ram. Then the DST was placed on the supporting mount between its two grippers, and two LVDTs were installed on the LVDT mounts.

Step 2: In this step, the grippers were bolted on the sides of the DST's steel platens using four bolts and four nuts. The bolts and nuts are illustrated in step 2 of Figures 4-9 and 4-10.

Step 3: This step was slightly different for the RSCH test and the FSCH test. For the RSCH test, using the electrical motor of the UTM-25, the supporting table was slowly moved up until the depression on the aluminum platen got very close to the bottom of the loading attachment. Then the DST was placed in a position that the depression on the aluminum platen lined up exactly with the loading attachment. In addition, the supporting mount provided additional movement when it was required to get the DST to exact position. Using the hydraulic power, the actuator was slowly moved down until the loading attachment touched the surface of the depression on the aluminum platen. During this step, the stress level on the actuator was monitored to prevent applying any excessive stresses to the specimens. For the FSCH test, the supporting table was moved up similarly until the edges of the coupling pieces got close to each other. Then the DST was positioned in a place that the circumferential edge of the coupling piece on the actuator's ram lined up with the inner edge of the coupling piece on the aluminum platen. Then the supporting table was slowly moved up while the coupling upper piece was going inside the lower piece. The supporting table was moved up until the holes on the coupling pieces matched and the pin was inserted.

Step 4: In this step, first the bolts on the supporting mount were tightened to fix the supporting mount's position on the supporting table of the UTM-25. Then the adjusting bolts on the grippers were tightened to fix the position of the DST on the supporting mount. In addition, for the FSCH test, the nut on the coupling was tightened, while the level of stresses on the actuator was monitored to prevent inducing excessive stresses to the specimens.

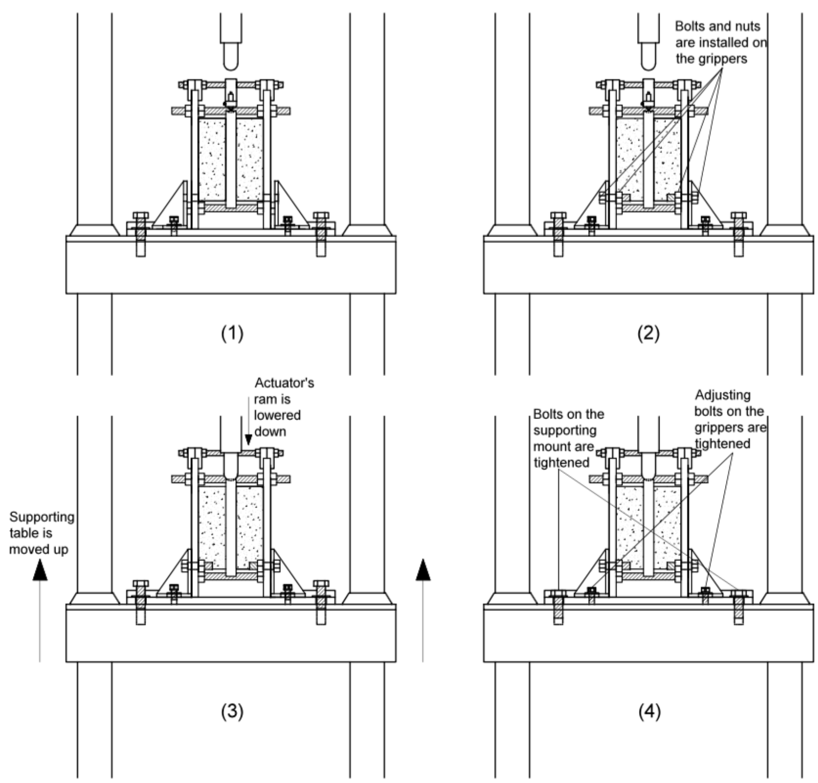

Figure 4-9 Installing the DST on the UTM-25 for the RSCH Test

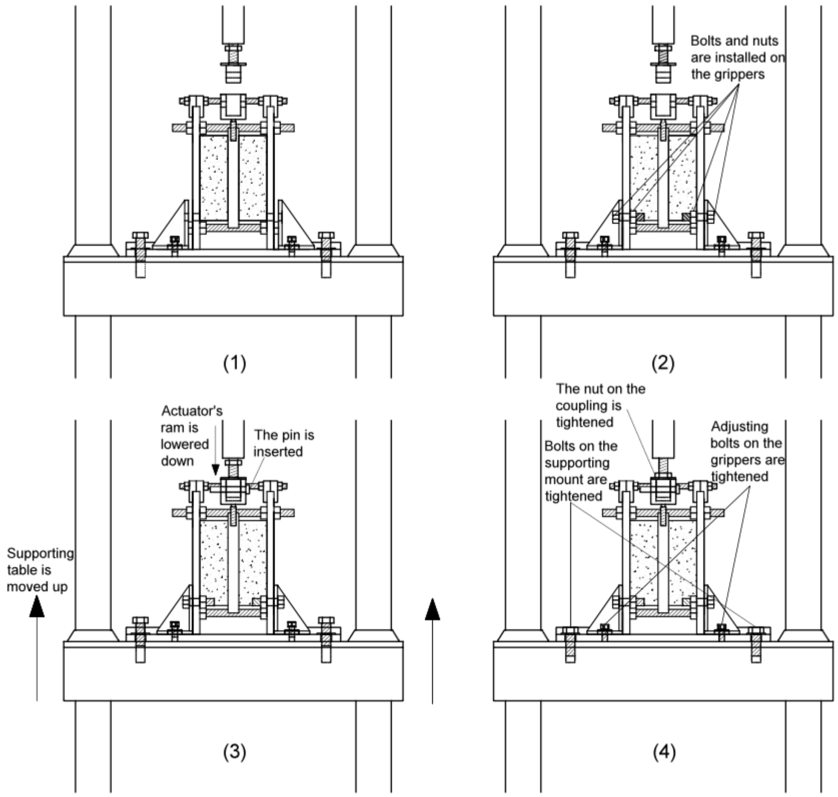

Figure 4-10 Installing the DST on the UTM-25 for the FSCH Test

4.7 Executing the Shear Test Procedures Utilizing the UTM-25

4.7.1 Execution of the FSCH test Utilizing the UTM-25

The DST utilized the UTM-25 testing equipment developed by IPC Global™ to conduct shear tests. The UTS-023 test module developed by IPC Global™ for the AASHTO TP 62 Dynamic Modulus Test was used to execute the FSCH test procedure for the DST. This program is designed to determine the dynamic modulus of asphalt mixture under a dynamic axial load. However, through modification of inputs, such as the diameter of the specimen and gauge distance, the needed outputs can be produced for the shear dynamic modulus test.

The DST loads two asphalt concrete specimens at the same time, and the shear load is divided between the two specimens. Each specimen has a diameter of 150 millimeters and a height of 50 millimeters. To have an accurate measurement of surface area and shear stress level, the input diameter in the software should compensate the surface areas of two specimens. Consequently a diameter of 212.13 millimeters was used instead of 150 millimeters in order to account for the two shear surfaces. An input height of 50 millimeters or the average platen-to-platen height of the specimens was used as the gauge distance in the program, as the shear deformation of both specimens under the shear load are equal due to configuration of the DST.

Prior to execution of the FSCH test, appropriate levels of shear stresses at each frequency for test sweeps are needed. Appropriate levels of shear stresses result in shear strains between 75 to 125 micro-strains or more preferably 100 micro-strains. To determine the proper shear stress level at each frequency for each mixture, the program was run in the tuning condition. This condition is one of the features of the UTS-023 test module, which enables the user to apply a dynamic load to the specimen and measure the response parameters.

The sequence of determining the appropriate stress levels at different frequencies for each mixture started at highest load frequency or 10 Hertz, since the specimens were expected to have the highest dynamic modulus at this frequency. In the “Tuning Parameters” tab of the program, the maximum and minimum levels of load are required as inputs. These load levels are the minimum and maximum of a haversine load. In the tuning condition, UTM-25 can only support dynamic load in one direction. Consequently the minimum level of load was selected as zero, and the maximum level of load was determined through an iterative procedure. A maximum load lower than 1.4 KN was selected as the first seed value; this force induces 100 micro-strains to a mixture with shear dynamic modulus of 400 MPa at that frequency. After assigning the maximum load, a dynamic haversine load at the selected level was applied to the specimens for 10 cycles. The program returned several measured parameters including “Deviator (Dynamic) Stress” and “Average recoverable axial strain”. Considering the linear behavior of the specimen, the load level that induced 100 micro-strains was calculated from multiplying the ratio of 100 over the “Average recoverable axial strain” by the maximum load. The outcome was used as the new maximum load and the dynamic haversine load was applied one more time. When the new “Average recoverable axial strain” was close to 100 micro-strains, the “Deviator (Dynamic) Stress” was picked as the convenient level of shear stress for that frequency. A similar procedure was conducted for the other lower frequencies and the appropriate levels of shear stresses were detected. Considering that the dynamic modulus decreases at lower frequencies, a lower level of maximum load was selected as the first seed. Based on the author’s experience, 75 percent of the maximum load for the previous sweep was selected as the first seed for the next frequency.

After the determination of the appropriate levels of shear stresses for all ten frequencies, those stress levels were entered in the “Test Parameters” tab of the test module along with the frequencies and the number of load cycles and the FSCH test was executed. Moreover, it is expected that specimens made from the same mixture and under similar conditions of sample preparation will have similar shear dynamic moduli. Consequently, same levels of shear stresses were used to test the specimens of the same mixture.

In this test, the shear stresses and strains under the dynamic load at different frequencies were recorded. The dynamic modulus and the phase angle calculated by the test module for each load frequency were reported as the average shear dynamic modulus, $|G^*|$, and the phase angle, Φ.

4.7.2 Execution of the RSCH test Utilizing the UTM-25

The DST utilized the UTM-25 to perform the RSCH test procedure. IPC Global™ has developed UTS014 test module for asphalt permanent deformation test. This test module is designed to measure the permanent deformation of asphalt concrete specimen under a repeated cyclic pulse or static axial loading. Through inputs modifications, such as the diameter of the specimen and gauge distance, UTS014 test module was used for the DST to measure permanent deformation of asphalt mixtures under repeated cyclic shear pulses.

As it was discussed for the FSCH test procedure, the DST loads two asphalt concrete specimens at the same time. The shear load is divided between the two specimens and both specimens deform equally under shear loads. Therefore a diameter of 212.13 millimeters was used as the diameter and a height of 50 millimeters or average platen-to-platen height of the specimens was used as the gauge distance in the software.

To implement RSCH test in accordance to the AASHTO T-320 standard test method, a haversine load with stress level of 69 kPa, and loading cycles of 0.1 second and a rest period of 0.6 second were used in the program. In addition, a seating stress of 3.4 kPa was selected to ensure the proper seating of the actuator head on top of the aluminum platen and reducing stress error during the loading cycles. The cyclic shear loads were repeated for 5,000 or until the shear deformation exceeded the LVDTs measuring range.

In this test, the shear stresses and strains under the cyclic pulse loads were recorded. The permanent deformation calculated by the program was reported as the average shear permanent deformation of the specimens.

4.8 Shear Test Results for the Asphalt Mixture

Different pairs of specimens were prepared from the four asphalt mixtures and their dimensions are presented in Tables 4-6 to 4-9. In order to measure the shear properties of each mixture, three pairs of specimens were tested using the FSCH test procedure at the temperature of 30°C. Since the FSCH test is theoretically performed in the linear viscoelastic behavior domain, the FSCH test was performed twice on some specimen pairs of the three dense-graded mixtures. It was assumed that, due to the long duration of load applications at very low frequencies, executing the FSCH test more than two times on each pair of specimens may disturb the specimens' structure and affect the test results. Once the FSCH tests were completed for each mixture, the specimens were tested using the RSCH test procedure at the temperature of 50°C to measure the shear response of the specimens under cyclic shear load. The RSCH test continued up to 5,000 loading cycles. Figure 4-11 shows the DST device installed on the UTM-25 device.

Under the RSCH test for Mixture 1, the permanent deformation of the pair "N1" exceeded the measuring level of one of the LVDTs at the loading cycle of 2,845. As a result the permanent deformations at loading cycle of 2,845 are reported for this mixture. Incorrect calibration curves were selected for the LVDTs during the RSCH test for the pair "N3" of Mixture 2. Consequently, the RSCH test results for that pair was discarded and the test was repeated on the pair "N4" of Mixture 2 as the replacement.

The complete FSCH and the RSCH test results for each mixture are given in Appendix A. The summaries of the test results, including the average values and the coefficient of variances of the measured parameters, are presented in Tables 4-10 to 4-14.

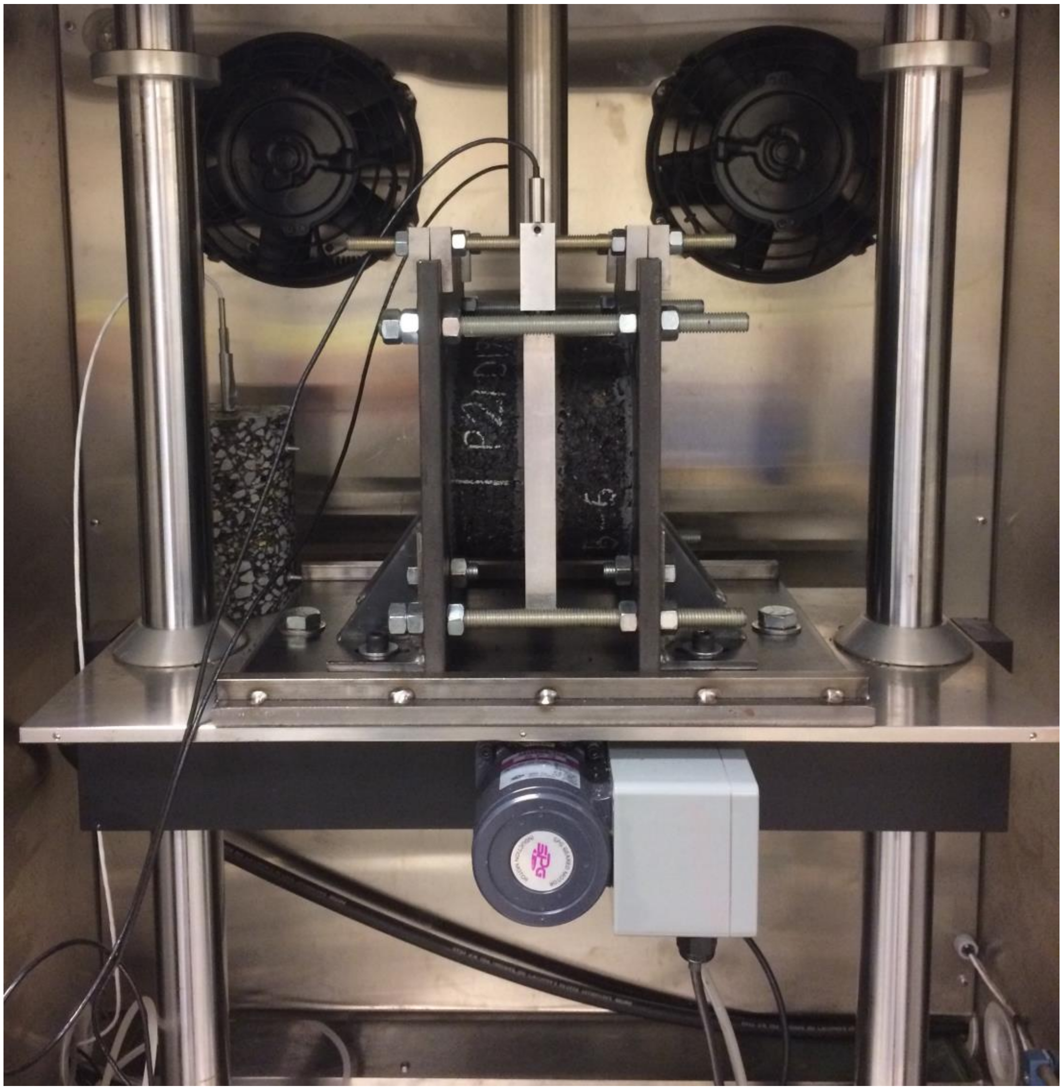

Figure 4-11 The DST installed on the UTM-25

Table 4-10 Summary of the FSCH Test Results, Shear Dynamic Modulus

FSCH- Shear Dynamic Modulus |G*| (MPa) at 30°C											
Mixture #	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Mixture 1	Average	**694.0**	**510.3**	**374.8**	**296.3**	**236.5**	**171.5**	**139.3**	**114.7**	**87.2**	**74.7**
	STD	29.0	19.9	20.9	23.4	22.9	23.5	25.6	26.9	26.2	28.1
	COV %	*4.2*	*3.9*	*5.6*	*7.9*	*9.7*	*13.7*	*18.4*	*23.5*	*30.0*	*37.6*
Mixture 2	Average	**1135.3**	**911.7**	**696.0**	**565.5**	**466.5**	**341.3**	**267.8**	**213.7**	**161.2**	**131.2**
	STD	61.6	60.3	52.1	46.2	39.6	33.3	28.4	24.3	21.0	18.9
	COV %	*5.4*	*6.6*	*7.5*	*8.2*	*8.5*	*9.8*	*10.6*	*11.4*	*13.0*	*14.4*
Mixture 3	Average	**802.7**	**622.7**	**455.3**	**375.7**	**306.3**	**225.0**	**180.3**	**147.3**	**111.7**	**92.7**
	STD	150.1	141.2	117.8	104.9	92.3	78.1	71.0	65.0	56.6	52.2
	COV %	*18.7*	*22.7*	*25.9*	*27.9*	*30.1*	*34.7*	*39.4*	*44.1*	*50.7*	*56.3*
Mixture 4	Average	**1113.0**	**856.2**	**628.5**	**488.0**	**392.5**	**293.7**	**237.3**	**200.2**	**159.8**	**142.3**
	STD	82.5	68.8	57.7	47.1	40.1	36.8	27.0	23.4	19.9	21.5
	COV %	*7.4*	*8.0*	*9.2*	*9.7*	*10.2*	*12.5*	*11.4*	*11.7*	*12.5*	*15.1*

Table 4-11 Summary of the FSCH Test Results, Phase Angle

FSCH- Phase Angle (Degree) at 30°C											
Mixture #	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Mixture 1	Average	**31.8**	**33.9**	**34.3**	**34.5**	**32.2**	**24.8**	**23.7**	**27.8**	**27.2**	**28.2**
	STD	0.9	0.9	1.4	1.9	3.2	2.6	3.2	2.9	3.3	3.9
	COV %	*2.7*	*2.7*	*4.0*	*5.4*	*9.8*	*10.6*	*13.4*	*10.5*	*12.2*	*13.9*
Mixture 2	Average	**24.4**	**26.2**	**27.9**	**29.1**	**27.7**	**21.5**	**21.7**	**26.7**	**26.9**	**28.7**
	STD	0.9	1.5	1.6	1.6	1.1	1.7	1.9	1.9	2.2	2.2
	COV %	*3.7*	*5.7*	*5.7*	*5.6*	*3.9*	*7.8*	*8.8*	*7.2*	*8.0*	*7.6*
Mixture 3	Average	**27.2**	**29.8**	**31.7**	**32.0**	**30.1**	**23.2**	**22.8**	**26.9**	**26.6**	**27.9**
	STD	3.4	3.5	3.9	4.3	2.8	5.0	5.4	5.2	5.5	5.6
	COV %	*12.5*	*11.9*	*12.2*	*13.5*	*9.3*	*21.6*	*23.9*	*19.5*	*20.6*	*20.1*
Mixture 4	Average	**26.4**	**29.2**	**31.2**	**32.6**	**31.5**	**23.5**	**22.4**	**26.1**	**25.0**	**25.6**
	STD	0.6	0.9	1.1	1.0	1.1	1.5	1.3	1.7	2.0	2.2
	COV %	*2.3*	*3.2*	*3.6*	*3.0*	*3.5*	*6.2*	*5.8*	*6.4*	*8.0*	*8.7*

Table 4-12 Summary of the Repeated FSCH Test Results, Dynamic Modulus

Dynamic Modulus |G*| (MPa) at 30°C												
Mixture #	Specimen #	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Mixture 1	N1	Average	**664.5**	**488.0**	**351.0**	**271.0**	**212.5**	**148.0**	**115.0**	**89.5**	**63.0**	**49.5**
		STD	29.0	25.5	19.8	17.0	16.3	12.7	11.3	10.6	8.5	7.8
		COV %	*4.4*	*5.2*	*5.6*	*6.3*	*7.7*	*8.6*	*9.8*	*11.9*	*13.5*	*15.7*
	N2	Average	**722.5**	**526.0**	**383.5**	**301.0**	**239.0**	**171.5**	**137.0**	**111.5**	**83.5**	**69.5**
		STD	27.6	21.2	21.9	24.0	22.6	21.9	24.0	23.3	21.9	21.9
		COV %	*3.8*	*4.0*	*5.7*	*8.0*	*9.5*	*12.8*	*17.5*	*20.9*	*26.3*	*31.5*
Mixture 2	N1	Average	**1206.0**	**972.5**	**744.5**	**605.5**	**498.0**	**363.5**	**283.5**	**223.5**	**166.5**	**134.0**
		STD	32.5	12.0	4.9	0.7	1.4	3.5	6.4	7.8	9.2	9.9
		COV %	*2.7*	*1.2*	*0.7*	*0.1*	*0.3*	*1.0*	*2.2*	*3.5*	*5.5*	*7.4*
	N2	Average	**1113.0**	**856.2**	**628.5**	**488.0**	**392.5**	**293.7**	**237.3**	**200.2**	**159.8**	**142.3**
		STD	82.5	68.8	57.7	47.1	40.1	36.8	27.0	23.4	19.9	21.5
		COV %	*7.4*	*8.0*	*9.2*	*9.7*	*10.2*	*12.5*	*11.4*	*11.7*	*12.5*	*15.1*
Mixture 4	N1	Average	**1132.5**	**856.0**	**620.0**	**479.0**	**384.5**	**292.5**	**233.5**	**203.0**	**164.5**	**153.5**
		STD	21.9	8.5	8.5	9.9	10.6	9.2	9.2	11.3	12.0	14.8
		COV %	*1.9*	*1.0*	*1.4*	*2.1*	*2.8*	*3.1*	*3.9*	*5.6*	*7.3*	*9.7*
	N2	Average	**1022.5**	**787.5**	**575.5**	**446.0**	**357.0**	**257.5**	**212.5**	**175.5**	**138.0**	**117.5**
		STD	37.5	24.7	21.9	19.8	15.6	12.0	10.6	9.2	4.2	2.1
		COV %	*3.7*	*3.1*	*3.8*	*4.4*	*4.4*	*4.7*	*5.0*	*5.2*	*3.1*	*1.8*

Table 4-13 Summary of the Repeated FSCH Test Results, Phase Angle

Phase Angle (Degree) at 30°C												
Mixture #	Specimen #	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Mixture 1	N1	Average	**32.5**	**34.5**	**35.4**	**36.1**	**34.7**	**27.2**	**26.7**	**30.5**	**30.3**	**31.9**
		STD	1.2	1.1	0.9	1.3	1.7	1.4	1.4	0.9	1.0	1.0
		COV %	*3.8*	*3.1*	*2.6*	*3.7*	*4.8*	*5.0*	*5.2*	*3.1*	*3.2*	*3.2*
	N2	Average	**32.2**	**34.4**	**34.8**	**35.1**	**33.3**	**25.3**	**24.2**	**28.2**	**27.5**	**28.5**
		STD	0.7	1.0	1.3	1.7	2.1	2.4	2.8	2.6	2.9	3.4
		COV %	*2.2*	*3.0*	*3.7*	*5.0*	*6.3*	*9.4*	*11.4*	*9.3*	*10.5*	*12.0*
Mixture 2	N1	Average	**24.3**	**26.0**	**27.8**	**29.1**	**27.3**	**22.0**	**22.6**	**27.9**	**28.4**	**30.4**
		STD	0.1	0.0	0.1	0.3	0.3	0.7	0.9	1.1	1.2	1.4
		COV %	*0.6*	*0.1*	*0.2*	*1.1*	*1.2*	*3.0*	*3.8*	*3.8*	*4.3*	*4.6*
	N2	Average	**23.5**	**24.8**	**26.4**	**27.4**	**26.9**	**19.6**	**19.5**	**24.5**	**24.4**	**26.3**
		STD	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		COV %	*0.3*	*0.8*	*0.1*	*0.1*	*0.1*	*0.3*	*0.1*	*0.2*	*0.1*	*0.4*
Mixture 4	N1	Average	**26.9**	**30.1**	**32.1**	**33.4**	**32.5**	**24.0**	**23.3**	**27.4**	**26.5**	**27.2**
		STD	0.4	0.4	0.5	0.6	0.7	1.0	1.3	1.6	1.5	1.6
		COV %	*1.3*	*1.2*	*1.6*	*1.8*	*2.3*	*4.2*	*5.4*	*5.7*	*5.6*	*6.0*
	N2	Average	**26.5**	**29.2**	**31.5**	**32.9**	**31.7**	**24.5**	**22.9**	**26.7**	**25.8**	**26.5**
		STD	0.1	0.0	0.1	0.4	0.2	0.2	0.5	0.6	0.0	0.0
		COV %	*0.3*	*0.2*	*0.4*	*1.1*	*0.8*	*0.9*	*2.3*	*2.1*	*0.1*	*0.0*

Table 4-14 Summary of the RSCH Test Results, Shear Permanent Deformation

RSCH- Shear Permanent Deformation (%)			
Mixture 1	Cycle	2,845	
	Average	**0.8701**	
	STD	0.0900	
	COV %	*10.35*	
	SE	*0.0520*	
Mixture 2	Cycle	2,845	5,000
	Average	**0.8658**	**0.9777**
	STD	0.1033	0.1246
	COV %	*11.94*	*12.74*
	SE	*0.0597*	*0.0719*
Mixture 3	Cycle	2,845	5,000
	Average	**0.7512**	**0.8220**
	STD	0.0822	0.0800
	COV %	*10.94*	*9.73*
	SE	*0.0475*	*0.0462*
Mixture 4	Cycle	2,845	5,000
	Average	**0.9448**	**1.0717**
	STD	0.0852	0.1007
	COV %	*9.02*	*9.40*
	SE	*0.0492*	*0.0582*

4.9 Discussion of the DST Test Results

4.9.1 Discussion on the FSCH Test Results

Tables 4-10 and 4-11 present the average values of the shear dynamic moduli and the phase angles of the four mixtures at different frequencies measured using the DST along with the standard deviation (STD) and the coefficient of variation (COV). Asphalt concrete is a viscoelastic material and its shear stiffness is dependent on the speed of loading. As expected, the shear dynamic moduli decreased as the frequency of the dynamic shear loads decreased. However for the phase angle, no absolute decreasing or increasing trend with the change in the frequency of the loadings was observed.

The coefficient of variation indicates the extent of variability of the measurements relative to the mean of the measurements. The percent of COV is a good measure to compare the degree of variation of the measurements from one mixture to another, as well as to express the reliability and repeatability of the test measurements. A COV lower than 10 percent indicates a relatively low variation in the results and a reliable measurement.

The COVs for the shear dynamic modulus and the phase angle has generally increased as the frequency of loading decreased for all the mixtures. According to Table 4-10, the COVs for the shear dynamic modulus of Mixtures 1, 2 and 4 (the dense-graded mixtures) are lower than 10 percent for the frequencies of 0.5 Hz to 10 Hz. This indicates that the degrees of variation in the shear dynamic moduli at the first five high frequencies are low for the specimens of dense graded mixtures. The variability in the measurement increases as the COVs of the shear dynamic modulus increases at the frequencies lower than 0.5 Hz. The COVs for the measured phase angles of these three mixtures were comparably lower than the ones for the shear dynamic modulus. According to Table 4-11, the COVs of the phase angle are lower than 10 percent at the frequencies of 0.5 Hz to 10 Hz, similar to the COVs obtained for the shear dynamic modulus.

The COVs for Mixture 3 (SMA mixture) are relatively high for the shear dynamic modulus and the phase angle at all the frequencies. The variation in the measurements can be due to the variation in the specimens and the repeatability of the device measurements. However, for this mixture, a large portion of the variation may be due to the high dissimilarity in the specimens. The dissimilarity is expected to have arisen from the difficulty in hand working and compacting of the SMA sample during the specimens' preparation, which is more difficult than for dense graded mixtures.

The average shear dynamic moduli of the four mixtures at the frequencies between 0.01 Hz to 10 Hz at 30°C are given in Figure 4-12. In addition the standard error bars (Standard deviation of the mean) are included to describe the variation in the results. As can be seen in this graph, the dynamic modulus for the mixtures can be ranked at the frequencies of 0.5, 1 and 2 Hz. At these frequencies, Mixtures 2, 4, 3 and 1 have the highest shear dynamic modulus respectively. At the frequencies of 5 Hz and 10 Hz the modulus of Mixtures 2 and 1 are close to each other and their error bars overlap. However at frequencies of 5 Hz and 10 Hz Mixtures 1 and 3 have the lowest modulus respectively. At frequencies lower than 0.5 Hz the rankings of the mixtures are not clear as the error bars overlap each other.

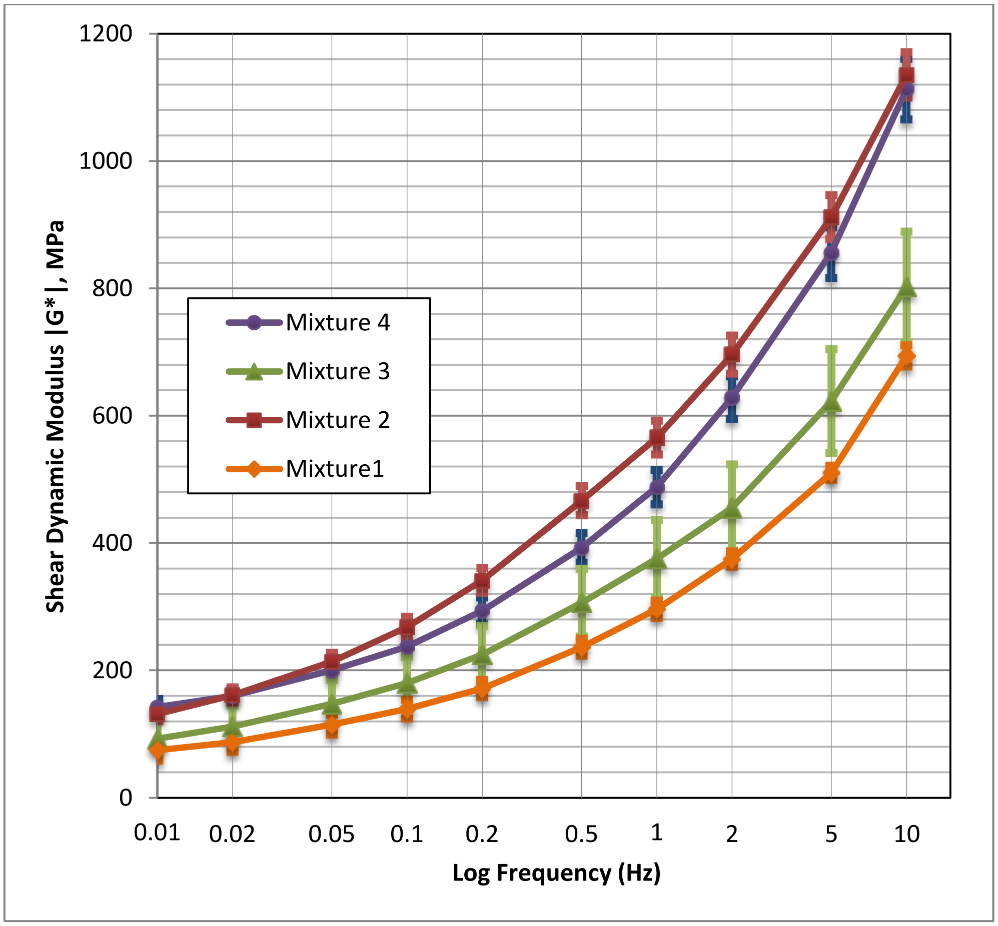

Figure 4-12 Shear Dynamic Modulus of the Mixtures at 30°C

To evaluate the repeatability and reliability of the measurements of the DST, the FSCH tests were repeated on two pairs of specimens for each dense-graded mixture. Summaries of the repeated FSCH tests' results are presented in Tables 4-12 and 4-13. According to Table 4-12, the COVs for the shear dynamic modulus of all the specimens are less than 10 percent at the frequencies between 0.5 Hz to 10 Hz. The repeatability and reliability of the measurements of the DST over the first five high frequencies is confirmed with the low COVs at the high frequencies. According to Table 4-13, the COVs for the phase angle are less than 10 percent for all the specimens at all the frequencies, except for the pair "N2" of Mixture 1 at frequencies of 0.1, 0.02 and 0.01 Hz that are slightly over 10 percent. This indicates that the phase angle measurements of the DST are reliable and repeatable at frequencies of 0.01 to 10 Hz.

4.9.2 Discussion on the RSCH Test Results

Table 4-14 presents the average values of the permanent deformation of the four asphalt mixtures measured under a cyclic shear load using the DST. The permanent shear deformations of the mixtures are reported at 2,845 and 5,000 loading cycles. According to Table 4-14, the COVs of permanent shear deformation for Mixture 4 are lower than 10 percent at the both loading cycles, which indicates a low variability among the test results of this mixture. For Mixture 3, the COV of shear permanent deformation at 5,000 loading cycles is lower than 10 percent and at 2,845 cycles is 10.94 percent. For Mixtures 1 and 2, the COVs are slightly over 10 percent, which indicates a mild variability among the specimens of Mixtures 1 and 2. Figure 4-13 represents the average shear permanent deformation of the mixtures under cyclic load at 50°C at 2,845 and 5,000 loading cycles. The standard error bars (Standard Deviation of the mean) are illustrated to describe the variation among the test results. According to this figure, Mixture 3 has the lowest shear permanent deformation at both of the loading cycles, 2845 and 5000. Mixture 3 was a Stone Matrix Asphalt (SMA) designed specifically to resist rutting (permanent deformation). This observation agrees with the original design assumption for this mixture that the SMA mixtures usually resist permanent deformation better than the dense graded mixtures. The rankings of the other mixtures are not very clear as their average values are close and their error bars overlap.

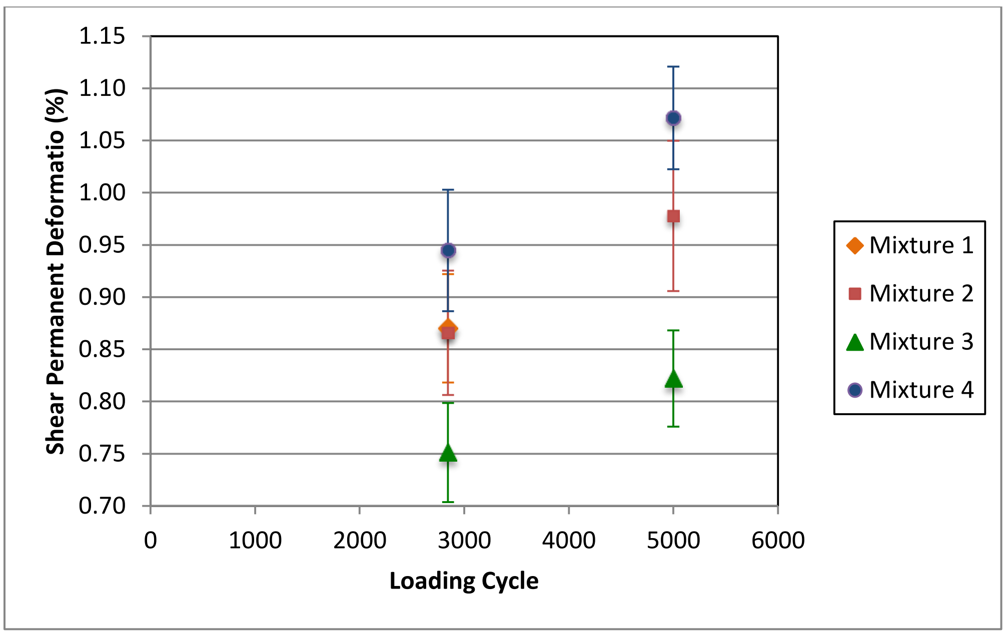

Figure 4-13 Shear Permanent Deformation of the Mixtures at 50°C

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The objective of this study was to develop a new test device that can provide direct measurement of the mechanical shear properties of asphalt mixtures. Measuring shear properties of asphalt mixtures can be quite helpful in predicting the rut resistance of asphalt mixtures. This study has developed a new test device, the Duplicate Shear Tester (DST), which replicates the loading conditions and constraints of the Superpave Shear Tester. The major feature is that it determines an average of the mechanical shear properties of two specimens.

The DST uses a universal testing machine to provide the required loading, hydraulic, control and data acquisition systems as well as the temperature control chamber. This leads to two major advantages of the DST device:

1) The DST is a simple device that can be manufactured at a low cost.
2) The DST can be used with most universal testing machines, which are available in many asphalt mix laboratories.

The current DST has utilized the UTM-25, which is a universal testing machine developed by IPC™ Global. The DST can be modified easily to utilize other universal testing machine with similar capabilities, provided that it meets the minimum requirements of the AASHTO T-320 standard test method.

The DST can be used for two of the Superpave Shear Test procedures: the FSCH and the RSCH. The shear dynamic modulus and the permanent shear deformation measured using these test procedures have been proven in many studies to be correlated to the permanent deformation and the rut depth observed in the field.

Testing of four asphalt mixtures has provided the information on the variability of the shear properties and responses of mixtures, as well as valuable information regarding the capabilities and limitations of the DST when used in the UTM-25 system. The review of the variability of the measured dynamic moduli and phase angle of the mixtures concluded that the current DST is highly repetitive and reliable in measuring the shear dynamic modulus and phase angle at load frequencies ranging from 0.5 Hz to 10 Hz. At lower load frequencies, the high variability in the test results has limited the reliability and repeatability of the measurements.

The results of the permanent deformation tests have confirmed the ability of the DST in determining the permanent shear deformation of asphalt mixtures under cyclic load. Due to the mild variability observed in the permanent deformation of each mixture, it is recommended to conduct more than three permanent deformation tests for each mixture.

The DST has successfully satisfied the considered design and development objectives of a new test device. The product of this study is a simple, reliable test device that can provide direct measurement of fundamental shear properties and responses of asphalt mixture and at a low cost.

The DST can be adopted as a potential simple performance test equipment to complement the mix design methods by providing valuable information in quality control and acceptance of asphalt mixtures. Further enhancement and development of the DST can provide fundamental input variables to improve the pavement performance prediction models and the mechanistic pavement design procedures.

5.2 Recommendations for Future Studies

- Repeatability and reliability of the DST can be further evaluated by performing multiple (5 to 10) FSCH tests on two or more replicates of different mixtures at high frequencies that do not disturb the specimens' structure.
- The DST is designed to replicate the Superpave shear tests. A future study will be beneficial to compare in parallel the results obtained on the same mixes with the DST and the SST.
- Field verification of the DST can be beneficial to evaluate how the measurements of this device are correlated to the field observations. This verification will be critical to acceptance and utilization of the DST.

Appendix A

Shear Test Results

Table A-1 FSCH Test Results, Mixture 1

Mixture 1												
Pair	Trial	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
N1	1	G* (MPa)	685	506	365	283	224	157	123	97	69	55
		Phase Angle (Degrees)	31.59	33.71	34.75	35.11	33.53	26.2	25.7	29.79	29.64	31.15
		Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1
N1	2	G* (MPa)	644	470	337	259	201	139	107	82	57	44
		Phase Angle (Degrees)	33.35	35.22	36.04	36.99	35.88	28.14	27.67	31.11	31.03	32.59
		Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1
N2	1	G* (MPa)	742	541	399	318	255	187	154	128	99	85
		Phase Angle (Degrees)	31.69	33.65	33.91	33.86	31.81	23.63	22.23	26.3	25.47	26.11
		Temperature (°C)	30	30	30	30	30	30	30	30	30	30
N2	2	G* (MPa)	703	511	368	284	223	156	120	95	68	54
		Phase Angle (Degrees)	32.67	35.1	35.75	36.33	34.8	27	26.12	30.02	29.57	30.93
		Temperature (°C)	30	30	30	30	30	30	30	30	30	30
N3	1	G* (MPa)	695	517	390	317	258	195	166	143	115	105
		Phase Angle (Degrees)	30.86	32.84	32.77	32.45	28.67	21.98	20.37	24.64	23.71	24.06
		Temperature (°C)	30.4	30.5	30.6	30.6	30.7	30.8	30.9	30.9	30.9	31

Table A-2 FSCH Test Results, Mixture 2

Mixture 2												
Pair	Trial	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
N1	1	G* (MPa)	1229	981	748	606	497	361	279	218	160	127
		Phase Angle (Degrees)	24.2	25.99	27.85	29.31	27.53	22.51	23.21	28.64	29.27	31.37
		Temperature (°C)	30.2	30.2	30.3	30.3	30.3	30.3	30.3	30.3	30.2	30.1
N1	2	G* (MPa)	1183	964	741	605	499	366	288	229	173	141
		Phase Angle (Degrees)	24.41	26.04	27.76	28.84	27.05	21.58	21.98	27.13	27.55	29.41
		Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.1
N2	1	G* (MPa)	1113	928	714	586	488	363	289	235	182	151
		Phase Angle (Degrees)	23.56	24.7	26.38	27.42	26.91	19.68	19.55	24.52	24.41	26.32
		Temperature (°C)	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2
N2	2	G* (MPa)	1101	893	691	566	471	352	281	228	176	146
		Phase Angle (Degrees)	23.45	24.98	26.35	27.39	26.93	19.61	19.51	24.45	24.43	26.18
		Temperature (°C)	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.3	30.3
N3	1	G* (MPa)	1093	852	641	515	422	303	235	186	138	111
		Phase Angle (Degrees)	25.29	27.81	29.55	30.68	28.93	22.87	23.01	27.73	27.81	29.51
		Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30	30	30	30

Table A-3 FSCH Test Results, Mixture 3

Mixture 3											
Pair	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
N1	G* (MPa)	950	759	568	475	394	301	251	213	170	147
	Phase Angle (Degrees)	23.93	26.85	28.48	28.16	28.1	18.41	17.48	21.74	21.12	22.22
	Temperature (°C)	29.9	29.9	29.9	29.9	29.9	29.9	29.8	29.8	29.8	29.9
N2	G* (MPa)	808	632	465	386	315	229	181	146	108	88
	Phase Angle (Degrees)	27.05	28.86	30.74	31.26	28.86	22.68	22.45	26.76	26.61	28.11
	Temperature (°C)	29.5	29.5	29.5	29.5	29.5	29.5	29.5	29.5	29.5	29.5
N3	G* (MPa)	650	477	333	266	210	145	109	83	57	43
	Phase Angle (Degrees)	30.74	33.75	36.02	36.7	33.29	28.4	28.36	32.23	32.07	33.47
	Temperature (°C)	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9

Table A-4 FSCH Test Results, Mixture 4

Mixture 4												
Pair	Trial	Frequency	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
N1	1	G* (MPa)	1117	850	614	472	377	286	227	195	156	143
		Phase Angle (Degrees)	27.14	30.33	32.44	33.84	33.04	24.75	24.22	28.53	27.56	28.31
		Temperature (°C)	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.4
N1	2	G* (MPa)	1148	862	626	486	392	299	240	211	173	164
		Phase Angle (Degrees)	26.64	29.83	31.73	32.98	31.98	23.323	22.45	26.33	25.47	26.02
		Temperature (°C)	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.5
N2	1	G* (MPa)	996	770	560	432	346	249	205	169	135	116
		Phase Angle (Degrees)	26.43	29.28	31.59	33.14	31.92	24.7	23.29	27.15	25.78	26.55
		Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.2	30.2	30.2
N2	2	G* (MPa)	1049	805	591	460	368	266	220	182	141	119
		Phase Angle (Degrees)	26.55	29.21	31.42	32.64	31.57	24.39	22.56	26.34	25.75	26.54
		Temperature (°C)	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8	29.8
N3	1	G* (MPa)	1184	925	690	539	436	331	266	222	177	156
		Phase Angle (Degrees)	25.71	28.24	29.91	31.49	30.34	21.8	20.89	24.26	22.74	23.03
		Temperature (°C)	29.9	29.9	29.9	29.9	29.9	29.9	29.9	30	30	30

Table A-5 RSCH Test Results, Mixture 1

Pair	Mixture 1		
N1	Total Permanent Strain (Percent)	0.877	
	Temperature (°C)	48.9	
	Cycle	2845	
N2	Total Permanent Strain (Percent)	0.957	1.07
	Temperature (°C)	50.8	50.8
	Cycle	2845	5000
N3	Total Permanent Strain (Percent)	0.777	0.86
	Temperature (°C)	50.4	50.4
	Cycle	2845	5000

Table A-6 RSCH Test Results, Mixture 2

Pair	**Mixture 2**		
N1	Total Permanent Strain (Percent)	0.764	0.856
	Temperature (°C)	48.6	48.6
	Cycle	2845	5000
N2	Total Permanent Strain (Percent)	0.971	1.105
	Temperature (°C)	50.6	50.6
	Cycle	2845	5000
N4	Total Permanent Strain (Percent)	0.862	0.972
	Temperature (°C)	50.4	50.4
	Cycle	2845	5000

Table A-7 RSCH Test Results, Mixture 3

Pair	**Mixture 3**		
N2	Total Permanent Strain (Percent)	0.75	0.82
	Temperature (°C)	50.7	50.7
	Cycle	2845	5000
N1	Total Permanent Strain (Percent)	0.67	0.743
	Temperature (°C)	50.1	50.1
	Cycle	2845	5000
N3	Total Permanent Strain (Percent)	0.84	0.903
	Temperature (°C)	48.8	48.8
	Cycle	2845	5000

Table A-8 RSCH Test Results, Mixture 4

Pair	**Mixture 4**		
N1	Total Permanent Strain (Percent)	0.908	1.033
	Temperature (°C)	50.7	50.7
	Cycle	2845	5000
N2	Total Permanent Strain (Percent)	1.042	1.186
	Temperature (°C)	50.7	50.7
	Cycle	2845	5000
N3	Total Permanent Strain (Percent)	0.884	0.996
	Temperature (°C)	49.4	49.4
	Cycle	2845	5000

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Biographical Information

Mohammadreza Khajeh Hosseini was born in Tehran, Iran. He received the Bachelor of Science in Civil Engineering from Shiraz University in 2012. In January 2014, he started his Master of Science program in Civil Engineering at the University of Texas at Arlington. During his graduate studies, he has worked as a Graduate Research Assistant in the funded project from TXDOT on the Performance Evaluation of Recycled Asphalt Mixtures. He joined the Metropolitan Infrastructure PLLC in May 2015 and continued working there as an Infrastructure Engineer.

His research was focused on Development of the Duplicate Shear Test for Asphalt Mixtures. He has completed this research under the supervision of Dr. Stefan A. Romanoschi and received his M.Sc. degree in December 2015.