IMPROVEMENTS TO THE DUPLICATE SHEAR TESTER

By

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

DECEMBER 2017

Acknowledgements

First of all, I would like to express my sincere gratitude to my advisor Prof. Stefan Romanoschi for his patient guidance, motivation, and advice throughout my time as his student. His guidance helped me to write and finish this Master thesis properly and successfully; I have been extremely lucky to work under his supervision. He cared so much about my research, and responded to my queries so promptly. I would also like to thank my thesis committee: Prof. Sahadat Hossain and Prof. Xinbao Yu, for reviewing this thesis and their insightful comments.

A very special recognition and respect goes to my sponsor, Mutah University, Jordan for supporting me to pursue my graduate studies in Civil Engineering. I am also thankful for all the staff of the Civil Engineering department in The University of Texas at Arlington for giving me the best education and knowledge in the Infrastructure System Engineering and Management field.

Last but not the least, my profound gratitude to my parents, Suleiman and Manal Jweihan, who have taught me to be persistent and independent through their moral and emotional support in my life. I am also grateful to my brothers, fiancée, and friends for their overwhelming motivation, love, and encouragement along the way of my study. This accomplishment would not have been possible without them.

November 16,2017

Abstract

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Rutting in the asphalt concrete layer is a major distress in flexible pavements caused by the permanent shear deformation in asphalt mixes. The shear deformation is induced by heavy truck axis during hot summer days. Rutting affects directly the safety and users comfort. Therefore, developing of an appropriate test device for measuring the fundamental shear properties of asphalt mixes is important in order to improve the rutting resistance of asphalt mixes and pavement performance. The desired device should be simple, inexpensive, and accurate to be able to be incorporated for a quality control or quality assurance process, as well as to be accepted as a simple performance shear test device. The Duplicate Shear Tester (DST) is a device developed recently by Khajeh-Hosseini (2015) to measure the average shear asphalt properties of two specimens at the same time. Even though the DST has satisfied the objectives of a new test device for measuring the fundamental shear properties of asphalt mixes at low cost relative to the SST device, it provides reliable measurements solely for the dynamic shear modulus and phase angle of asphalt mixes at load frequencies ranged from 0.5 to 10 Hz. Therefore, this study aimed mainly to improve the DST as well as to assess the variability of the results obtained with the improved device by conducting the FSCH and RSCH tests.

The modified DST includes an additional mini linear rail system that ensures the movement of the aluminum plate only in the vertical plane. It replicates the loading conditions and constraints of the Superpave Shear Tester (SST) to measure the dynamic shear modulus, phase angle and permanent shear deformation as an average for two asphalt concrete specimens at the same time. This device is used to perform the two common SST tests: the FSCH and RSCH in accordance to the standard test method AASHTO-T 320. The tests were performed by utilizing a universal testing machine equipment (UTM-25) developed by IPC^{TM} Global.

To evaluate the effectiveness of the modified DST, two dense graded asphalt mixes were tested for FSCH and RSCH tests. For each mix, eight pairs of specimens were tested. The FSCH tests were conducted first at 30°C to measure the shear dynamic modulus and phase angle of the mixes at ten different load frequencies ranged from 10 Hz to 0.01 Hz. The RSCH tests were performed at 50°C after that on the same samples to measure the permanent shear deformation of the specimens by applying 5,000 shear load cycles of controlled stress. Since the FSCH tests are performed in the linear viscoelastic domain of asphalt mixes, the same pairs of two mixes were used for both tests. The obtained results have proved the ability of the modified DST device to provide reliable measurements for shear dynamic modulus, phase angle, and shear permanent deformation of the tested asphalt mixes with relatively low coefficient of variations: 7% to 23% for the dynamic shear modulus (FSCH), 3% to 11% for the phase angle (FSCH), and about 20% for the permanent shear deformation at 5,000 shear load cycles (RSCH).

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Chapter 1

Introduction

Rutting or permanent deformation is a major distress in flexible pavement. It is the permanent longitudinal depression in the wheel paths with small upheavals to the sides. This distress is caused by the repetitive heavy load traffic passing on the asphalt pavements. Rutting causes a serious impact on the road safety especially in winter when water accumulates in the ruts and may cause vehicles to slide. Densification of asphalt mixes and shear deformation are the two factors causing rutting. Rutting can develop not only in the surface wearing layer but also in the other layers of the pavement structure (Sousa, Craus, & Monismith, 1991).

The design of the asphalt mix has a major influence on the rutting development in asphalt layers. Dense graded mixes with low air voids mitigate the permanent deformation by enhancing the interlock between aggregates better than the open or gap graded mixes. Rough aggregates with high angularity reduce also the potential of rutting more efficiently than round aggregates. Also, asphalt binders modified with polymers increase rutting resistance because of their high viscosity. Nevertheless, some other factors like binder content, air void content, compaction, temperature, pavement layers' thicknesses and moduli also affect rutting resistance. The ability of asphalt mixture to withstand rutting is altered by varying any of these factors. Therefore, all of these factors should be considered in order to reduce the rutting potential (Sousa, et al., 1991).

On the other hand, fatigue cracks in the surface layers play an important role in expediting the rutting in the unbound layers. Water infiltrates through the cracks into the underneath granular base and subgrade soil. As a result, the stiffness of underneath layers reduces and the rutting is induced (White, Haddock, Hand, & Fang, 2002).

The majority of HMA rutting occurs usually within the top 3 to 4 inches of the HMA layer, so a high quality mixture is required in the top layer. Even though all asphalt mix components have a major effect on rutting, it is obvious that no single parameter can be used for rut predication with a high level of confidence (Brown & Cross, 1992). Therefore, the appropriate laboratory test methods are required to determine the susceptibility of asphalt mixes to permanent deformation.

Many design methods were developed for asphalt mixes over the years. In the 1930s, the Hveem design method was developed in California and has been extensively applied in the western states. The Marshall method was developed later in Mississippi in the 1940s. These methods used density/void analysis and stability/flow tests for asphalt design to be widely used in the United States and around the world. In 1993, the Strategic Highway Research Program (SHRP) developed a new method as a last product of its research called the Superpave design method to replace the old design methods. Superpave is an acronym for Superior Performing Asphalt Pavements. It is a comprehensive method and it includes an improved system for specifying asphalts, aggregates, mix design, and pavement performance analysis (NHI, 2000). Even though the Superpave is a comprehensive design method, it has one major deficiency. It is based solely on volumetric analysis with no strength or durability test like in the Marshall and Hveem methods where the flow and stability tests are used. To address this deficiency, the development of laboratory simple performance tests (SPT) for evaluating rutting and fatigue performance was imperative. It was desirable that the tests could be also used for the QC/QA testing (Goodman, 2000).

FHWA developed the Simple Performance Tests (SPT) which is a group of accurate and reliable laboratory test methods that measure the asphalt mixture responses and characteristics caused by traffic and climate actions. SPT test results allow to evaluate the asphalt mixes ability to resist fracture and permanent deformation (Witczak, Kaloush, Pellinen, El-Basyouny, & Quintus, 2002).

Rutting can be measured by many empirical tests. Examples of empirical tests include the French Rut Tester, the Hamburg wheel tracking device, and the Georgia Loaded Wheel Test. These tests asses the rutting susceptibility of HMA through repeated rolling rubber or steel wheel over asphalt concrete specimens. Other tests like the Supperpave Shear Tester (SST) and Field Shear test (FST) evaluate rutting susceptibility by measuring the shear strength and shear modulus of asphalt mixes (Goodman, 2000).

Superpave Shear Tester (SST) and Field Shear Tester (FST) are the main devices for measuring the shear parameters of asphalt concrete. The SST was developed under the SHRP program to measure the asphalt mixture properties and predict the permanent deformation by measuring the shear dynamic modulus of laboratory HMA specimens compacted with the

Superpave gyratory compactor (SGC). In the SST, a prepared asphalt concrete specimen is subjected to horizontal shear force along with a vertical axial force to maintain the specimen height constant during the shear. The FST device measures the dynamic shear modulus for the SGC specimens along different planes to the aggregate orientation. A prepared specimen is placed in the FST device in a position similar to that in the indirect tensile test to be sheared along its diameter axis by moving a shaft attached to the specimen holders (Witczak, et al., 2002).

The first FST device was developed during the NCHRP Project 9-7 to be used as an alternative device to the SST. It was found that the FST prototype had some problems, so it was recommended to modify the original FST device to be suitable for QC testing applications. During the NCHRP Project 9-18, the first FST device was modified to be compact and easy to use for measuring the shear dynamic modulus of HMA mixture in the field within 10 minutes. However, it was found that this device could be used only for QC/QA applications due to the complexity of stress and strain distributions near the specimen grips (Christensen, Bonaquist, & Handojo, 2002).

An experimental plan was performed to select the best test method between the SST and FST for quantifying the HMA deformability. Different mixes of HMA were sampled from different field projects for the evaluation process. A statistical analysis was used individually for each project samples to determine the level of correlation between mixes response parameters and rut depth. The correlation between the rut depth and stiffness parameters measured with the FST was found very poor comparing to the correlations obtained by the SST device. Thus, the FST was dropped from further evaluations and any other experimental tests (Witczak, et al., 2002).

In total, six tests can be performed by the SST device. However, only two tests are commonly used to characterize asphalt performance against rutting. Those tests are the Frequency Sweep Test at Constant Height (FSCH) and the Repeated Shear Test at Constant Height (RSCH). The FSCH test is used to measure the complex shear modulus and phase angle of asphalt mixes, whereas the RSCH test is used to measure the cumulative permanent shear deformation. Although some of the SST tests are effective to predict the potential of asphalt pavements rutting, the SST system is expensive and complex. This was prevented the SST to be widely used as a simple performance test device (Pavement Interactive, 2008). Therefore, the need for a simple and inexpensive test device capable to evaluate the shear properties of asphalt mixes is quite significant.

Recently, Khajeh-Hosseini (2015) has developed a new device able to characterize asphalt mixes similar to the SST device. The new device has been developed in the University of Texas at Arlington to replicate the loading conditions in the SST. This device measures the average mechanical shear properties of two cylindrical specimens at the same time, so it has been named the "Duplicate Shear Tester (DST)". In contrast to the SST device, the DST is a user friendly and inexpensive device. These advantages are achieved by utilizing a universal testing machine (UTM) for performing the DST test. This test is used to perform the two common SST test: the FSCH and RSCH. Moreover, the DST device has proved its high repeatability and reliability in measuring the shear dynamic modulus and phase angle at load frequencies ranged from 0.5 to 10 Hz. It is also able to determine the permanent shear strain of asphalt mixes under cyclic loading. Nevertheless, further improvements are needed for this device to improve the testing procedure and to reduce the variability of the tests.

In this study, the DST device was improved to obtain more reliable outputs for the rutting prediction. This study aims to modify the DST device assembly to assure a completely vertical motion for the DST middle plate and to assess the variability of the results obtained with the improved device.

Chapter 2

Background

The development of an appropriate test device for measuring the fundamental shear properties of asphalt mixes is quite significant. Since rutting is a major distress in asphalt pavement that affect directly the safety and users comfort, researchers attempt to measure the shear properties and responses to improve the asphalt pavement performance. The desired device should be a simple, inexpensive, accurate, and vital for a quality control or quality assurance purpose to be accepted as a simple performance shear test device.

In this chapter, several shear test systems are discussed. The general objective of these test systems is to measure the fundamental properties and responses of asphalt mixes under shear loads. These tests focused on rutting prediction parameters. Two tests are developed for field quality control or quality assurance purposes: The Field Shear Test (FST), and the In-Situ Shear Stiffness Tester (InSiSST™). The other three tests are laboratory tests: The Dynamic Shear Rheometer (DSR), the Superpave Shear Tester (SST) and the Duplicate Shear Tester (DST). As mentioned previously, the DST device was developed to replicate the loading conditions and constraints of the SST device. Thus, the SST tests are discussed in more details.

2.1 Field Shear Test (FST)

2.1.1 Background

Even though many test devices and methods were developed during SHRP, the SST become an appropriate device for rutting prediction due to the Frequency Sweep Test at Constant Height (FSCH) and Repeated Shear Test at Constant Height (RSCH). However, the SST is too large, complex, expensive device, and the testing system is not suitable to be used for routine laboratories uses or in hot mix plants. Therefore, researches after SHRP have mentioned the need for a simple, quick, and inexpensive test device for pavement performance evaluation (Christensen, et al., 2002).

In order to assure that the quality of the hot mix asphalt mixtures is satisfying the Superpave performance requirements, NCHRP Project 9-7 established a comprehensive procedure and developed equipment for quality control and quality assurance through field tests. The Field Shear Tester (FST) was developed in 1996 from funding provided through NCHRP Project 9-7 to measure the permanent deformation properties of HMA in the field. This device is derivate from the Superpave Shear tester (SST) to perform the Frequency Sweep at Constant Height (FSCH) and Simple Shear at Constant Height (SSCH) tests (Cominsky, Killingsworth, Anderson, Crockford, 1998).

The FST device was developed to be able to test a gyratory compacted specimen with a height up to 150 mm, as well as HMA field core specimens. In this device, a repetitive controlled load of various cycles is applied in a vertical direction across the specimen diameter to measure the complex shear modulus (G*) of HMA. The obtained modulus can be used only for QC applications. The differences between the FST device and the laboratory SST device are in the loading condition and specimen orientation. FST simulates the laboratory SST frequency sweep test by adjusting the applying load and stress to maintain a constant strain for the specimen while decreasing the applied load frequency. It was observed from the dynamic modulus and load frequency data that the measured stain is not ideally constant. Thus, it was recommended for additional evaluations for the FST device to improve its performance. The first FST device is shown below in Figure 2-1 (Cominsky, et al., 1998).

Although the procedure of the first FST device is simple, the device has no temperature chamber. This means that the test specimen needs to be conditioned before being installed inside the device. Also, it is found that the obtained complex modulus has a poor accuracy due to the poor performance of its servo-pneumatic loading system at high frequencies. Because of the mentioned FST drawbacks and limitations, a need to modify the FST became a necessity (Christensen, et al., 2002).

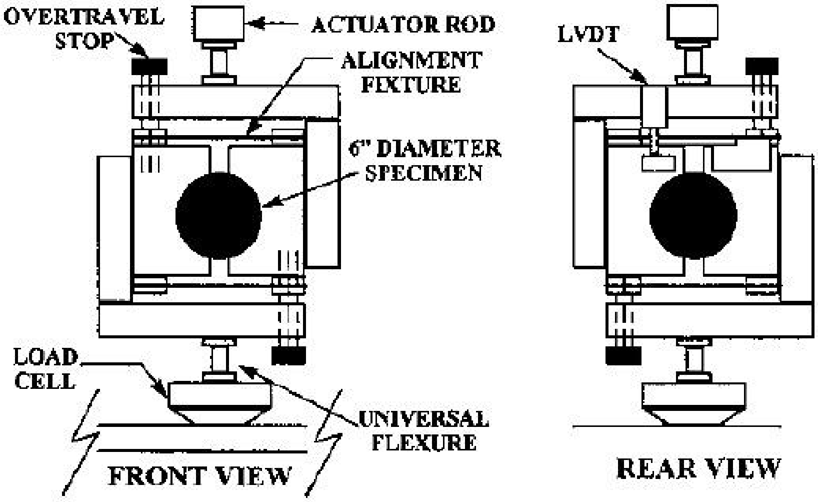


Figure 2-1 First FST Test Device (Christensen, et al., 2002)

Therefore, it was decided during the NCHRP Project 9-18 to redesign the first (original) FST device to be more similar to the SST device and to be more suitable for QA/QC HMA testing. The main improvement for the original FST was the device geometry. This improvement made the new FST capable to perform a frequency sweep test like the SST does. Other improvements were considered in the redesigned FST including better temperature control and hydraulic clamping systems. Figure 2-2 below shows a photograph of the new FST device (Christensen, et al., 2002).

Figure 2-2 New FST Photograph (Christensen, et al., 2002)

Another improvement for the new FST includes an enhancement to its ability to apply high shear stress. Since asphalt mix exhibits different viscoelastic and nonlinear plastic behaviors at different applied loads and temperatures, SST load conditions and limitations are determined in order to assure the linear behavior for asphalt mix during the test. The maximum applied shear stress in SST was 35 ± 1 kPa while the maximum shear strain was 0.01 %. It was suggested in the NCHRP Project 9-18 that the FST should be able to apply shear stress up to 100 kPa and strain up to 0.1 %, which makes the suggested limit higher than the SST stress limits. This improvement means that the new FST will be simple, less expensive and probably more accurate for using. That suggestion was based on findings proposed by the researchers at Pennsylvania State University. It was found that specimens could maintain a linear behavior during the FST test even with increasing the applied shear stress above the stress used in the SST (Christensen, et al., 2002).

2.1.2 Description of the FST device.

The new FST device is compact and easy to use. Its new geometry can test a compacted gyratory HMA specimen of 150 mm in diameter and 115 mm in height. Hydraulic clamps are used to hold the compacted specimen inside two identical cups. The space between the two cups is 22 mm after placing the specimen. The specimen is sheared in similar way like in the SST with a direction parallel to its ends. The new FST contains a servo-pneumatic system able to apply a maximum shear stress of 1260 kPa by applying a sinusoidal load to the specimen. A sketch diagram of the new FST is shown in Figure 2-3 (Christensen, et al., 2002) & (Christensen, 2003).

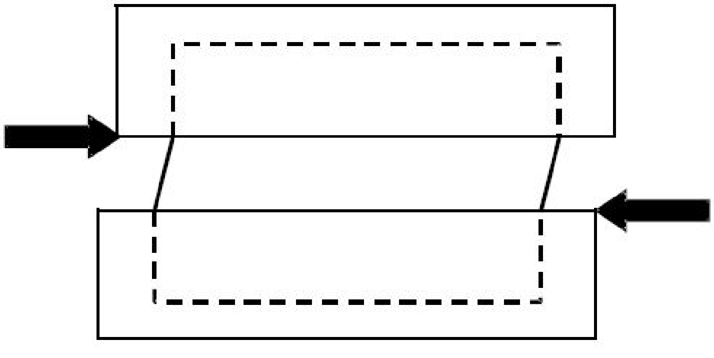


Figure 2-3: Sketch Geometry of the new FST (Christensen, et al., 2002)

2.1.3 FST Specimen Preparation

The specimen preparation is quite simple. A compacted gyratory specimen of 150 mm diameter and 115 mm height should be held directly inside the FST device between two identical semicircular clamps. A shear load is then applied diametrically without any previous preparation like sawing or gluing (Christensen, et al., 2002).

2.1.4 FST Test Procedure

Four replicate HMA gyratory compacted specimens should be prepared. The specimens are preconditioned for at least two hours in an environmental chamber till they achieve the test temperature of 40°C, followed by placing the specimen inside the FST device between the two closed hydraulic clamps. A hydraulic pressure of 10.3 MPa is applied by the hydraulic clamps. Then, the door of the chamber is closed and the mounted specimen is equilibrated for five minutes before performing the frequency sweep test. Once the frequency test is finished, the hydraulic clamps are released and the specimen is rotated 90°. The process is repeated four times for each specimen. Finally, the dynamic shear modulus is determined by calculating the average measurements of the four samples. The test can be performed in less than 10 minutes (Christensen, 2003).

2.1.5 Evaluation of the new FST

In order to evaluate the stress and strain distribution of the original FST, the modified FST, and the SST device, several finite element analyses were performed. In those analyses, plane strain conditions and stress higher than that in the SST device were assumed for the FST devices as discussed previously. The results of the analyses showed a significant nonlinear behavior for both FST devices. As a result, the original FST geometry was not involved in any further analysis because of the non-uniform distribution of stresses that was exhibited during the evaluation. On the other hand, the stress and strain in the new FST were not uniform especially near the grips. However, the new FST is small and user friendly for determining the HMA shear modulus. Thus, it could be used only for QC/QA testing and its result should be considered as an approximate (Christensen, et al., 2002).

2.2 In-Situ Shear Stiffness Test (InSiSST ^{TM})

2.2.1 Background

Abd El Halim and Abd El Nabi developed the concept of the shear strength of asphalt pavement in (1990) by constructing the Carleton In-Situ Shear Strength Test (CiSSST) device in Carleton University in Canada. The concept of the CiSSST is known as a surface plate method. A vertical force is applied on this device to generate a torque through a steel plate glued on a pavement surface using epoxy resin. The idea of applying the torque directly over the asphalt surface is to mitigate the potential damage to the surface comparing to the coring technique, as well as to obtain a quick measurement for shear properties with no need to collect specimens. Generally, the torque is applied at constant rate until the failure occurs while the twist angle is measured.

The CiSSST device represents the first step for measuring the asphalt shear properties such as mixes stiffness and strength. It is very simple to perform, effective, and direct test with no special preparation for the pavement surface. The results of Abd El Nabi (1995) showed that the CiSSST was able to determine the shear properties not only between the different mixes but also within the same mix in different geometries. This finding means that the device is sensitive to measure the shear properties of mixes and could distinguish the rutting resistance ability between mixes (Goodman, 2000).

In addition to the previous result, other deficiencies have been observed in the CiSSST device that lead to develop the In-Situ Shear stiffness (InSiSST ^{TM}) test device. The heavy weight of the CiSSST device (110 Ibs) is considered the main drawback for the device portability. Therefore, the test requires at least four operators to conduct the test. Furthermore, the motor and gearbox of the CiSSST prototype were unable to provide sufficient torque to fail some mixes at all test temperature. Long curing time of epoxy, on the other hand, was required to close the test site twice within a 24-hours period; once for the epoxy application and another for the actual test. This problem led to traffic congestion while performing the CiSSST test (Goodman, 2000 & El Halim, 2007).

As mentioned previously, the InSiSST ^{TM} device is designed to mitigate the deficiencies of the CiSSST and correlate the test results to the pavement performance indicators such as rutting and cracks. Moreover, the InSiSST ^{TM} was developed to meet some other objectives studies operator safety and ease of use while operating the device in fields, low cost and testing time along with the portability of the device. Furthermore, the InSiSST ^{TM} was designed to help in three areas: mix design, quality control, and long term pavement performance (Goodman, 2000).

2.2.2 *InSiSST ^{TM}* Test Device Description

As stated previously, the InSiSST ^{TM} device is a “surface-plate method”. It measures the shear properties of asphalt mixes by applying a torque to an epoxy glued loading plate until failure. Figure 2-4 illustrates the test methodology.

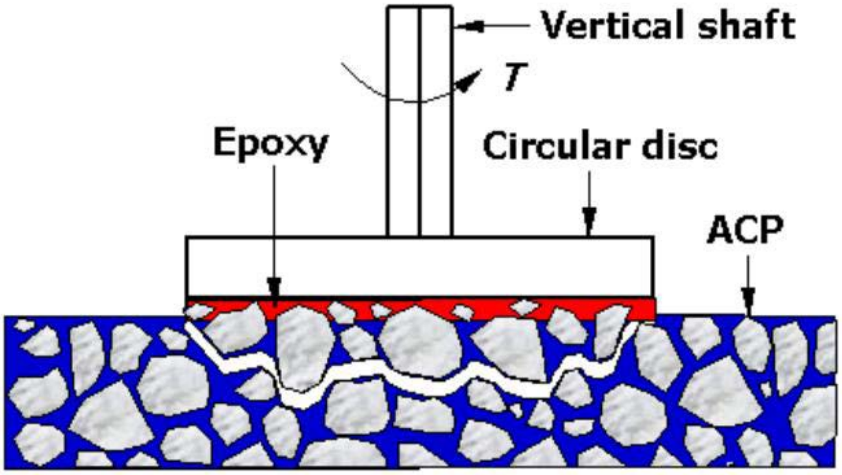


Figure 2-4 Surface-Plate Loading Method for InSiSST ^{TM} (El Halim, 2007)

The motor and gearbox combination are mounted vertically over a steel platform attached transversely to the direction of the InSiSST ^{TM} trailer with two sets of slides. The top two slides are fixed perpendicularly over the lower slides that keep the positioning in the longitudinal direction of the trailer. Four jacks are used to attach the whole positioning system to the trailer frame. Those jacks protect the trailer frame against damage while transporting the InSiSST ^{TM} device as well as to lower the frame to the ground for conducting the shear test. Once the device takes a place in field, the stability of the test frame will be achieved with no rotational movement while performing the test. This stability is developed because of the generated frictional force between the bottom of the test frame and the pavement surface; the weight of the trailer is supported by the test frame. At each lowering, up to five shear tests can be conducted due the configuration of the positioning system and test frame.

An acquisition system and a laptop computer are used not only to collect the measured torque and twist angle but also to acquire other information like test location, temperature, and weather conditions for future analysis. InSiSST ™ contains other features like a plastic storage in the front of the device trailer to store the electronic tools. A generator is mounted in the back of the trailer to supply the InSiSST™ with electricity. The InSiSST™ is shown below in Figure 2-5 (Goodman, 2000 & El Halim, 2007).

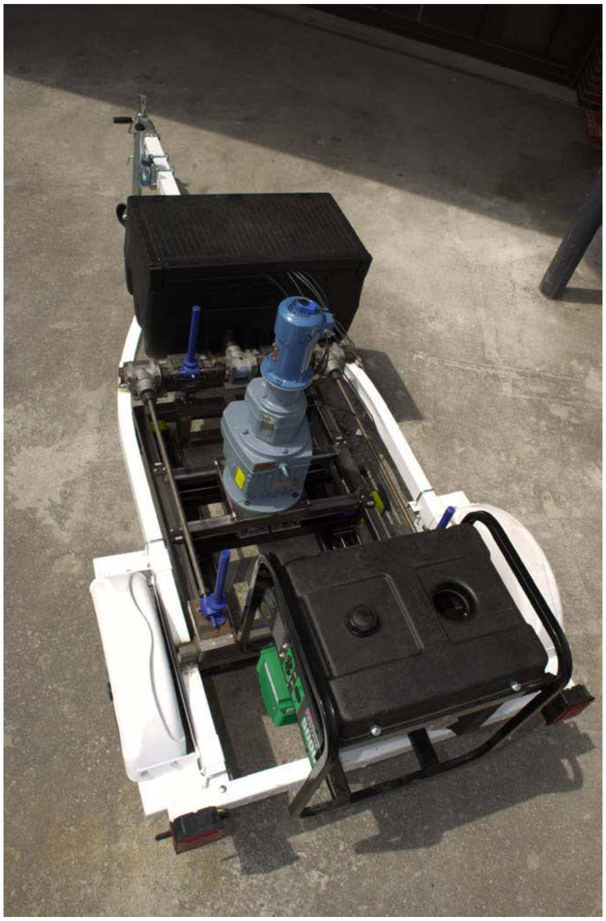


Figure 2-5 Top View of the InSiSST™ Facility (El Halim, 2007)

2.2.3 *InSiSST ™* Site Preparation

The pavement surface should be prepared properly for an effective use of the *InSiSST ™.*. The asphalt pavement surface should be cleaned of dirt or oily materials before performing the test in order to assure sufficient bonding between the asphalt surface and the steel loading plate of the device. In general, a stiff brush or broom could be used to remove dusty substances. Soap and water could be used also in some causes for better cleaning. However, the asphalt surface should be dried prior to lower the loading plate. Enough epoxy resin must be applied to achieve high bonding strength between the loading plate and pavement surface. Before compressing the plate, however, the epoxy should be spread properly with no air bubbles at the bottom of the plate. Excess epoxy around the plate can be removed by a clean towel. Based on the manufacturer specifications, the epoxy should be left for enough curing time prior starting the test (Goodman, 2000).

2.2.4 *InSiSST™* Test Procedure

Once the epoxy resin is cured, the InSiSST™ device is detached from the towing vehicle and centered over the first test plate. The torque cell and gearbox are then setup and aligned before lowering the test frame. Once the frame is lowered to the ground and the trailer suspended, the laptop computer is turned on. The pavement temperature is then recorded for future analysis. After that, the torque cell is connected over the test plate for taking the test readings. The torque cell calibration process must be done before the test is started. To initiate the test, the strain rate should be selected first from the motor controller software. Based on the strain rate, the torque increases till the mix failure occurs.

The depth of the failure surface is then measured with a caliper for analysis purpose. The procedure is repeated for the remaining loading plates at the site. However, once the desired tests are completed, test equipment should be collected and returned for future use. The site should be left clean and the test holes should be sealed with a slurry material to protect against water infiltration (Goodman, 2000).

2.2.5 Evaluation of the *InSiSST™* Test device

The InSiSST ™ device was able to address the observed deficiencies with the previous CiSSST device. The InSiSST ™ device is portable, repeatable, stable and rugged. Another advantage is that one operator is required to perform the test in the field rapidly with a simple preparation. Also, the results obtained by this device prove how the device is accurate for measuring the shear properties of asphalt pavements (Goodman, 2000).

Even though the InSiSST ^{TM} device has a lot of advantages, some modifications have recommended to improve its performance. As the asphalt is a viscoelastic material and its behavior varies based on the surface temperature, a temperature master curve is required first to normalize the test results. The normalization process is required to make a comparison between the obtained results and other sections or standard temperature. Other recommendations proposed that InSiSST ^{TM} should use a hydraulic or pneumatic system instead of the existing electromechanical system. By using this system, the number of component in the InSiSST ^{TM} will be reduced to be within one pump unit. Also, the test will be more accurate and quicker. Using other epoxies material that cured faster reduces the test time. In general, this device is able to measure the in-situ shear properties of asphalt pavements effectively (Goodman, 2000).

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

2.3.1 Background

Dynamic Shear Rheometer (DSR) device is used usually to measure the linear viscoelastic properties of asphalt binders at medium to high temperature. It can also be used for either original or aged asphalt binders that having a shear modulus between 100 Pa to 10 Mpa. A thin specimen of asphalt binder is sandwiched between two circular metal plates inside a control temperature chamber. The bottom plate is fixed while the upper plate generates a shear force by oscillating back and forth as shown in Figure 2-6. The upper plate moves from point A to B. Then from point B, the plate rotates back to point C passing point A. Finally, from point C, it moves back to the point A. This complete movement represents one cycle. The movement rate of 10 rad/sec simulates the shear action developed by traffic at 55 mph speed. Measuring the viscoelastic behavior is used to specify the Superpave performance grading (PG) of asphalt binder (Pavement Interactive, 2011) (ASTM-D7175-05, 2005) (NHI, 2000).

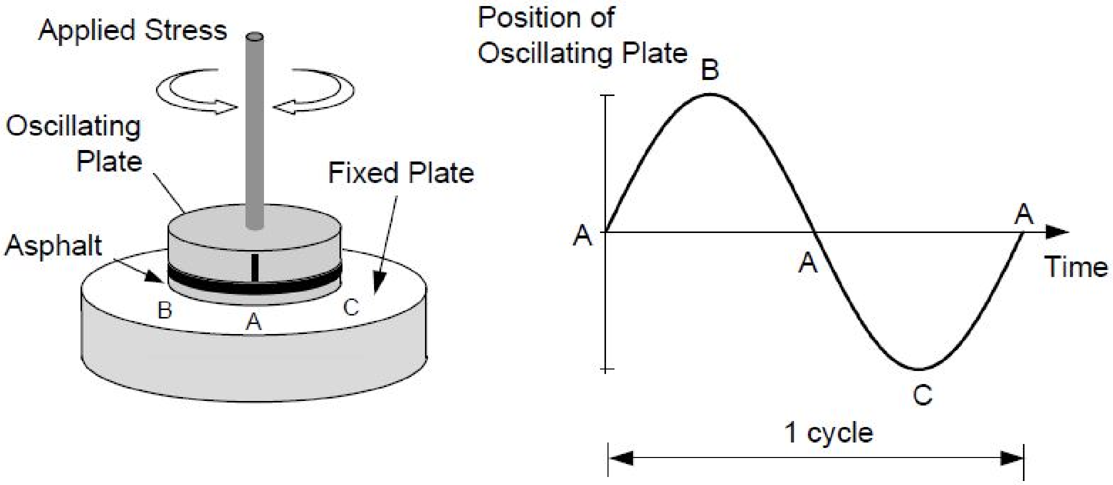


Figure 2-6 The Oscillatory Movement of the DSR upper plate (NHI, 2000)

As generally known, asphalt binder is a viscoelastic material. It means that asphalt behaves partly like a viscous liquid with unrecoverable deformation after releasing the load, and it behaves like an elastic solid material with a recoverable deformation. This behavior varies based on the temperature and applied loads. The DSR measures the linear viscoelastic properties of asphalt binder by measuring the complex shear modulus (G*) and phase angle (δ) under repeatable shear stresses. The complex shear modulus is defined as the ratio of the maximum shear stress to the maximum shear strain. It is an indicator to the asphalt stiffness or the total resistance of asphalts to the shear deformation. Stiff asphalt binders with high G* resist the shear deformation more effectively. The phase angle (δ) is related to the time lag between the applied shear stress and the corresponding deformation (shear strain). The phase angle is 0 for the perfectly elastic material and 90° for the purely viscous material, as shown in Figure 2-7. Lower phase angle, a more elastic binder, indicates the ability of asphalt binders to return to its original shape after being deformed (NHI, 2000).

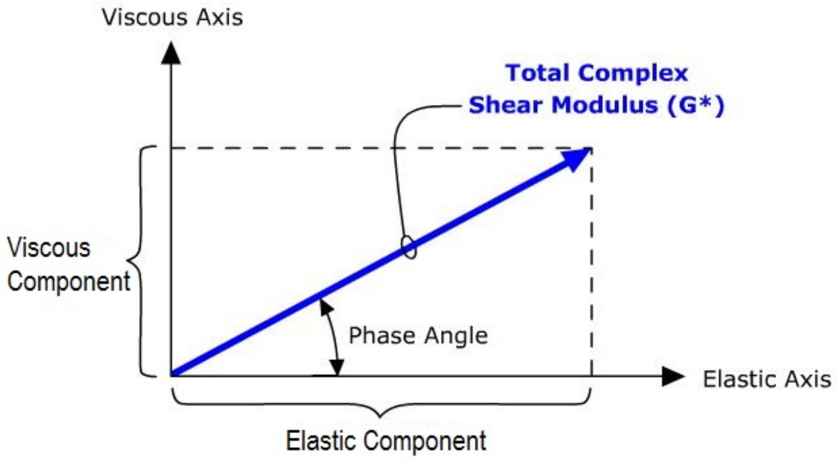


Figure 2-7 Complex Shear Modulus and Phase angle of an asphalt binder (Pavement Interactive, 2011)

The complex shear modulus and phase angle measurements are used to predict the HMA rutting and fatigue cracking. For rutting resistance, the binder should be stiff enough to resist shear deformation, as well as elastic enough to return to its original shape after the shear stress is removed. For fatigue cracking resistance, the binder should be ductile and elastic to dissipate the energy and resist cracking (Pavement Interactive, 2011).

The DSR can be used regularly to measure the viscoelastic properties of asphalt binders, but it was modified to be able to measure the complex shear modulus of bituminous mixtures. It is capable of testing asphalt mix samples that have modulus greater than 10 Kpa at temperature ranged from 10 to 76 C°, frequencies of 0.01 Hz to 25 Hz, and strains of 0.001% to 0.1%. Regardless of the binder type or grade, the bituminous samples used in this device could be either laboratory compacted mixes or core field extruded. The mixes should be also dense graded mixes with a maximum 19 mm nominal maximum aggregate size (ASTM-D7552-09, 2009).

Reinke and Glidden (2004) used the DSR device to perform other tests for bituminous mixtures. They used the same approach of measuring the complex shear modulus for asphalt mixtures to perform two creep tests: static and repeated recovery creep tests. The static creep test includes applying a constant rotational stress of 15kPa on a prepared rectangular bituminous sample till failure while the dynamic creep test consists of applying stress of 25 kPa for 1 second followed that by 9 seconds rest period to allow the sample to recover the performed strain. It was concluded, however, that the results obtained from the DSR are well correlated to the rutting behavior in the field (Reinke & Glidden, 2004).

2.3.2 Description of the Dynamic Shear Rheometer Device

Two test fixtures are used to hold a prepared rectangular test specimen of a bituminous mixture in a vertical plane. A torque wrench is used to apply a torque of 0.25 N.m ± 0.05 N.m to tighten the mounted specimen properly. An environmental chamber and temperature controller are used to control the temperature of the test specimen. To maintain the test specimen temperature, a compressed laboratory air or a bottled air is used in the environmental chamber. Water bath or Peltier system cannot be used because of moisture effects; the moisture weakens the mix specimen and affects the results. The temperature controller is responsible for keeping the temperature within ± 0.1°C of the desired value. An internal platinum thermometer is mounted inside the temperature chamber near the bottom grip to measure and maintain the specimen temperature constant during the test. If there is a need to maintain the temperature during the test below the ambient temperature, an additional cooling system is needed (ASTM-D7552-09, 2009).

The DSR is associated with a loading device that applies a sinusoidal oscillatory load. This device is able to apply load with a frequency ranged from 0.01 Hz to 15 Hz. The role of the loading device is to provide a controlled load frequency and strain with 1% accuracy throughout the test. A data acquisition system records the test data with an accuracy of at least 1%. The recorded data include the temperature, frequency, deflection angle, applied stress, strain, and torque. A digital caliper is used to measure the test specimen dimensions (ASTM-D7552-09, 2009).

2.3.3 Specimen Preparation of Asphalt Mixture for the DSR

As previously mentioned, a bituminous mixture specimen could be prepared from either a laboratory compacted sample or cored from existing pavement layers. The laboratory specimen could be compacted by either a Superpave gyratory compactor or Marshall method. To ensure the air voids uniformity within the gyratory compacted sample, the outer surrounding side of 25 mm should be cut and discarded. If the sample used is obtained from the field core, there is no need to discard the outer side. An approximate 12 mm thick bituminous disk is then sliced from the sample, followed by cutting a 50 mm wide portion. The final torsion rectangular prismatic specimens of 10 mm wide are then sawed from the sliced portion. The selected specimens for test should be straight with no deformation. All sawing process should be performed by using a water cooled diamond blade to assure the surface smoothness and prevent the specimen damage. Figure 2-8 illustrates the sample preparation steps. The prepared sample should be dried at ambient temperature for a period of at least 5 hours before conducting the test. The specimen should be protected from air and light exposure. However, if the test will not be conducted within one week, the specimens should be stored in plastic bags (ASTM-D7552-09, 2009).

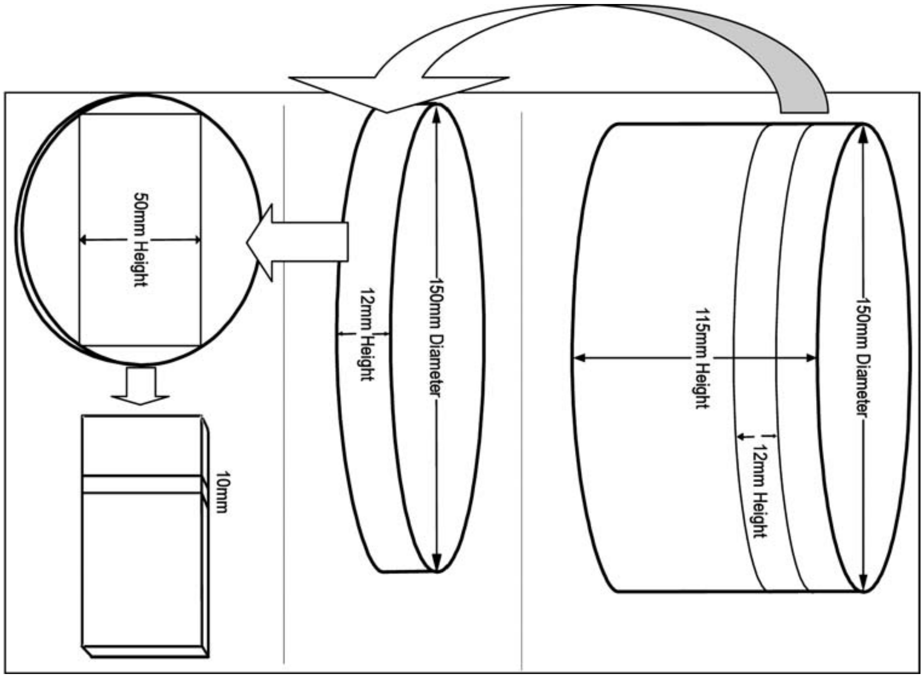


Figure 2-8 Schematic of Preparing a Rectangular Specimen for the DSR device (ASTM-D7552-09, 2009)

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

The DSR device needs first to reach the test temperature or the mean temperature. The environmental chamber is then opened. The sample is then mounted in the right place vertically between the two fixtures. Next, a torque of approximately 0.2 N.m is applied carefully to tighten the sample. Care must be taken while tightening the sample to not apply normal forces more than 5 N. This amount of force will be eliminated while rising up the specimen temperature to the test temperature. After the specimen is mounted, the environmental chamber door should be closed to start warming up the specimen to the desired test temperature. A thermal equilibrium process is then following for 15 minutes before launching the test. The specimen temperature should be within the tolerance of ± 0.1C° of the test temperature after the equilibrium period. The test must be started within 5 minutes after the equilibrium. From the highest to the lowest temperature, a frequency sweep test should be performed to measure the complex shear modulus of the test specimen. The obtained complex shear modulus is comparable with that obtained from the frequency sweep at constant height on the SST device (ASTM-D7552-09, 2009). Figure 2-9 shows the mounted rectangular specimen before and after the DSR testing.

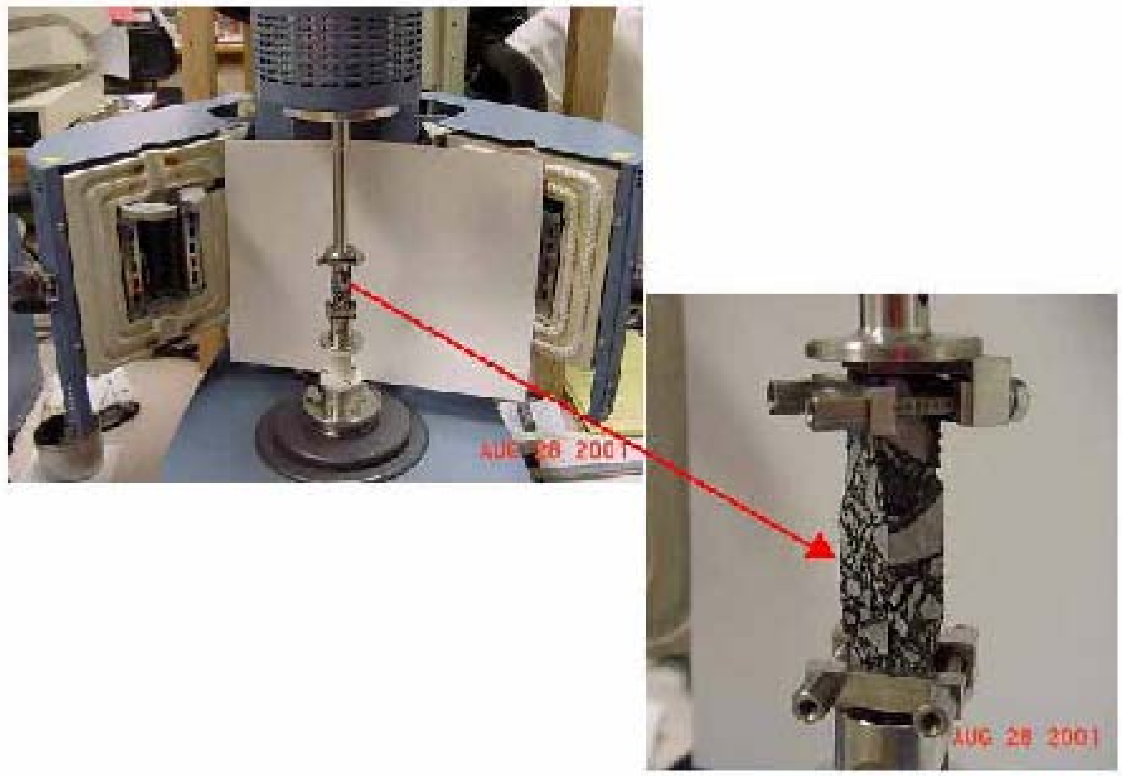


Figure 2-9 HMA Specimen Mounted Inside the DSR and CLose-up Showing the Specimen after testing (Reinke & Glidden, 2004)

2.3.5 Evaluation of Asphalt Mixtures Shear Properties obtained by the DSR

As stated previously, the DSR device measures the complex shear modulus of asphalt binders and bituminous mixtures. It is suitable to measure the shear properties either for a laboratory compacted sample or field core specimen from pavements surface regardless the type of binder grades or age that used in the mixes. The DSR is able to measure the complex shear modulus for samples contain Reclaimed Asphalt Pavement (RAP). However, the DSR is not suitable to be used for the open graded or stone mastic asphalt (SMA) mixtures. The geometry of the tested rotational rectangular specimen is the main reason for this limitation (ASTM-D7552-09, 2009).

2.4 Superpave Shear Tester (SST)

2.4.1 Background

The USA Congress established the Strategic Highway Research Program (SHRP) in 1987 to improve the USA roads performance, safety and durability. The Superpave design method was developed later in the 1990s as a last product of SHRP program. This mix design method is a comprehensive method for asphalt mix design and analysis process which provides several test protocols for a various test conditions. Superpave Shear Tester (SST) and Indirect Tensile Tester (ITT) were the two devices developed by SHRP for quantifying the HMA mix performance (Chowdhury & Button, 2002).

The Superpave Shear Tester, shown in Figure 2-10, is an associated device to the Superpave design method. It is designed to perform all load related performance tests on asphalt concrete. SST device is also capable to measure some basic properties of asphalt mix that are related to the permanent deformation such as nonlinear elastic property, Vermeer plastic property, viscoelastic and tertiary creep properties (Chowdhury & Button, 2002).

SHRP researches proposed six deferent SST tests that able to determine the permanent deformation and fatigue resistance of asphalt mixes. These tests are the following:

- Volumetric Test
- Uniaxial Test

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

Figure 2-10 Superpave Shear Tester (SST) (Chowdhury & Button, 2002)

2.4.2 SST System

The SST is used to determine all load related performance parameters for asphalt materials. It is a servo hydraulic system with a closed loop feedback system. This system can be maintained in either by a stress or strain control. The SST device mainly consists of four components, as shown in Figure 2-11:

- Testing apparatus
- Control unit
- Environmental control unit
- Hydraulic system.

The testing apparatus is the main part of the SST. It applies vertical, shearing and confinement loads to the test sample. The applied loads can be static, increased, decreased, or repetitive loads with different waves. The SST device includes temperature and pressure controls and hydraulic actuator. The Testing apparatus composed of a reaction frame and a shear table. The reaction frame is a very rigid part that assures the accuracy of the displacement measurements of a tested specimen. The shear table holds the test specimen during the test. It can also be actuated to generate a shear stress to the specimen. The applied loads are transferred to the specimen through loading plates glued the specimen ends. Based on the applied test, different linear variable different transducers (LVDTs) are used to measure the specimen responses during the test by sending a signal to the SST closed-loop feedback system.

The control and data acquisition system is used to record and control some parameters automatically during the test. It records the time, applied loads, specimen deformations and the test chamber temperature. It is a combination of software and hardware systems. The hardware system includes the input and output transducers, the device computer and, the controllers. The software system represents the algorithms that are required to control the apparatus and collect the test data.

The environmental unit maintains the temperature and pressure constants inside the test chamber. The temperature will be controlled to be within a wide range from 1 to 80 °C and an accuracy of ± 0.5°C. The air pressure is supplied from a compressed air stored in a storage tank that provides a confinement pressure to the test specimen. The environmental unit controls the air pressure precisely to be applied at a rate of 69 kPa per second up to the maximum pressure of 840 kPa.

The hydraulic system provides the force required to the test specimen in different testing conditions. It consists of horizontal and vertical actuators attached to the specimen. Each actuator has a capacity of almost 32 KN force and a 2 N of resolution. The vertical actuator applies a normal force to the specimen while the horizontal actuator develops a shear force to the specimen by actuating the shear table. This system can also apply a confinement pressure of 1000 kPa capacity (Chowdhury & Button, 2002) (NHI, 2000).

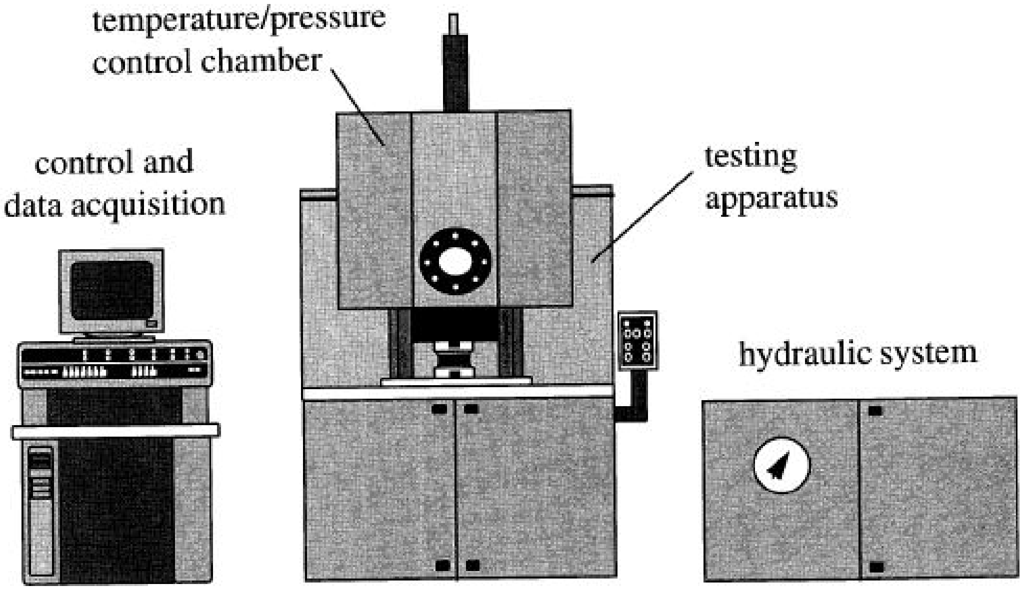


Figure 2-11 Schematic View of a Superpave Shear Tester (SST) Device (Kennedy, et al., 1994)

2.4.3 SST Tests

Volumetric Test

In the volumetric test, a confining pressure only is applied to the test specimen. It is referred as a "hydrostatic" test because the specimen volume is subjected to change due to the applied hydrostatic stress around the test specimen. In this test, the specimen perimeter or circumferential strain changes during the test since the specimen is not attached (glued) to loading plates. Figure 2-12 illustrates schematically the test concept.

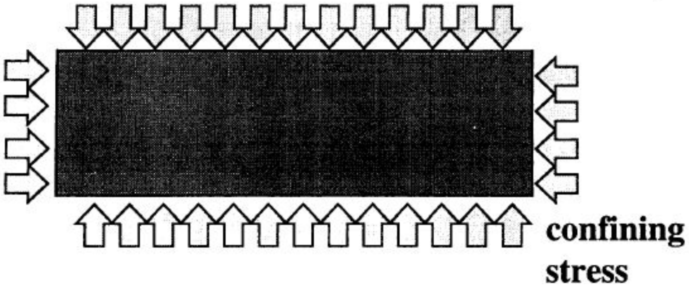


Figure 2-12 Conceptual view of the Volumetric Test (Kennedy, et al., 1994)

The volumetric test is applied at three different temperatures and pressures, as specified in Table 2-1. The test is performed by increasing a confining stress steadily at a rate of 70 kPa per second up to the certain level of a specified pressure depending on the test temperature. Followed that by keeping the pressure constant for a period of 10 seconds. Then the pressure decreases slowly to zero, as shown in Figure 2-13. A radial LVDT is used to measure the circumferential strain of the test specimen during the test. The significance of performing this test is to determine the permanent deformation and fatigue cracking characteristics (Chowdhury & Button, 2002) (NHI, 2000) (Kennedy, et al., 1994).

Table 2-1 Volumetric Test Pressure (NHI, 2000)

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

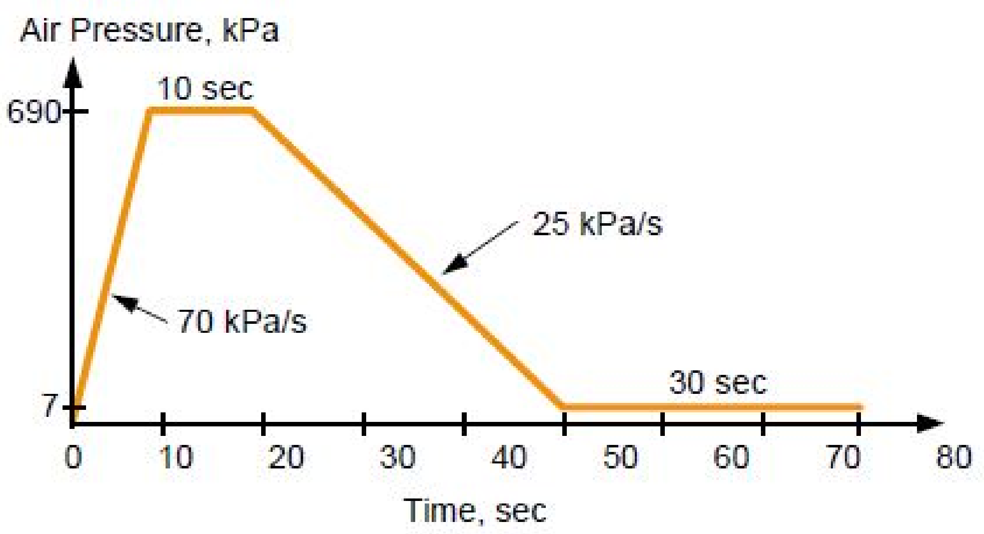


Figure 2-13 Ramping of Confining Pressure, Volumetric Test at 20 °C (NHI, 2000)

Uniaxial Test

In the uniaxial test, a test specimen is subjected to an axial compressive load and confining pressure. When the axial load is applied to the specimen, its diameter tries to increase. Meanwhile, radial LVDTs attached to the specimen sense this increase and send a signal to the feedback system to apply a confining air pressure surround the specimen. This action maintains the specimen diameter constant with no radial deformation. Figure 2-14 illustrates schematically the test concept. (Kennedy, et al., 1994) (NHI, 2000)

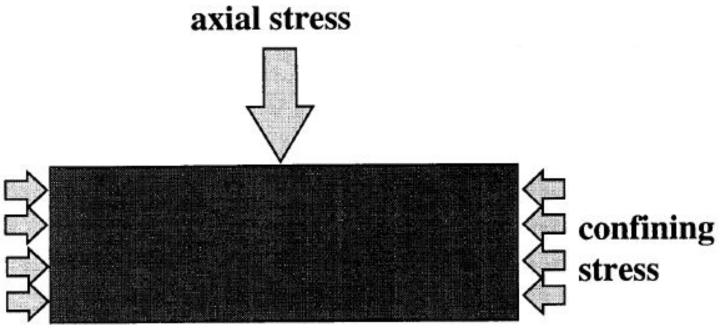


Figure 2-14 Conceptual View of the Uniaxial test (Kennedy, et al., 1994)

The uniaxial test is performed by increasing the axial load at constant rate of 70 kPa per second up to a certain stress level. Table 2-2 shows the desired axial stress depending on the test temperature. The axial stress then remains constant for a period of 10 seconds before it decreases slowly to zero. A variable confining air pressure is applied while applying the axial load in order to prevent any radial deformation. Figure 2-15 illustrates the application of the axial and confining stresses during the test. The output of this test is the axial deformation. This test measures the elastic and plastic characteristic of asphalt mixes which are used for rutting and fatigue cracking analysis. (Chowdhury & Button, 2002) (NHI, 2000)

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

Temperature, °C	Axial Stress, kPa
4	655
20	550
40	345

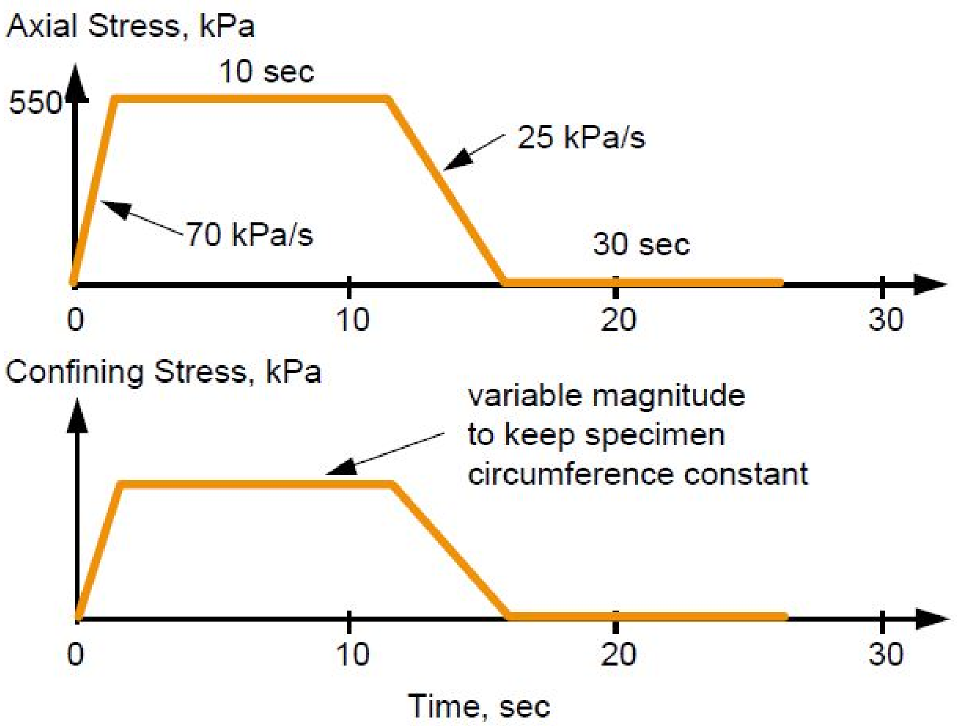


Figure 2-15 Axial Stress and Confining Stress versus Time, Uniaxial Test at 20°C (NHI, 2000)

Repeated Shear Test at Constant Height (RSCH)

The RSCH is a stress-controlled test that consists of applying axial and haversine shear loads simultaneously to a compacted HMA specimen. This test is called as “unconfined” test because there is no air confining pressure like in the volumetric and uniaxial tests (Pavement Interactive, 2008). In this test, the variable axial load is necessary to maintain a constant height for the test specimen during the test, while the haversine shear load cycle is applied to achieve a shear stress of 69 kPa. The shear stress is applied for a period of 0.1 second followed by 0.6 second of rest. The total period of 0.7 second represents one load cycle, as illustrated in Figure 2-16. The test is performed by applying 5,000 shear load cycles or till the specimen achieves 5% of permeant shear strain, whichever comes first. For a specific pavement project, the test temperature is selected based on the maximum 7-days daily temperature recorded at 2 inches depth in site location. This test is performed to interpret the rut depth (rutting susceptibility), as shown in Table 2-3, based on the measured accumulative permanent shear deformation (Chowdhury & Button, 2002) (NHI, 2000) (Brown, et al., 2001). At the end of the test, the permanent shear deformation is calculated by using Equation 2-1 (AASHTO T-320, 2004).

The concept of RSCH test, however, is that the specimen dilates by applying the repeated shear loads. Meanwhile, axial LVDTs sense this expanding in height and send a signal as a feedback to the vertical actuator to apply a sufficient axial force against the dilating (NHI, 2000).

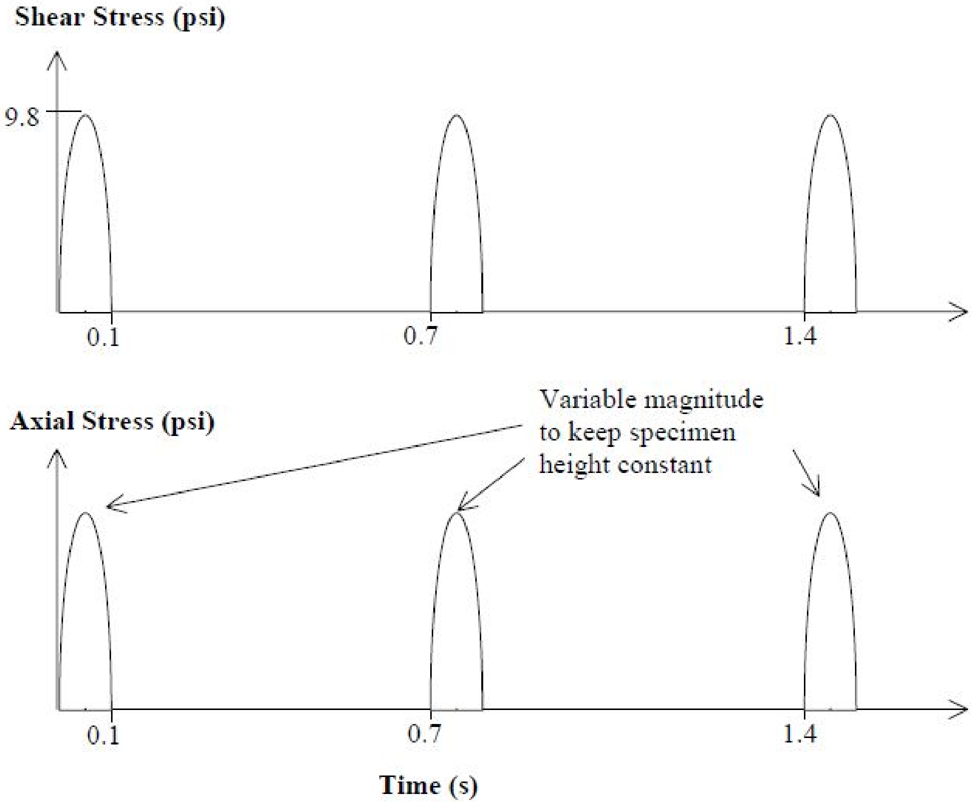


Figure 2-16 RSCH Shear and Axial Stresses versus Time (Chowdhury & Button, 2002)

Table 2-3 Criteria for Evaluating Rut Resistance Using RSCH Permanent Shear Strain (Brown, et al., 2001)

RSCH Maximum Permanent Shear Strain (%)	Rut Resistance
< 1.0	Excellent
1.0 to < 2.0	Good
2.0 to < 3.0	Fair
3.0	Poor

$$\gamma\text{p} = \frac{(\delta\ \text{shear,final} - \delta\ \text{shear,initial})}{h} \qquad (2\text{-}1)$$

γp= permanent shear strain.

δ shear, final= final recorded deformation by the LVDT at the end of the test.

δ shear, initial= initial shear deformation at the start of the test (nominally zero).

h= specimen height (plate-to-plate height).

In RSCH test, the permanent shear strain is measured and recorded by LVDTs and an acquisition data system. The permanent shear deformation (Strain) accumulates with increasing the shear load cycles and follows the typical permanent strain curve. This curve consists of three parts, as shown in Figure 2-17. In the primary zone, the specimen deforms rapidly with high strain and few loading cycles due to the initial compaction. A linear steady rise is obtained in the secondary zone. In this zone, the plastic deformation occurs because the rate of unrecoverable deformation per cycle decreases with increasing shear loading cycles. The latter part of the curve indicates the tertiary zone. This portion occurs when the deformation accelerates toward failure due to the decreasing of air voids content below some certain level, and it represents the tertiary rutting which indicates the instability of asphalt mix (Chowdhury & Button, 2002) (Brown, et al., 2001).

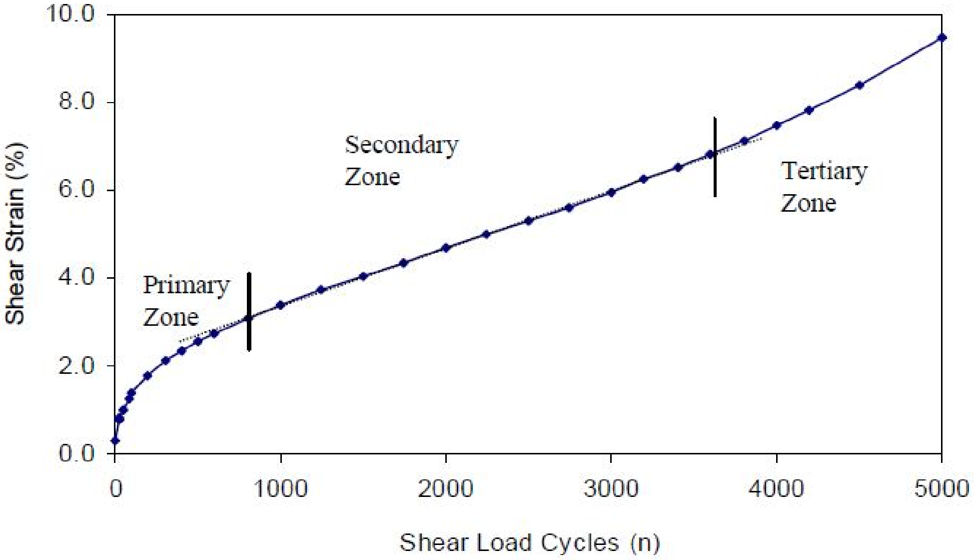


Figure 2-17 Typical Permanent Strain Deformation Curve- RSCH test (Brown, et al., 2001)

Shear Frequency Sweep Test at Constant Height (FSCH)

The FSCH test is an unconfined test that applies a strain controlled dynamic shear load and an axial load to an asphalt specimen. The shear load is applied at different frequencies and temperatures while the axial load is applied only to keep the specimen height constant during the test. Figure 2-18 illustrates schematically the test concept. This test is performed to determine the mixture stiffness by measuring the asphalt complex shear modulus (G*) and phase angle (Φ) (AASHTO T-320, 2004) (Chowdhury & Button, 2002) (Kennedy, et al., 1994). The shear dynamic modulus and phase angle can be calculated by using these equations: (Witczak, et al.,2002)

$$|G^*| = \tau 0 / \gamma 0 \qquad (2\text{-}2)$$

$$\Phi = ti / tp \qquad (2\text{-}3)$$

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

$|G^*|$ = Shear Dynamic Modulus

G^* = Complex Shear Modulus

τ 0 = Peak Dynamic Shear Stress

γ 0 = Peak Recoverable Shear Strain

ti = Time Lag between Stress and Strain Cycles

tp = Time for a Stress Cycle

The FSCH is performed by applying a repeated sinusoidal shear load till the specimen achieves a maximum controlled strain of 0.01%. This load is applied at several frequencies and cycles, as specified in Table 2-4. The load is applied beginning from the higher to the lower frequency. The specimen tends to dilate while applying the shear force. Consequently, a vertical actuator applies an axial force to maintain the specimen height constant. The axial force is induced by a close-loop feedback signal received from axial LVDTs attached to the test specimen (Chowdhury & Button, 2002) & (NHI, 2000). Figure 2-19 illustrates the application of shear strain and axial stress during the FSCH test.

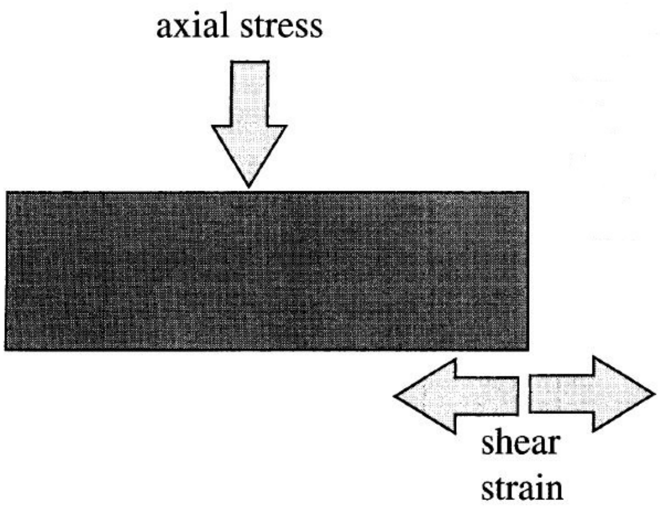


Figure 2-18 Conceptual View of the FSCH test (Kennedy, et al., 1994)

Table 2-4 FSCH Test Parameters (AASHTO T-320, 2004)

Frequency, Hz	Number of load 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

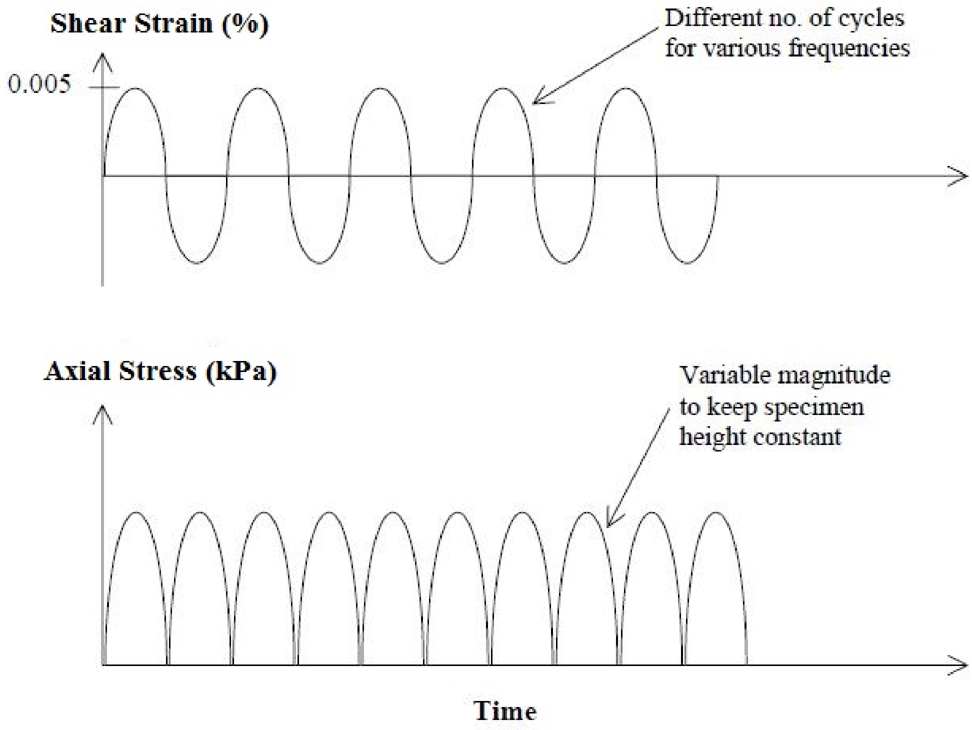


Figure 2-19 Shear Strain and Axial Stress Pulses - FSCH Test (Chowdhury & Button, 2002)

Simple Shear at Constant Height (SSCH)

The SSCH test is an unconfined test that applies a controlled shear load as well as a static axial load to an asphalt specimen. The same specimen that has been tested in the FSCH can be used in this test. The axial load is applied to maintain the specimen height constant during the test. Figure 2-20 illustrates schematically the test concept. SSCH test is a shear creep test that determines the elastic and plastic properties of asphalt mixes by measuring the ability of asphalt mixes to resist the permanent shear deformation (Chowdhury & Button, 2002) (NHI, 2000) (Pavement Interactive, 2008). The maximum shear strain and recovery for the tested specimen can be calculated using the following equations (AASHTO T-320, 2004).

$$\gamma \text{ max} = \frac{(\delta \text{ shear,max} - \delta \text{ shear,initial})}{h} \qquad (2\text{-}5)$$

$$Recovery = \frac{(\delta \text{ shear,max} - \delta \text{ shear,final})}{\delta \text{ shear,max}} \qquad (2\text{-}6)$$

γ max = Maximum Shear Strain.

δ shear, max = Maximum Recorded Deformation by the Shear LVDT.

δ shear, initial = Initial Shear Deformation at the Start of the Test (Nominally Zero).

δ shear, final = Final Shear Deformation at the end of the Test.

h = Specimen Height (Plate-to-Plate Measure only).

Recovery = Calculated Recovery of the Specimen.

Similar to the FSCH test, the specimen height tends to expand while applying the shear force. However, the specimen height is maintained constant by applyied a static axial force to the specimen. The axial force is induced by the closed-loop feedback system using axial LVDTs. The shear stress is increased at a rate of 70 kPa per second till it achieves a certain level of stress depending on the test temperature. The stress is then kept constant for 10 seconds before it is decreased steady to zero at a rate of 25 kPa per second. Afterwards, the stress continues for a period of other 10 seconds. Figure 2-21 illustrates the application of shear strain and axial stress during the SSCH test. (Chowdhury & Button, 2002) (NHI, 2000)

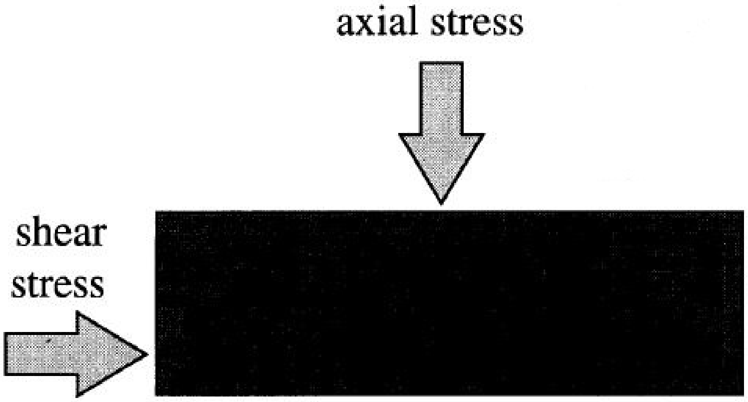


Figure 2-20 Conceptual View of the SSCH test (Kennedy, et al., 1994)

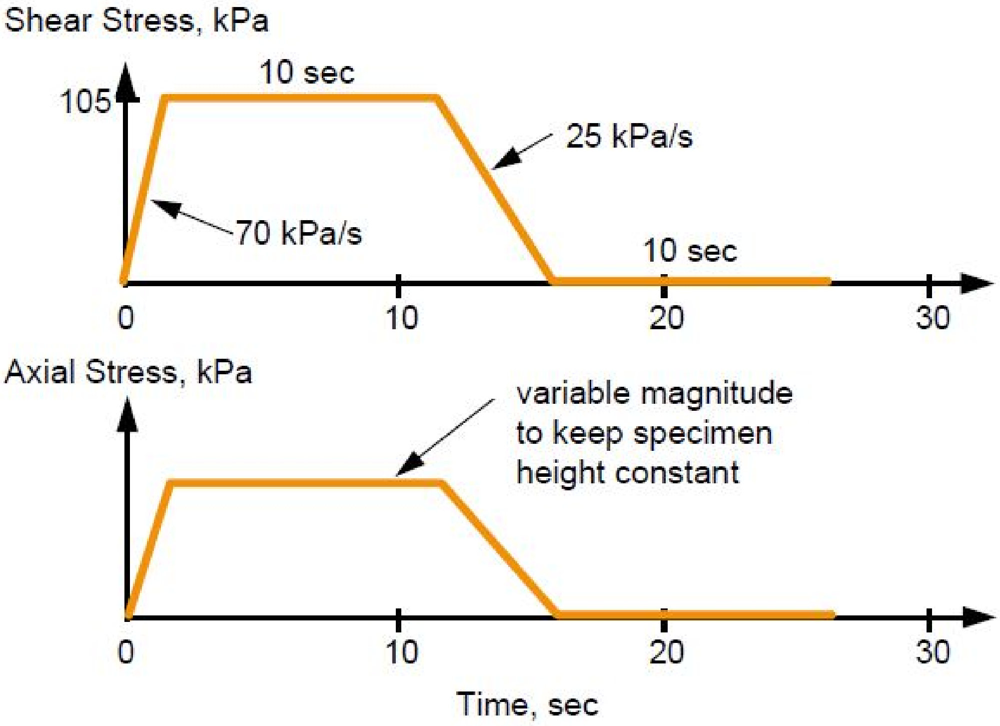


Figure 2-21 Shear and Axial Stresses versus Time, SSCH Test at 20°C (NHI, 2000)

Repeated Shear at Constant Stress Ratio Test (RSCSR)

The RSCSR test consists of applying repeated synchronized haversine shear and axial load pluses to a compacted HMA specimen. Similar to the RSCH test, the total shear load cycle of 0.7 seconds consists of 0.1 second load application followed by 0.6 second of rest, as illustrated in Figure 2-22. During the test, the ratio of the axial to the shear load is maintained constant within a range of 1.2 to 1.5. The test is performed by applying 5,000 shear load cycles or till the specimen achieves 5% of the permeant shear strain, whichever comes first. However, the researchers have found that some mixes may not show a tertiary rutting at the 5,000 cycles. Thus, the researchers adapted 10,000 cycles for performing the test. Researchers decided to conduct this test at temperature 55°C similar to the RSCH test. The permanent shear strain can be calculated as in the RSCH by using Equation 2-1 (Chowdhury & Button, 2002). RSCSR test is performed to identify the susceptibility of asphalt mixes to the tertiary rutting by measuring accumulated permanent shear strain (NHI, 2000).

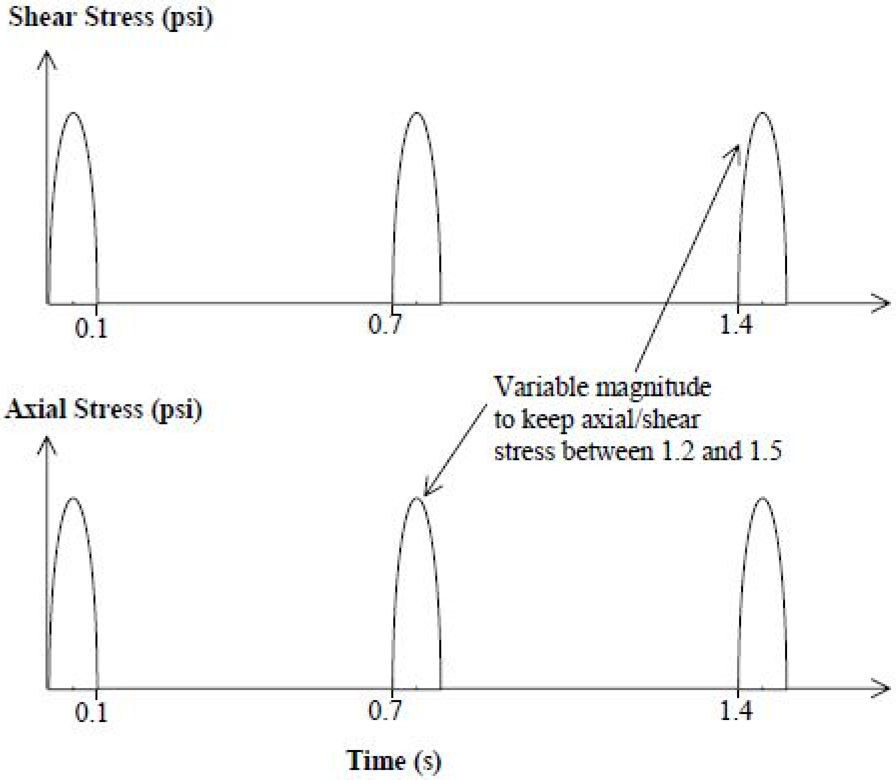


Figure 2-22 RSCSR Shear and Axial Stresses versus Time (Chowdhury & Button, 2002)

2.4.4 SST Test Procedure

The SST specimen can be prepared in a laboratory or cored from a pavement surface layer. It is a cylindrical asphalt specimen with 150 mm diameter and 50 mm maximum height. The height varies depending on the nominal maximum aggregate size (NMAS) of mixes. The NMAS is defined as one sieve bigger than the first sieve having at least 10% retained of total aggregates. The specimen height should be 50 mm for asphalt mixes with a 19 mm NMAS while a 38 mm height should be for mixes with 12.5, 9.5, and 4.75 mm NMAS (AASHTO T-320, 2004). However, researchers recommend the 50 mm as a standard height for the test specimens regardless the NMAS of asphalt mixes. This height represents the final height of the test specimen after the saw cutting process (Chowdhury & Button, 2002).

Typically, a primary gyratory compacted specimen should have a diameter of 150 mm and 75mm height after compaction. After the specimen is left to cool at room temperature, the top and bottom ends of the compacted specimen should be cut to achieve the 50 mm height.

After sawing, the specimen height and cut faces should be inspected. Both faces must be smooth and parallel to each other. The specimen height variation must not exceed 2 mm. Otherwise; the specimen should be discarded. Based on the intended SST test type, the number of specimens is determined. For example, five test specimens are preferred to perform the RSCH test while three specimens are sufficient for both the FSCH and SSCH tests (AASHTO T-320, 2004).

Specimens are often compacted in a laboratory with a higher air void percentage than the expected percent in the cut specimens. Those percentages depend on the SST tests type as specified in Table 2-5. The aim of increasing the air voids content in the specimen is that the specimen density will increase (lowering the air voids) after sawing the top and bottom ends.

Table 2-5 Appropriate Air Void Percentage for Compacted SST Specimens (AASHTO T-320, 2004)

Test	Air Voids, %
Repeated Shear Test	3.0 ± 0.5
Simple Shear Test	7.0 ± 0.5
Shear Frequency Sweep Test	7.0 ± 0.5

For the unconfined SST tests, two loading plates are glued at top and bottom of the test specimen. These plates are made of aluminum with thickness of at least 20 mm and diameter greater than the specimen diameter by at least 6.35 mm. They should be parallel to avoid any stress concentration while testing. An adhesive material of epoxy cement is used to bond the plates to the specimen ends. The epoxy should have at least 2,000 Mpa modulus. A thin layer of the epoxy is coated on the top of the specimen and on the bottom plate. Then the cylindrical specimen is centered on the bottom plate. The top plate piece is then lowered onto the top of the specimen at center. A light pressure of 35 kPa is applied for five minutes to assure sufficient bonding between the specimen ends and plates. A plate-specimen assembly device could be used to facilitate the bonding process by squeezing the specimen between the plates firmly as well as keeping the plates parallel. Figure 2-23 illustrates the concept of this device. Excess epoxy at the specimen sides should be removed once the specimen is compressed. Finally, the epoxy should be allowed to cure as recommended by the manufacturer (AASHTO T-320, 2004).

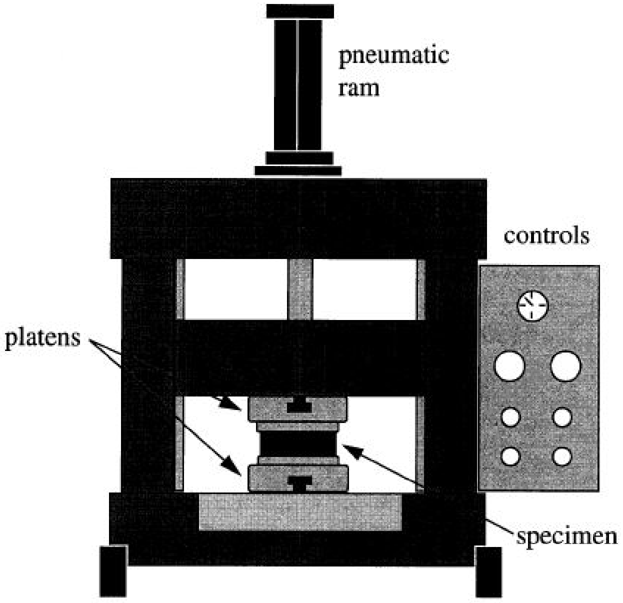


Figure 2-23 Conceptual View of the SST Plate Gluing Device (Kennedy, et al., 1994)

For the confined SST tests, on the other hand, same preparation procedure of the specimens should be followed as in the unconfined tests. However, the plates are placed at top and bottom of the specimen without the gluing process. Also, a rubber membrane underneath the attached radial LVDTs is placed around the specimen, as shown in Figure 2-24 (Kennedy, et al., 1994).

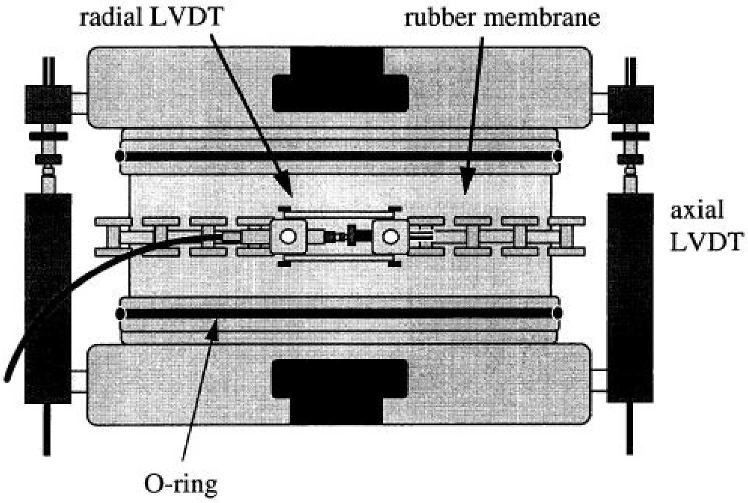


Figure 2-24 Set-Up of Confined SST Specimens (Kennedy, et al., 1994)

The SST hydraulic system should be warmed up at least one hour before launching the test. The specimen should be preconditioned also in the conditioning chamber from 2 to 4 hours followed that by the removing of the specimen from the chamber and the placing it on the shear table. Depending on the test procedure, appropriate axial, horizontal, and radial LVDTs should be attached to the specimen or specimen-plate assembly to measure the load and deformation responses. Only axial LVDTs are used for the confined SST tests (Volumetric and Uniaxial). The specimen is then centered between the vertical heads to be secured before closing the environmental chamber. The test after that can be launched (Chowdhury & Button, 2002) & (AASHTO T-320, 2004).

Once the test has been executed, the specimen should be cleaned from the plates. The specimen-plates assembly is placed in an oven for one hour at 135 °C so that the specimen can be removed. Then a scraper can be used to get rid of adhesive materials stuck on the plates. Any remained adhesive materials can be cleaned by using acetone, kerosene, or any other solvents (AASHTO T-320, 2004).

2.4.5 Evaluation of the SST

Chowdhury & Button, (2002) stated in the AASHTO provisional standard, Interim Guide for April 2001, that three tests of the SST were recommended to be adopted: the Simple Shear at Constant Height (SSCH), Frequency Sweep at Constant Height (FSCH) and Repeated Shear at Constant Height (RSCH) tests. The Volumetric and Uniaxial tests were eliminated because of the complexity of the test setup procedure rather than the lack of the test results accuracy. The RSCSR, on the other hand, provided similar properties like those provided by the RSCH.

Moreover, Chowdhury & Button, (2002) conducted a research study to identify the best SST test protocol among four SST tests for predicting the asphalt pavement performance. In that study, rutting performance of four different asphalt mixes was measured by using the FSCH, SSCH, RSCH, and RSCSR. The results obtained from the four SST tests were compared with results obtained from other three laboratory scale accelerated wheel loaded tests: the Asphalt Pavement Analyzer (APA), 1/3-Scale Model Mobile Load Simulator (MMLS3), and Hamburg Wheel Tracking Device. These tests measured the rutting susceptibility of same mixes. it was found that the two common SST tests, the FSCH and RSCH, are capable to ranking the asphalt mixtures like the three wheel loaded tests. Both tests proved also that they are sensitive in their measurements. However, the FSCH test was selected as the best test SST test protocol for many reasons. Two fundamental properties of asphalt mixes can be measured by FSCH test. Those properties include the phase angle and complex shear modulus of asphalt mixes which can be used for rutting and fatigue predictions. In contrast, the RSCH can only measure the permanent shear strain which is temperature dependent and not a fundamental material property. Also, FSCH minimizes the specimen damage during the test more than the RSCH test because the FSCH is a strain controlled test, and not a stress controlled test, like what RSCH is. Furthermore, Witczak, et al., (2002) reported that the data measured by the RSCH and FSCH have a good correlation to the field measured rut depth.

2.5 Overview for the Duplicate Shear Tester (DST)

Since the SST is an expensive device and complex test to perform, the Duplicate Shear Tester (DST) was developed as a new device to replicate the SST loading conditions. Based on the SST tests evaluations, the new device was developed to perform the two common SST tests: the RSCH and FSCH. The DST measures the fundamental shear properties of asphalt mixes by utilizing a Universal Test Machine (UTM). The UTM was used to make the DST a simple and inexpensive test. The UTM contains some components that make the DST able to perform a controlled shear test similar to that in the SST device (Khajeh-Hosseini, 2015).

The DST accommodates two cylindrical asphalt concrete samples. They should be prepared similar to that for the SST and obtained from a uniform asphalt mix that used for pavement surfaces layers. Each DST set consists of two specimens that are glued to an aluminum plate in the middle and to two steel plates on the sides. A load is applied on the aluminum plate to develop shear forces in the specimens. The procedure of performing the FSCH and RSCH were adopted in the DST to measure the average shear properties of the two asphalt mixes at the same time (Khajeh-Hosseini, 2015).

The DST device has proved its high repeatability and reliability in measuring the shear dynamic modulus and phase angle at load frequencies ranged from 0.5 to 10 Hz. It is also able to determine the permanent shear strain of asphalt mixes under cyclic loading in the RSCH test. However, the high variability of the measured shear parameters of asphalt concrete at low load frequencies have limited the DST reliability. Therefore, it was recommended for further improvements for the DST device to improve the testing procedure and to reduce the tests variability (Khajeh-Hosseini, 2015). Since the objective of this thesis is to modify the DST for more reliable outputs for the rutting prediction, the DST test and its improvements are discussed in details in the next chapter.

Chapter 3

Duplicate Shear Tester (DST)

In this chapter, the Duplicate Shear Tester (DST) is discussed in details. The first part of this chapter discusses the sample preparation, procedure, and evaluation of the DST device. The second part of this chapter illustrates the modifications to the new DST device.

3.1 Development of the Duplicate Shear Tester

3.1.1 Background

Although the SST device has proved its ability to measure the fundamental shear properties of asphalt mixes effectively and sufficiently enough for rutting prediction, the SST is a complex test and very expensive testing device. For these reasons, A Duplicate Shear Tester (DST) has been developed in the University of Texas at Arlington as a replacement test device to the SST. The observed SST advantages and deficiencies have been considered in this device. The DST is capable of performing the two common SST tests: the FSCH and RSCH, in accordance to the standard test method AASHTO-T320. However, the DST measures the average shear properties for two specimens loaded at the same time. Overall, the DST is a simple and inexpensive testing device that provides reliable and repeatable measurements for the fundamental shear properties and responses of asphalt mixes (Khajeh-Hosseini, 2015).

The loading condition and constraints of the SST have been considered in the DST. As explained previously, the SST applies a static or dynamic shear load to an asphalt specimen in a direction normal to the compaction axis. However, applying a shear load to the compacted specimen makes the aggregates in the mix to roll over each other causing an expansion, as shown in Figure 3-1. Since this expansion is resisted in field due to the HMA confinement, the SST simulates this confinement by maintaining the specimen height constant during the test (Pavement Interactive, 2008). A close-loop feedback system represented by LVDTs measures the axial deformation of the SST specimen and applies an axial force to neutralize this deformation and keep the specimen height constant. Figure 3-2 illustrates the SST loading condition. The Duplicate Shear Tester (DST), however, replicates the SST loading condition and constraints but for two specimens at the same time.

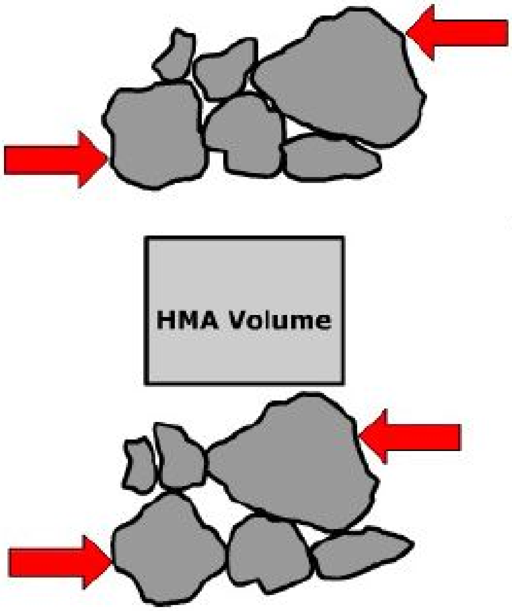


Figure 3-1 Change in the Volume of Compacted Sample Due to Shear Stresses (Pavement Interactive, 2008)

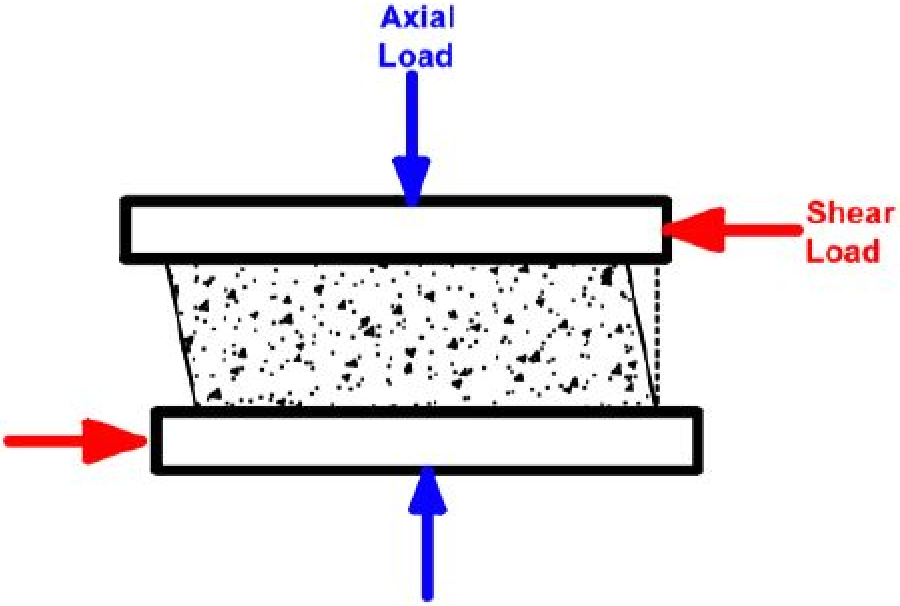


Figure 3-2 Illustration of the Superpave Shear Test Loads (Khajeh-Hosseini, 2015)

The DST device consists of two identical cylindrical specimens of asphalt mixes glued to an aluminum plate in the middle and to steel plates on the sides. The steel plates are fixed and tighten firmly together by threaten rods and nuts to maintain the test specimens’ height during the test. This prevents the specimens’ dilatancy. An axial load is applied on the aluminum plate between the two specimens to develop shear stresses on the specimens (Khajeh-Hosseini, 2015). Figure 3-3 illustrates schematically the DST load condition concept.

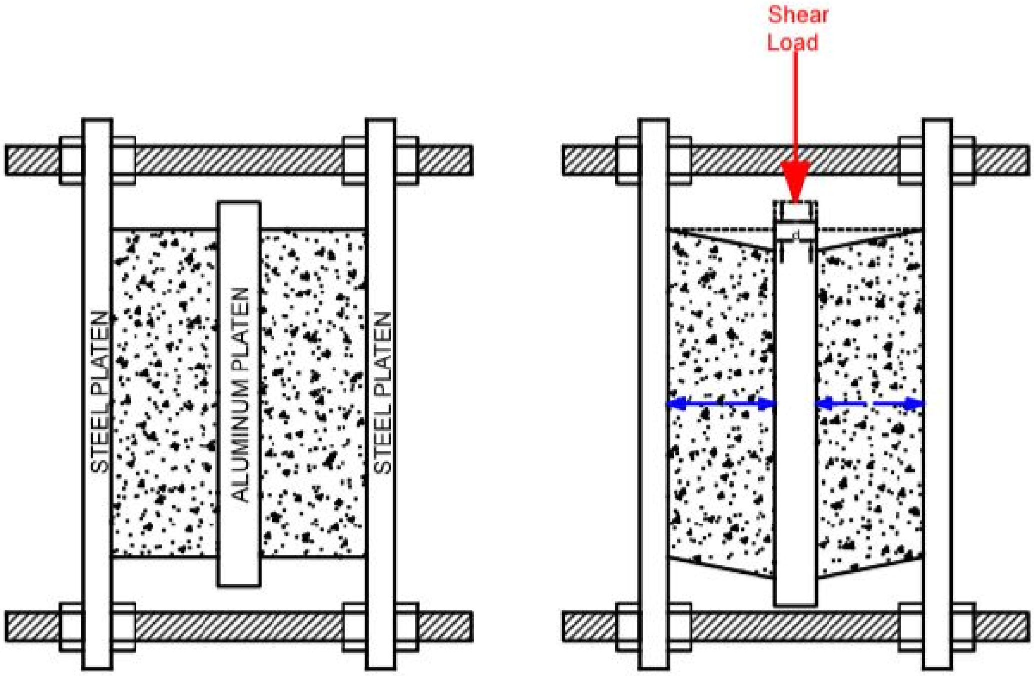


Figure 3-3 Simplifying view of the DST load condition (Khajeh-Hosseini, 2015)

Similar to the SST, the DST applies shear forces to the specimens, as well as it maintains their height constant during the test. When the axial load is applyied at the top of the aluminum plate, the specimens well be subjected to shear stresses. As a result, the specimens try to expand laterally causing normal forces on the aluminum plate and the steel plates. The normal forces are illustrated as blue arrows in Figure 3-3. Since the two specimens are identical because they are made of same asphalt mixes, it is assumed that the generated normal forces are equal. In spite of the developed lateral expansion, the DST maintains the specimens’ height constant by the fixed frame set up (Khajeh-Hosseini, 2015).

3.1.2 DST Description

As mentioned previously, the duplicate shear tester (DST) is a device that replicates the SST to measure the average mechanical shear properties of two asphalt specimens. It is a user friendly and inexpensive testing device. It consists of the following main parts:

- Two steel plates (10” ×10” × 0.5”).
- One aluminum plate (7” × 7” × 0.75”).
- Four threaded rods (0.5” standard size and 8.5” long).
- Sixteen nuts (0.5” standard).

The steel plates have a depression in one side with 1/16 inches depth and an average diameter of 5.9 inches. The middle plate of aluminum has also similar depressions but on both sides. Figure 3-4 shows the plates sections. These depressions are designed with an inner diameter of 5.85 inches and outer diameter of 5.95 inches to accommodate cylindrical specimens of asphalt mixes. These depressions contain an epoxy paste to glue the specimens to the plates as well as to assure placing the specimens at the center of the plates, as shown in Figure 3-3. Similar to the SST, the test specimens can be either compacted in a laboratory or cored from pavements surface layers; the cores must have a diameter of 150 mm (Khajeh-Hosseini, 2015).

As it is shown in Figure 3-4, the aluminum plate has four holes, whereas the steel plate has eight holes. The outer four holes of the steel plates are used to attach the steel plates together by using the threaten rods and adjustable nuts. The inner four holes of the steel plates along with the holes in the aluminum plate are used to line up the plates when assembling the DST (Khajeh-Hosseini, 2015).

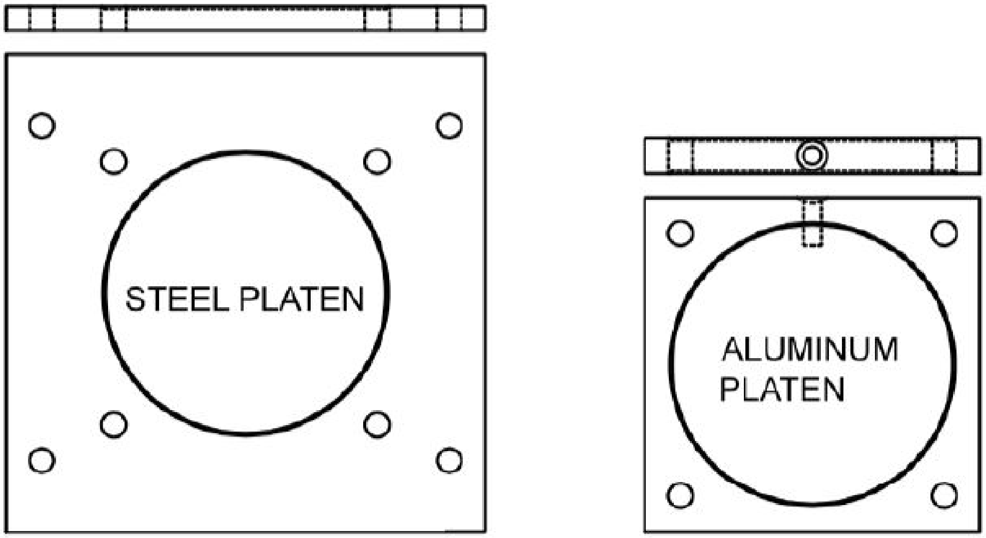


Figure 3-4 Steel and Aluminum Plates of the DST (Khajeh-Hosseini, 2015)

A universal test machine UTM-25, manufactured by IPC Global™, is utilized to perform the DST test. Using the UTM-25 device makes the DST simple and inexpensive. Furthermore, the UTM-25 includes some components that are essential to make the DST able to perform the controlled mechanical shear test similar to that in the SST device. Those components include: a loading system, a hydraulic system, a control and data acquisition system, and temperature control chamber. The loading system, including a vertical actuator and a loading frame, is capable to apply static and dynamic shear loads to the DST specimens. The loading system is supported and supplied with sufficient capabilities by the hydraulic system. While conducting the shear test, the data acquisition system is needed to control the loading levels, shape, and frequencies as well as record the specimens' response. The temperature chamber is used to perform the test at the specified temperatures. Utilizing the UTM-25 for performing the DST test not only reduces the DST's cost and complexity but also promotes the DST to be adopted universally (Khajeh-Hosseini, 2015).

Additional accessories have been developed for the DST device. Those fittings provide the ability to the UTM-25 to include the DST. They are simple and can be used for other universal testing machine. The accessories include: supporting plate, loading attachments, and LVDT mount (Khajeh-Hosseini, 2015).

The supporting plate is developed to make the UTM-25 applicable to accommodate the DST device as well as to assure an appropriate fixation of the DST to the UTM-25 loading frame. The supporting plate consists of a steel base plate with two guide rods and two grippers, as illustrated in Figure 3-5. The base plate is fixed to the loading table inside the UTM-25 loading frame by two bolts, and the grippers are fixed to the base plate by four bolts. Figure 3-6 shows the supporting plate installation inside the UTM-25 loading frame (Khajeh-Hosseini, 2015).

The loading attachments are designed to facilitate the UTM-25 for performing the DST tests. They provide a capability for the DST to perform the FSCH and RSCH tests. Depending on the shear test, a special attachment is mounted on the UTM-25 actuator ram. Figure 3-7 shows the loading attachments. The attachment used for the RSCH, is already an original attachment in the UTM that is used to perform compression tests. It can be used to perform the RSCH by applying shear loads in one direction (positive). This attachment is screwed into the UTM actuator from the upper side and attached to the DST aluminum plate from the lower side (Khajeh-Hosseini, 2015).

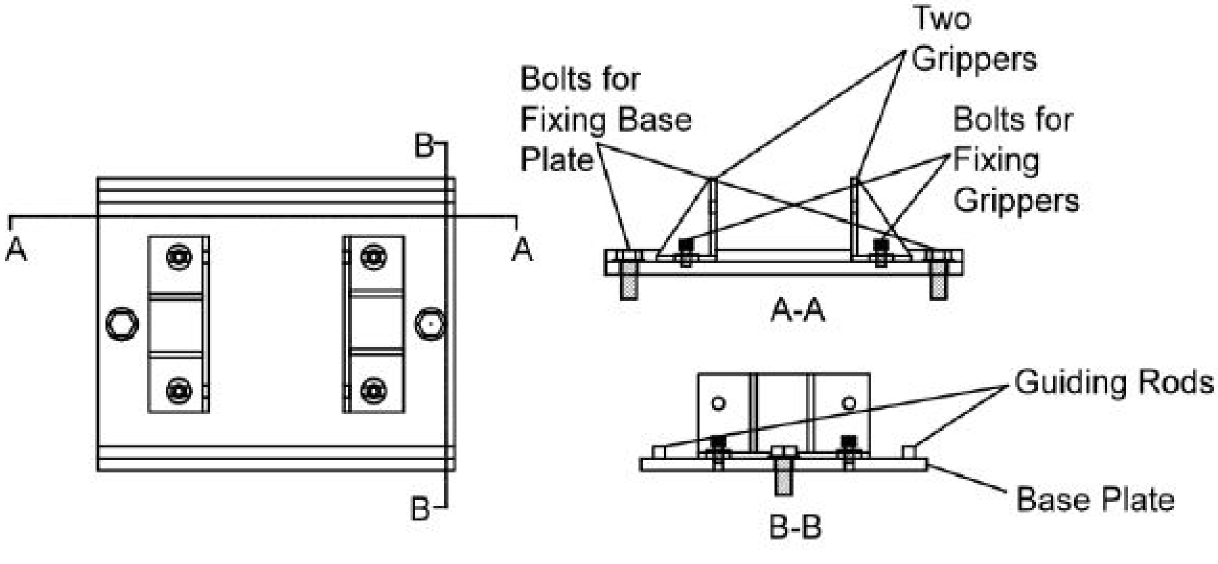


Figure 3-5 Supporting Plate of DST (Khajeh-Hosseini, 2015)

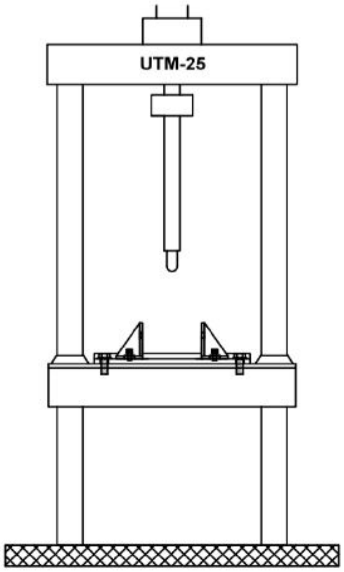


Figure 3-6 DST Supporting Plate Installed on the UTM-25 (Khajeh-Hosseini, 2015)

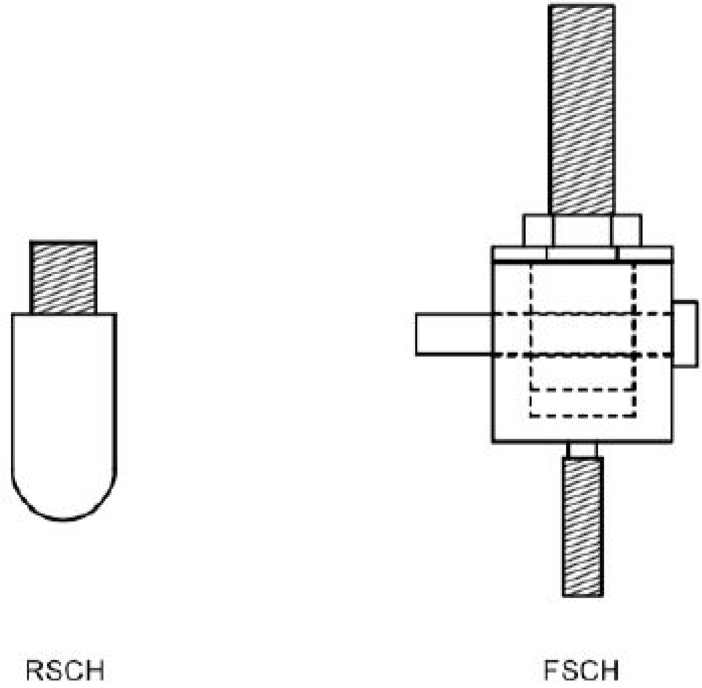


Figure 3-7 Loading Attachments for the DST (Khajeh-Hosseini, 2015)

The other loading attachment, shown in Figure 3-7, is specifically designed to the DST device for performing the FSCH. It provides the capability to apply dynamic shear loads in two directions (up and down). Figure 3-8 shows the coupling details. This coupling connects the UTM-25 actuator ram directly to the DST aluminum plate. It consists of two metal pieces linked firmly by a pin. Piece 1 is screwed in the middle at the top of the DST aluminum plate, while Piece 2 is screwed into the actuator ram of the UTM-25 (Khajeh-Hosseini, 2015).

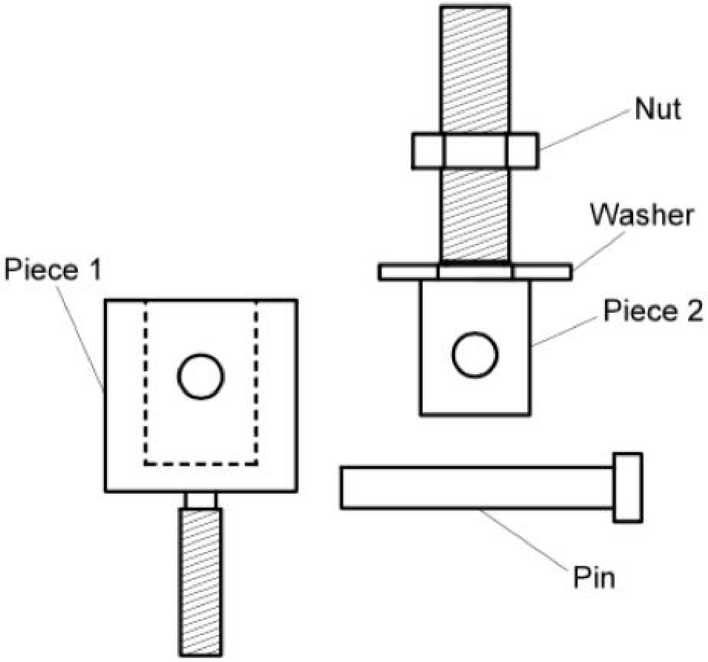


Figure 3-8 DST Coupling Attachment Details (Khajeh-Hosseini, 2015)

The Liner Variable Differential Transducers (LVDT) mounts hold axial LVDTs. The LVDTs are installed to measure the specimens' shear deformation by measuring the relative displacement between the aluminum plate and the steel plates. Two LVDT holders are fixed on the DST device assembly. Each mount consists of an aluminum LVDT holder, four steel clamps, a threaten rod, and four nuts, as shown in Figure 3-9. The threaten rod is fixed over the steel plates in a direction perpendicular to the plates plan. Two pairs of the steel clamps and the aluminum LVDT holder are fixed on the threaten rod. Each pair of the steel clamps is used to grab each of the steel plates at their ends. The aluminum LVDT holder is fixed in the middle of the threaten rod by an adjusting bolt. It attaches to the top of the aluminum plate and able to accommodate two different sizes of LVDTs (Khajeh-Hosseini, 2015).

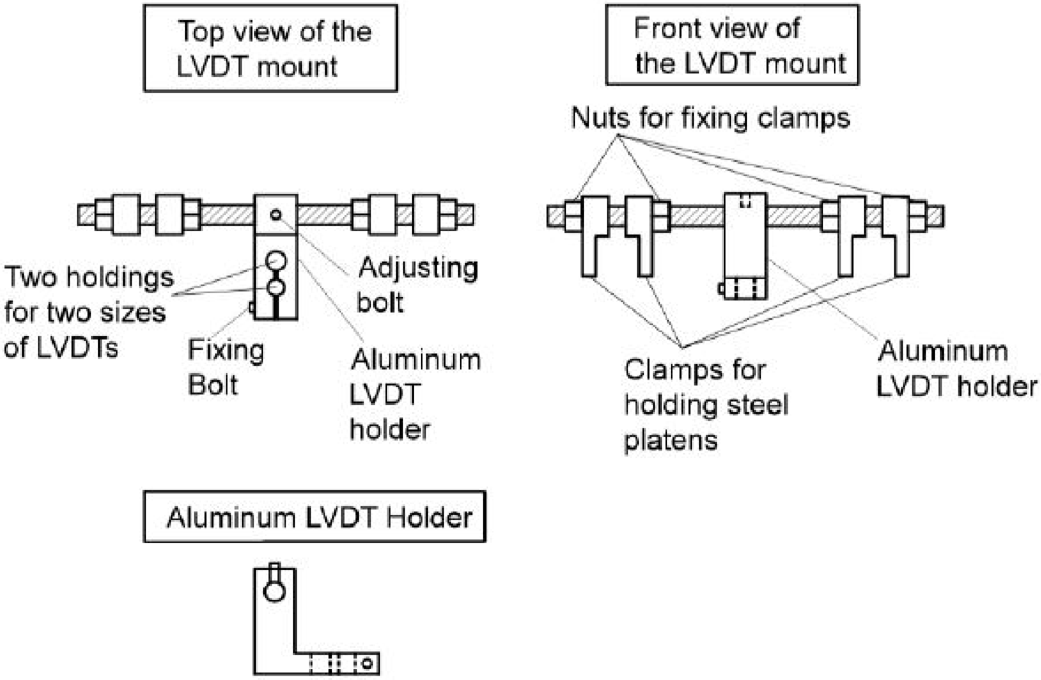


Figure 3-9 LVDT's Mount Components (Khajeh-Hosseini, 2015)

3.1.3 DST Sample Preparation

As discussed earlier, the DST device measures the mechanical average of shear properties of two asphalt specimens at the same time. Therefore, it is required to prepare two identical samples for each DST set. The specimens should be compacted in a Superpave Gyratory Compactor (SGC) according 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". DST specimen preparation includes compaction of mixture samples at a specific air voids percentage and cutting them to a specific height within the tolerance allowed by AASHTO T-320 (Khajeh-Hosseini, 2015).

Each pair of the test specimens should be obtained from a uniform asphalt mix. The asphalt mix should be used for surfaces layers because the rutting occurs in the upper two to four inches from the asphalt pavement surface (Khajeh-Hosseini, 2015). As recommended in the standard test method AASHTO T-320, the asphalt mix should be compacted to an air void percentage higher than the target percentage of the test specimens because the air void content of the test specimen will be reduced after cut process. The difference in air void percentages between the compacted and test specimens depends on the mixture gradation and NMAS. However, a 1.0 percent difference is enough to achieve an appropriate percentage of air voids in the test specimen (AASHTO T-320, 2004)

Khajeh-Hosseini (2015) conducted the DST test on four different asphalt mixes for the purpose of DST evaluation. He selected air voids of 7 % as the target for the DST test specimens for both the FSCH and RSCH tests. Therefore, asphalt mixes were compacted to a target of 8% air voids to achieve the desired 7% air voids after cutting. Asphalt mixes are compacted at specified temperatures based on performance grade (PG) of the asphalt binder used in the mix, as shown in Table 3-1.

Table 3-1 Mixing and Compaction Temperatures of Asphalt Mixes (Tex-241-F, 2005)

PG Grade	Mixing Temperatures	Compaction Temperatures
64 - 22	290 °F (143 °C)	250 °F (121 °C)
64- 28 and 70-22	300 °F (149 °C)	275 °F (135 °C)
70 -28, 76-16 and 76-22	325 °F (163 °C)	300 °F (149 °C)

Same procedure for cutting the SST specimens was adopted for the DST sample preparation. A wet saw of a 20 inches diamond blade was used to cut two test specimens of diameter 150 mm from each Superpave Gyratory sample, as shown in Figure 3-10. The gyratory sample was compacted to a height of 165 mm to perform two DST specimens. The cutting process should be performed one day after compaction; otherwise, specimens should be sealed by a plastic foil to prevent aging. While cutting the sample, the three saw cuts of average blade removal of 4.5 mm thick should be considered in order to end up with the two DST specimens of 50 mm thick of each (Khajeh-Hosseini, 2015).

Some volumetric measurements are needed before assembling the DST sets. The maximum theoretical specific gravity (Gmm) of asphalt mixes should be calculated according to the standard test method AASHTO T-209 “Theoretical maximum specific gravity and density of hot-mix asphalt”. The weight and height of each test specimen should be also determined after cutting. The height is measured with a caliper according to the standard test method ASTM-D3549. As specified in AASHTO T-320, any test specimen with a difference in height between the smallest and largest measurements more than 2 mm should be discarded. Also, air void percentage of each test specimen can be calculated by using Equation 3-1. However, it should be noted that the two test specimens of every DST set should be obtained from the same mix as well as their air voids percentages and heights should not differ more than one percent and two millimeters respectively. After the measurements, each pair of specimens should be kept inside a zip-lock bag to prevent aging (Khajeh-Hosseini, 2015).

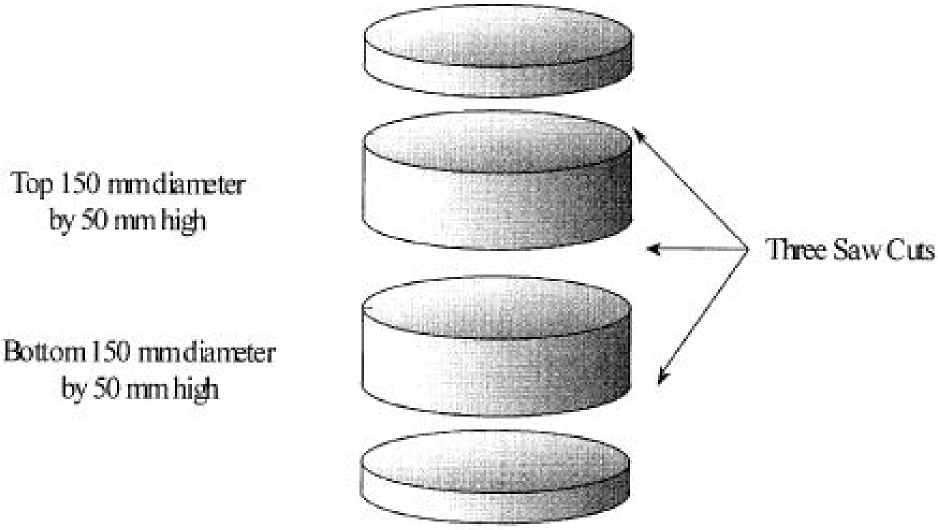


Figure 3-10 Fabricating Two Test Specimens from a SGC sample (Witczak, et al., 2002)

$$Mass = 17.671 \times Height \times Gmm \times (1 - AV) \tag{3-1}$$

Mass = Mixture batch weight (grams).

Height = Target compacted height (millimeters).

Gmm = Maximum theoretical specific gravity of the mixture.

AV = Percentage of air voids desired in decimals.

3.1.4 DST Procedure

As mentioned previously, the DST measures the average mechanical shear properties of two asphalt samples. The procedure of performing the FSCH and RSCH are adopted in the DST to measure the average complex shear modulus, phase angle, and the accumulated permanent shear deformation of two asphalt mixes simultaneously. The two test specimens should be produced from uniform mixes and compacted by using the SGC according to the standard test method AASHTO T-312. DST test specimens should be prepared similar to that for the SST specimens; according to the standard test method AASHTO T-320. The DST procedure include: assembling the DST sets, fixing the LVDT Mounts, conditioning the specimens, installing the DST on the UTM-25 Device, and performing the FSCH and RSCH tests utilizing the UTM-25.

To assemble the DST sets, test specimens should be glued to the plates and the threaten rods should be tightened properly. Khajeh-Hosseini, (2015) followed a special technique to glue the specimens to the steel and aluminum plates by using epoxy putty. Devcon™ Plastic Steel Putty (A) was used for gluing as it satisfied the AASHTO T-320 requirements for a quickest adhesive with a minimum modulus of 2,000 Mpa. Resin and Hardener are the two components of this epoxy that need to be mixed in a specific proportion according to the manufacture instructions. Since this epoxy needs 45 minutes to harden, a volumetric method is used to proportion the components to provide a sufficient epoxy quantity for assembling three DST sets at the same time within the 45 minutes. The 112.5 cm^3 of resin and 45 cm^3 of hardener were determined to provide the sufficient quantity of epoxy putty for three DST sets.

After preparing the epoxy paste, a thin layer of epoxy putty is applied in the middle of the first steel plate. The first specimen of asphalt is then placed in the middle on the steel plate inside the plate groove. The specimen is then pushed and rotated by hand to assure uniform bonding between the specimen and the plate. The first steel plate along with the specimen are then placed on the Plate-Specimen Assembly Stand, as shown in Step 1 in Figure 3-11. A level should be used to assure that the specimen surface is parallel with the steel plate. To check the center position of the first specimen, the aluminum plate is then placed temporary on the assembly stand; the specimen must be placed into the aluminum plate groove to be centered. The excess epoxy at the specimen edge should be removed, as well as it should be left for one hour or till the epoxy is hardened (Khajeh-Hosseini, 2015).

The steel plate along with the first specimen are then removed from the assembly stand. A thin layer of the epoxy putty is applied on the top of the first specimen, followed by pushing and rotating the aluminum plate over the first specimen till the epoxy gets out at the specimen edges. The whole device is then placed again on the assembly stand to assure the right position of the aluminum plate; the guide rods of the assembly stand assure the right position, as shown in Step 2. The process of leveling, removing excess epoxy, and hardening are then repeated similar to the Step 1. It should be mentioned that one corner of the aluminum plate is marked with a letter (B) to indicated its bottom. Similar label on the first steel plate is matched the aluminum mark at the same corner (Khajeh-Hosseini, 2015).

Similar to the procedure in Step 1 and 2, the second specimen of asphalt is glued over the aluminum plate. Also, the second steel plate is placed over the second specimen. Same procedure of leveling, positioning, and removing excess epoxy putty should be performed, as shown in Step 3 and 4. The whole DST device is then left on the assembly device for 24 hours at room temperature or until the epoxy is completely cured (Khajeh-Hosseini, 2015).

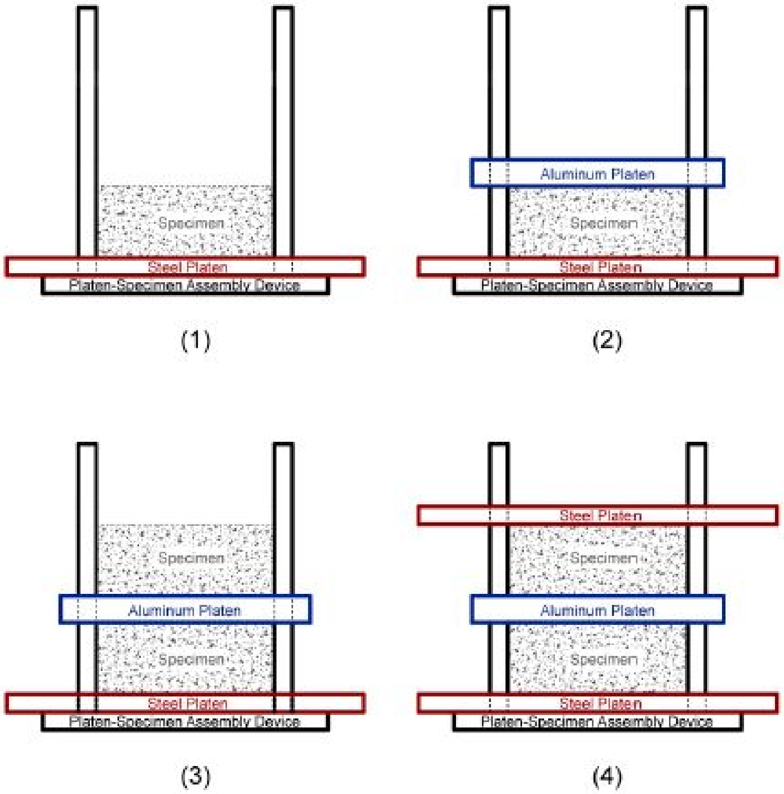
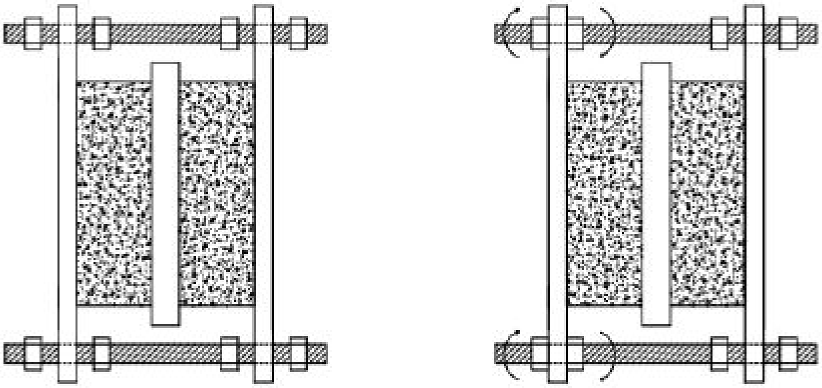


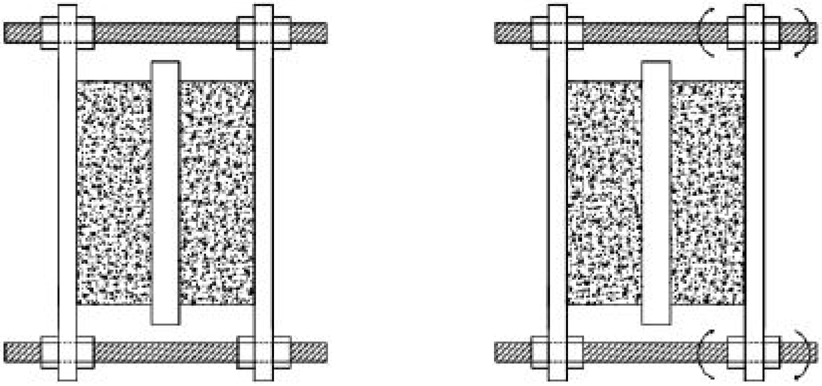
Figure 3-11 Gluing Process of DST Specimens (Khajeh-Hosseini, 2015)

Once the DST set is fully cured, it should be removed from the assembly stand to fix the tighten rods. The rods should be tightened firmly by nuts at both sides of one steel plate whereas the nuts on the second steel plate should be first tighten by hand only. After that, each pair of nuts on the second plate should be tighten at the same time for the rest pairs. This process of tightening prevents the development of axial forces through the specimens. Figure 3-12 illustrates the process of fixing the tightened rods and nuts (Khajeh-Hosseini, 2015).



Step 1, Put on the threaded rods and nuts

Step 2, Tighten the nuts on one side



Step 3, Hand tighten the nuts on the other side

Step 4, Tighten each pair of nuts with equal torques

Figure 3-12 Fixing Threaded Rods and Nuts on DST Plates (Khajeh-Hosseini, 2015)

Two LVDT mounts are then installed on the top of the DST set. The LVDT mounts should be placed exactly over the aluminum plate on its centerline. Their position should be symmetric in a way of 2.5 inch from the center of the aluminum plate, as shown in Figure 3-13 (Khajeh-Hosseini, 2015).

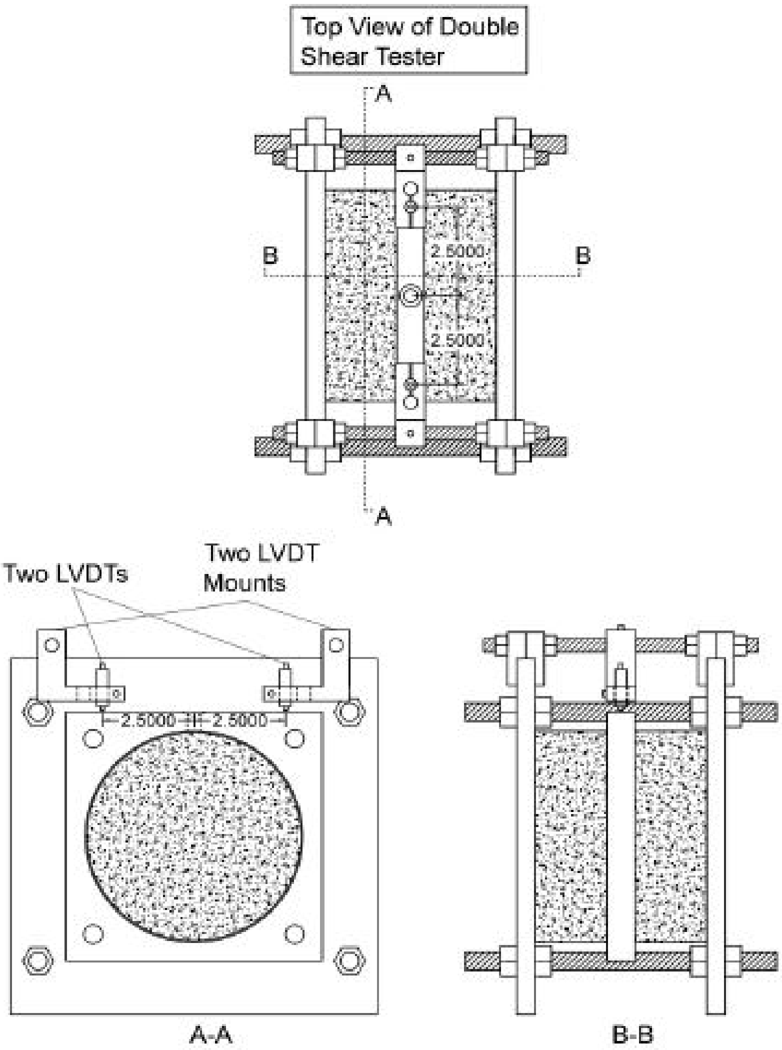


Figure 3-13 Position of the LVDT mount assembly on the DST (Khajeh-Hosseini, 2015)

The specimen sets are then preconditioned in an environmental chamber at a required test temperature. According to the standard test method AASHTO T-320, the FSCH test temperature should not be more than 12 °C below the high temperature grade of the asphalt binder used in the mixes. The RSCH test temperature is usually the 7-day maximum pavement temperatures at 50 mm depth for the project location. Theoretically, the FSCH is performed in the linear viscoelastic region, so the same specimens that have been tested by the FSCH can be used for the RSCH. This is because the RSCH affects the mixture properties by developing a permanent shear strain in the tested specimens. Therefore, it is considered a “destructive” test (AASHTO T-320, 2004).

Khajeh-Hosseini, (2015) preconditioned the DST sets inside the UTM-25 environmental chamber, which can provide temperatures between -15°C to 60°C with resolution of 0.2°C. Khajeh-Hosseini, (2015) selected test temperatures of 30 °C for the FSCH and 50 °C for the RSCH test based on asphalt binder grade used in the mixes and the maximum 7-day temperatures data respectively. The UTM-25 temperature chamber has enough room to accommodate three DST sets in addition to the one mounted on the loading frame. Three DST sets were preconditioned for 6 hours to conduct the FSCH test, and 8 hours for the RSCH test. To monitor and record the temperature during the test, a thermometer was inserted inside a dummy asphalt specimen with a diameter of 4 inches and a height of 6 inches.

After conditioning the DST sets, the whole DST device is installed inside the UTM-25 device, as shown in Figure 3-14. Depending on the test procedure, the proper loading attachment should be first fixed into the actuator ram. The DST set is then placed on the DST supporting plate on the UTM supporting table and the LVDTs are installed into the LVDTs mounts. The DST set is then fixed on the supporting plate by gripping the gripper bolts and nuts. Next, the loading attachment is fixed properly depending on the test procedure once for the RSCH and another for the FSCH test. For the RSCH test, the supporting table is moved up till the loading attachment gets close to the depression of the aluminum plate. The supporting mount is then adjusted to line up with the loading attachment. Then the actuator ram is lowered slowly till the loading attachment touches the surface of the aluminum plate depression. At this stage, the stress level on the actuator should be monitored to prevent any excessive stresses to the specimens. The set up for the FSCH test is similar to that for RSCH process, but the difference is that the upper edge of the coupling should be lined up with the lower edge of coupling before moving the supporting table up to pushing them inside each other. The pin is then inserted to link the coupling (Khajeh-Hosseini, 2015).

The last step is to fix the whole DST set on the loading table. First, the position of the supporting plate on the UTM loading table is fixed by tightening its bolts. Then, to fix the DST on the supporting plate, the adjusted bolts on the grippers are tightened. Only for the FSCH test, the nut on the coupling is tightened at the end while the stress level on the actuator is monitored similar to the RSCH. Figure 3-15 and 3-16 illustrate the installing steps for the RSCH and FSCH respectively (Khajeh-Hosseini, 2015).

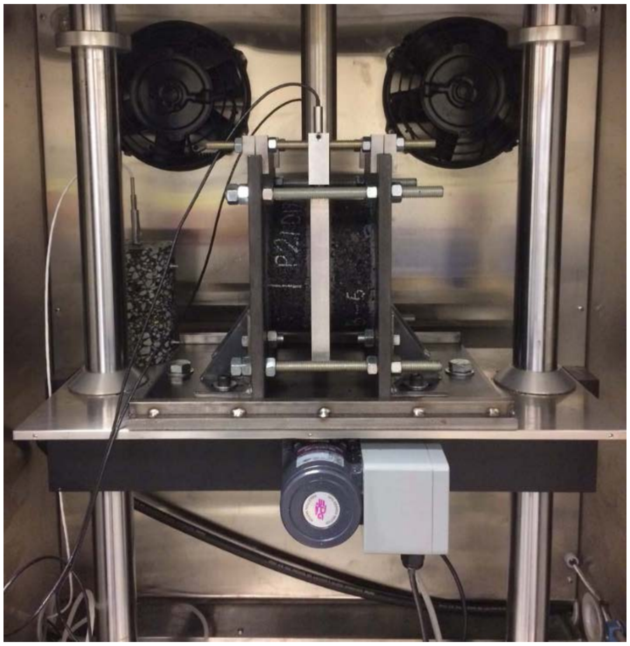


Figure 3-14 The DST installed on the UTM-25 Loading Table (Khajeh-Hosseini, 2015)

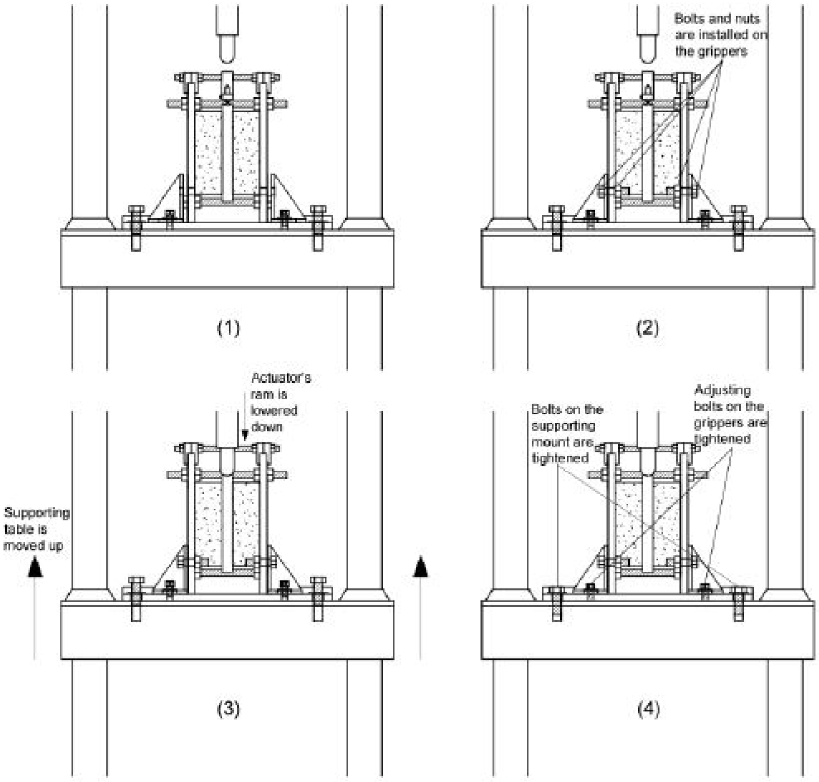


Figure 3-15 Installing the DST on the UTM-25 for the RSCH Test (Khajeh-Hosseini, 2015)

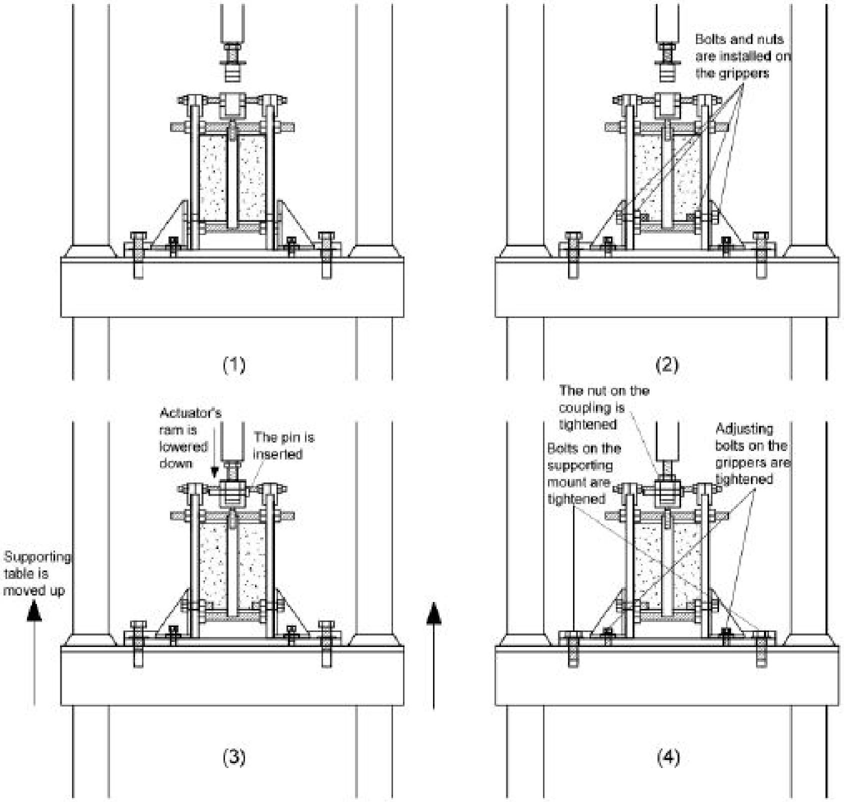


Figure 3-16 Installing the DST on the UTM-25 for the FSCH Test (Khajeh-Hosseini, 2015)

Once the DST set is installed and fixed on the UTM-25 loading table, the shear tests can be performed. As mentioned previously, the DST device adopted the FSCH and RSCH tests to measure the average shear properties of two asphalt specimens at the same time. To execute the FSCH test, the UTS-023 test software developed by IPC Global™ for the Dynamic Modulus test is used to perform the FSCH test for the DST. This program is usually used to measure the dynamic modulus for mixes under dynamic compressive axial force. However, by modifying some inputs for the specimen diameter and gauge distance, the shear dynamic modulus of asphalt mixture can be obtained. Since the load will be applied on the two identical specimens with a diameter of 150 mm and height of 50 mm, the input diameter for the UTS-023 should compensate for the shear area of the two specimens. The input diameter is modified to be 212.13 millimeter while the gauge distance is set as 50 millimeters. The gauge distance represents the specimen height or the average distance between the aluminum and steel plates (Khajeh-Hosseini, 2015).

Before conducting the FSCH test, some data should be determined and entered in the UTS-023 program as test parameters. It is required to determine the appropriate level of shear stresses for each mix at all test frequencies. The UTS-023 software can determine these levels by running the "tune condition" which allows to apply a dynamic load to the specimen and measure the parameters. Determining the proper maximum and minimum shear stress level should be measured from the highest to lowest frequencies for each mixture. Those levels along with the number of load cycles for each of the ten frequencies should be entered in the "Test Parameters" tab in the software. After that, the FSCH test can be executed and the shear stress and stain at each frequency are recorded. The average dynamic modulus and phase angle at each load frequency are then calculated by the software (Khajeh-Hosseini, 2015).

Once the FSCH tests are completed on DST specimen pairs, the specimens are tested again using the RSCH test procedure at the required temperature. To perform the RSCH test, the UTS-014 test software is used to measure the permanent deformation of asphalt specimens under repeated cyclic pluses or static axial load. This program was developed by the IPC Global™. Similar to the FSCH test, the diameter and gauge distance are modified as inputs to the software to measure permanent deformation of asphalt mixtures. As specified in the standard test method AASHTO T-320, the RSCH is performed by applying haversine cyclic loads with a stress limit of 69 kPa. In addition, a seated stress of 3.4 kPa is selected to assure proper seating of the actuator on the aluminum plate as well as to reduce the stress error during the test. The repeated cyclic load of 5,000 cycles is applied for a period of 0.1 second follows that by a rest period of 0.6 second. The reading results of shear stresses and strain are recorded and the average shear permanent deformation of specimens is calculated by the software (Khajeh-Hosseini, 2015).

3.1.5 DST Evaluation

Khajeh-Hosseini, (2015) performed DST tests utilizing UTM-25 to measure the shear parameters for four different asphalt mixes. The mixes were dense graded hot asphalt mixes except one mix was a Stone Matrix Asphalt (SMA). Khajeh-Hosseini, (2015) selected three sets of specimens from each mix to perform the FSCH and RSCH procedures using the DST. The results obtained from the FSCH and RSCH tests were analyzed to study the reliability and repeatability of the test measurements through studying the coefficient of variation (COV) of the results.

The results obtained from the FSCH test proved that the repeatability and reliability of the DST to measure the dynamic shear modulus and phase angle of asphalt mixes at load frequencies ranged from 10 to 0.5 Hz whereas the results obtained at low frequencies have limited the DST due to a high variability. Table 3-2 summaries the FSCH test results for shear dynamic modulus and phase angle of the four mixes at 30°C. It can be observed from the table that the average values of the shear dynamic moduli of all mixes decreased as the load frequency decreased while the phase angle followed unclear trend with the load frequency. Moreover, the degrees of variation in the shear dynamic moduli of the dense graded mixtures (Mixes 1, 2 and 4) were generally lower than or close 10 % at load frequencies of 0.5 Hz to 10 Hz. Similarly, for these mixes, the COVs of the phase angle were low at load frequencies of 0.5 Hz to 10 Hz (Khajeh-Hosseini, 2015).

However, the COVs for the SMA mixture (Mixture 3) are relatively high for the shear dynamic modulus and the phase angle at all frequencies. The high variations of this mixture might be happened due to the difficulty in hand working and compacting of the SMA specimens comparing with the others of the dense graded mixes (Khajeh-Hosseini, 2015).

Table 3-2 Summary of the FSCH Test Results, Shear Dynamic Modulus and Phase Angle (Khajeh-Hosseini, 2015)

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	**707.3**	**521.3**	**384.7**	**306.0**	**245.7**	**179.7**	**147.7**	**122.7**	**94.3**	**81.7**
	COV %	4.3	3.4	4.6	6.5	7.7	11.2	15.0	19.1	24.8	30.8
Mixture 2	Average	**1145.0**	**920.3**	**701.0**	**569.0**	**469.0**	**342.3**	**267.7**	**213.0**	**160.0**	**129.7**
	COV %	6.4	7.0	7.8	8.4	8.7	10.0	10.7	11.7	13.8	15.5
Mixture 3	Average	**802.7**	**622.7**	**455.3**	**375.7**	**306.3**	**225.0**	**180.3**	**147.3**	**111.7**	**92.7**
	COV %	18.7	22.7	25.9	27.9	30.1	34.7	39.4	44.1	50.7	56.3
Mixture 4	Average	**1099.0**	**848.3**	**621.3**	**481.0**	**386.3**	**288.7**	**232.7**	**195.3**	**156.0**	**138.3**
	COV %	8.7	9.1	10.5	11.2	11.8	14.2	13.3	13.6	13.5	14.8
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	**31.4**	**33.4**	**33.8**	**33.8**	**31.3**	**23.9**	**22.8**	**26.9**	**26.3**	**27.1**
	COV %	1.4	1.5	2.9	3.9	7.9	8.9	11.9	9.8	11.6	13.5
Mixture 2	Average	**24.4**	**26.2**	**27.9**	**29.1**	**27.8**	**21.7**	**21.9**	**27.0**	**27.2**	**29.1**
	COV %	3.6	6.0	5.7	5.6	3.7	8.1	9.4	8.0	9.2	8.8
Mixture 3	Average	**27.2**	**29.8**	**31.7**	**32.0**	**30.1**	**23.2**	**22.8**	**26.9**	**26.6**	**27.9**
	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**	**29.3**	**31.3**	**32.8**	**31.8**	**23.8**	**22.8**	**26.6**	**25.4**	**26.0**
	COV %	2.7	3.6	4.1	3.7	4.3	7.1	7.5	8.2	9.6	10.4

The results obtained from the RSCH test, on the other hand, proved the ability of DST to measure the permanent shear deformation of asphalt concrete under cyclic loads. Table 3-3 summaries the average values and COVs of the measured permanent shear deformation of each mixes at 2,845 and 5,000 loading cycles at 50°C. It can be observed from the table that the average values of the permanent shear deformation of the dense graded mixes are close together whereas the SMA mix has the lowest average shear permanent deformation. This is because the SMA mixtures usually resist permanent deformation better than the dense graded mixtures. However, it is recommended to perform more than three permanent shear deformation tests for each mixture due to the mild variability that has been observed for each mixture (Khajeh-Hosseini, 2015).

Table 3-3 Summary of the RSCH Test Results, Shear Permanent Deformation. (Khajeh-Hosseini, 2015)

RSCH- Shear Permanent Deformation (%)			
Mixture 1	Cycle	2,845	
	Average	**0.8701**	
	COV %	10.35	
Mixture 2	Cycle	2,845	5,000
	Average	**0.8658**	**0.9777**
	COV %	11.94	12.74
Mixture 3	Cycle	2,845	5,000
	Average	**0.7512**	**0.822**
	COV %	10.94	9.73
Mixture 4	Cycle	2,845	5,000
	Average	**0.9448**	**1.0717**
	COV %	9.02	9.4

In general, the DST can be adopted as a new simple performance test device for quality control and quality assurance tests. It can measure the fundamental shear properties of asphalt mixes at low cost and without any complexity. However, further improvements are needed in this device to reduce the results variability and enhance the pavement performance prediction models for rutting resistance (Khajeh-Hosseini, 2015).

3.2 The Modified Duplicate Shear Tester (DST)

3.2.1 Modification Objectives of the DST

In previous section, the DST was developed to replace the SST device for measuring the fundamental shear properties for asphalt mixes in a laboratory. Even though the SST device has proved its capability to measure the shear properties of asphalt mixes accurately and effectively, the high cost and complexity of the SST device have limited this device to be used widely. Among the six SST tests, the FSCH and RSCH tests were recommended to be used for measuring the shear stiffness and cumulative permanent shear deformation of asphalt mixes to estimate the rutting susceptibility. The DST device developed by Khajeh-Hosseini (2015) has replicated those two tests according to the procedures and recommendation of the standard test method (AASHTO-T320). It proved its capability to measure the average mechanical shear properties of two specimens at the same time easily and simply by utilizing the UTM-25. However, the high variability of the measured shear parameters at low loading frequencies have limited the DST reliability.

The DST variability could be caused due to many factors including: improper gluing to the specimens, materials variation, improper compaction and imperfect vertical movements of the aluminum plate. Since the DST set was fixed tightly by threated rods, as well as the specimens were made of the same mix and had almost same dimensions, Khajeh-Hosseini (2015) assumed that the specimens confined each other by applying identical normal forces to the aluminum plate; thus, means the specimen height remains constant during the test. However, the DST design does not ensure the perfect vertical movements to the aluminum plate. Therefore, it was decided to modify the DST device by adjusting its geometry at low cost to:

1- Include a linear guides system to ensure vertical movements of the aluminum plate.
2- Assess the variability of the results obtained with the improved device through conducting the FSCH and RSCH tests.

3.2.2 Main Modifications to the (DST) Device

The DST was modified at the University of Texas at Arlington by adjusting its geometry to be include a linear guides system to assure perfect vertical movements of the aluminum plate. The developed system for the DST device is a “Mini-Rail Miniature Linear guides”. This system usually consists of two lightweight aluminum pieces: a carriage and a linear rail. The carriage is mounted on the linear rail to provide smooth, gliding, and precise motion in a straight line with less vibration, as shown in Figure 3-17. The carriage contains linear sleeve bearings, that are suitable for dirty or corrosive environments. It is also able to withstand relatively high applied loads (Gamut, 2017). The Mini-Rail Linear Guides is an economic system that is manufactured at many standard sizes to be suitable for linear movement applications. Also, this system has no rolling elements which makes it safe against any catastrophic failure during movement (Pcblinear, 2017).

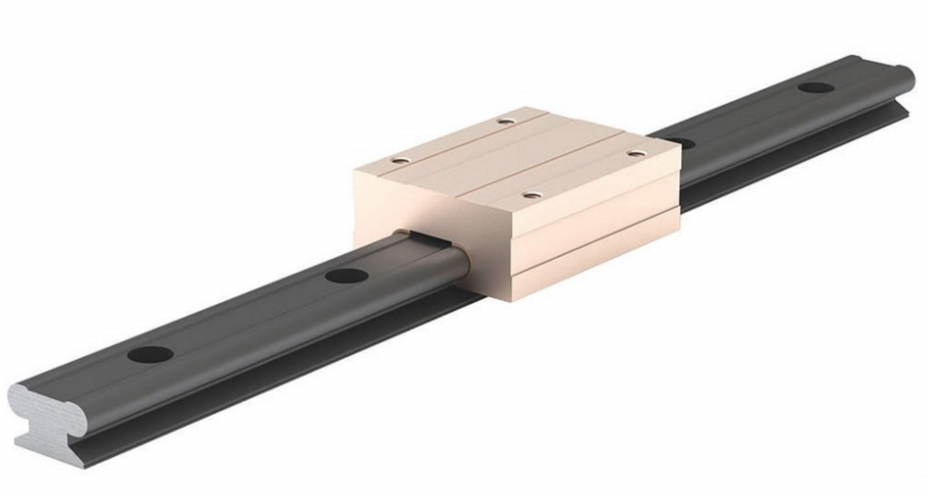


Figure 3-17 Mini-Rail Miniature Linear Guides System (Gamut, 2017)

To utilize the linear guides system for the DST device, two segments of the standard 12 mm mini-linear rail of 150 mm length were fixed permanently on the aluminum plate sides using screws. The DST supporting plate is modified also to accommodate the whole DST set. Two vertical stands of steel were fabricated and fixed on the supporting plate to carry two carriages on each side, as shown in Figure 3-18. Each stand consists of two vertical pieces: a flat and a square piece. The flat pieces of 7 in length, 5.5 in width and 0.5 in thickness were welded vertically to the sides of the supporting plate at center in order to hold the square pieces. The square pieces of 6.5 in length and 1.0 in width were fixed vertically on the flat pieces by three screws each. The second pieces were not welded to allow for any potential adjustability needed after welding. On each stand, two carriages of the linear guides system were fixed on the square piece by screws. The location of the stands along with the carriages were determined precisely so that the rails can slide easily inside the carriages after mounting the DST set on the supporting plate.

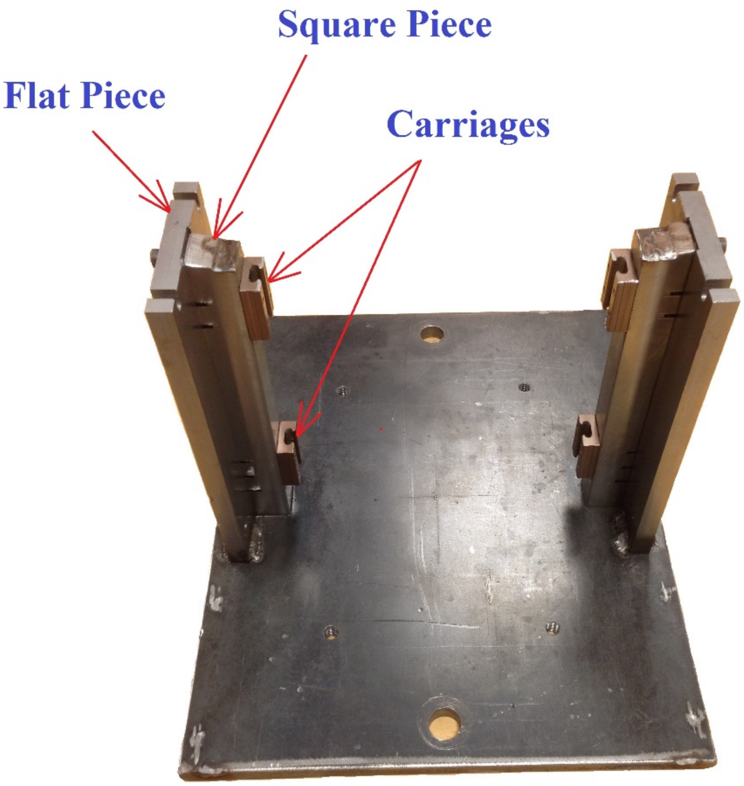


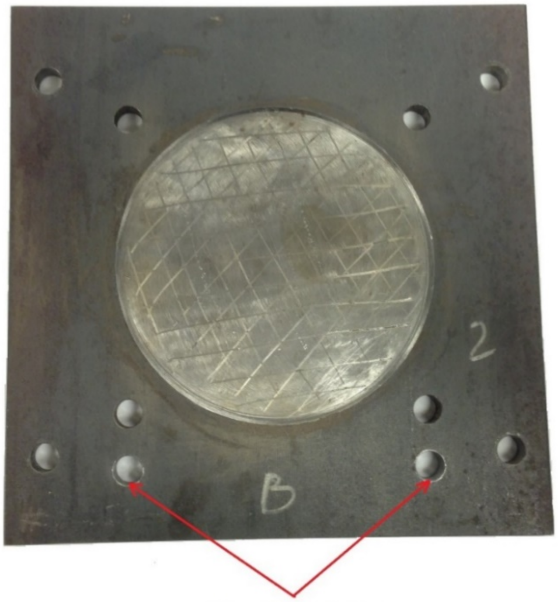
Figure 3-18 The Modified DST Supporting Plate

3.2.3 Other Modifications to the DST parts

Some imperative adjustments were done to the DST components to facilitate the linear guides system at low cost, while others to expedite the installation process. Those adjustments include:

- Location of the lower threated rods.
- Grippers geometry.
- Aluminum plate dimensions.

The previous geometry of the DST did not facilitate the new linear guides system. The location of the two threated rods at the bottom of the DST device interrupts the additional linear guides system, since the threated rods at bottom touch the new stands of the linear guide system. Therefore, it was decided to change the locations of the two threated rods at the bottom by drilling two new holes in the steel plates instead of fabricating new steel plates. In the modified DST device, the bottom threated rods are designed to pass under the aluminum plate, so the additional two holes were located just under the bottom interior holes of the steel plates with a space of half an inch. Figure 3-19 shows a modified steel plate.



The New Holes

Figure 3-19 A DST Steel Plate with the additional Two Holes

In addition, two new slots were required to be drilled on the grippers walls to correspond to the new holes in the steel plates. The threated rods of the previous DST device used to tight the steel plates with no interruption with the grippers at the bottom. In the modified DST, the new locations of the bottom threated rods interrupt with the DST grippers because the threated rods pass through the grippers walls. However, instead of replacing the previous grippers, it was decided to drill each gripper with additional two slots of 0.5-inch width and 1-inch length to match the position of the threated rods at the bottom of the modified DST device, as shown in Figure 3-20. The idea of making slots not holes is to allow adjustability while fixing the DST set on the supporting plate. It should be mentioned that the grippers will be considered as a part of the DST set since they will be mounted on the bottom threated rods at the time of assembling the device.

Furthermore, other slots of 3/8 in width and 1.25 in length were created to the grippers base. The base of the gripper in the previous DST device used to have two holes. Those holes matched the locations of other two holes on the supporting plate that are used to connect the DST set with the supporting plate by using adjusting bolts, as mentioned previously in step 4 in Figures 3-15 and 3-16. For the new DST device, those holes are adjusted to be slots, as shown in Figure 3-20. The slots at base help to fix the DST set on the supporting plate precisely and flexibly by matching the exact locations of the grippers holes on the supporting plate. This kind of adjustment is required to avoid any potential mismatching between the grippers and their location on the supporting plate when there is a minor variation in height between the two DST specimens.

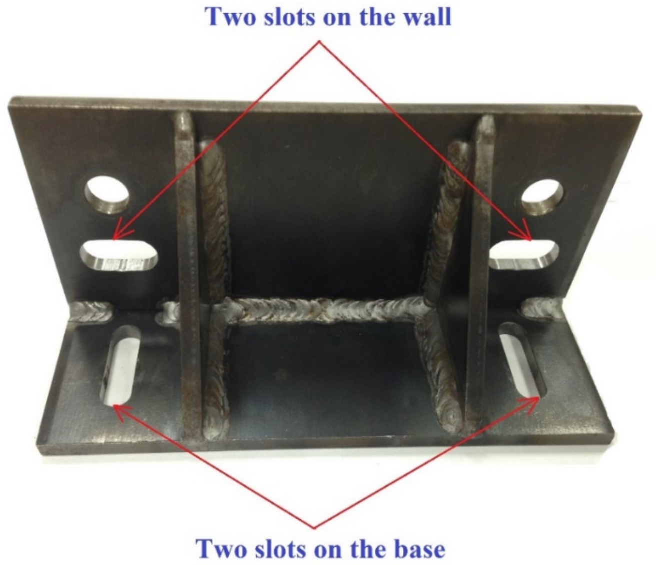


Figure 3-20 The Modified DST Gripper with new Slots

Beside the two linear rails that fixed on the aluminum plate sides, the aluminum plate dimension is adjusted to make the DST capable to perform shear tests with no interruption with the underneath threated rods. A quarter of inch (6.35 mm) of material was shaved along the bottom of the aluminum plate so that the aluminum plate can move vertically. In this case, the height of the aluminum plate will be 6.75 inches instead of the 7 inches. Figure 3-21 shows the modified aluminum plate.

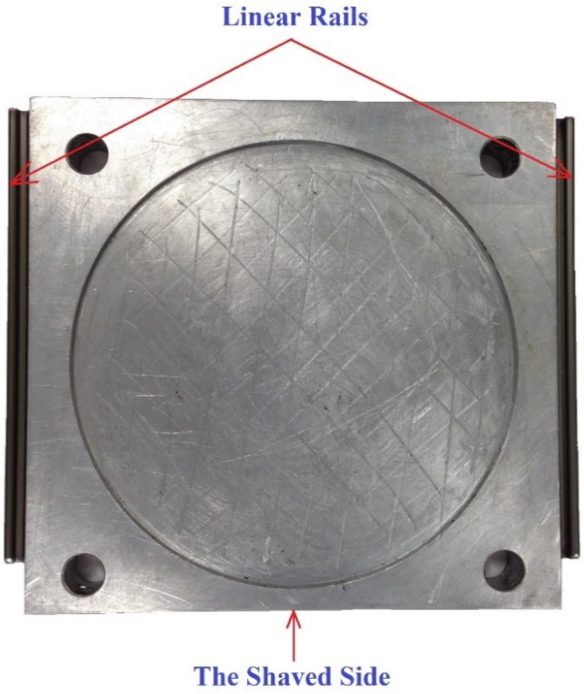


Figure 3-21 The Modified DST Aluminum Plate

3.2.4 Loading Conditions and Constraints of the Modified DST

The loading conditions and constraints of the Modified DST are similar to that in the previous DST except that the modified device has a linear guide system. The modified (DST) replicates the SST loading conditions and constraints but for two asphalt specimens sheared at the same time. It accommodates two identical cylindrical asphalt specimens prepared similarly to the SST samples. Those specimens are glued to an aluminum plate in the middle and to steel plates on the sides. An axial load is applied on the top of the aluminum plate between the two specimens to develop shear stresses on the specimens. As a result, the specimens try to expand laterally in a direction normal to the applied shear forces, as shown previously in Figure 3-3. This dilatancy in specimens is prevented by tightening the two steel plates firmly together using threated rods and adjustable nuts. The rigid frame set-up of the DST along with the linear rails maintain the test specimens' height constant during the test as well as ensure the vertical movement to the aluminum plate.

3.2.5 The Modified DST set Components

The modified DST set consists of the following parts:

- Two steel plates (10" ×10" × 0.5").
- One aluminum plate (7" × 6.75" × 0.75").
- Two Mini-Linear Rails of aluminum (6" length).
- Four threaded rods (0.5" standard size and 8.5" long).
- Sixteen nuts (0.5" standard).
- Two grippers.

Similar to the original DST device, the steel plates are designed to have a depression in one side with 1/16 inches depth and an average diameter of 5.9 inches. The middle aluminum plate has also designed with similar depressions but on both sides, as illustrated previously in Figure 3-4. The depressions are designed with an inner diameter of 5.85 inches and outer diameter of 5.95 inches to accommodate cylindrical specimens of asphalt mixes with a diameter of 150 mm. These depressions will contain an epoxy paste to glue the specimens to the plates surfaces as well as to assure placing the specimens at the center of the plates.

The aluminum plate has four holes at corners, whereas the steel plate has eight holes. In the steel plates, the outer four holes of the steel plates are used to attach the steel plates together by using threated rods and adjustable nuts after gluing the specimens. The inner four holes of the steel plate match the locations of the aluminum plate holes. Those holes are used only to line up the DST plates to be centered while assembling the DST set.

The 12 mm standard Mini-linear Rail segments are attached to the aluminum plate sides, as shown in Figure 3-21. The 150 mm rails are fixed permanently on the right and left sides of the plate by six screws on each side. These segments are parts of the developed “Mini-Rail Linear Guides” system. Their aim is to allow the aluminum plate to slide inside the “Mini-Carriages” on the vertical stands of the supporting plate performing the tests.

Four threated rods with adjustable nuts are used to tighten the steel plates firmly together after the gluing process of the specimens. These rods connect the two steel plates of the DST together from the top and bottom. Also, they connect the modified grippers with the steel plates at the bottom.

Chapter 4

DST Test Methodology, Results and Discussion of the Results

In this chapter, the modified DST is evaluated through conducting the FSCH and RSCH tests according to the standard test method (AASHTO T-320). Two asphalt mixes used in Texas for surface and intermediate layers were selected to perform the test specimens. The procedure of preparing the specimens and performing the tests are also described in this chapter. Finally, the variability of the measured shear dynamic modulus, phase angle, and permanent shear deformation are analyzed to evaluate the variability of the test results with the modified device.

4.1 Asphalt Mixes

In Texas, the asphalt concrete mixtures are selected for flexible pavement construction based on traffic load, speed, and expected pavement performance. Dense-Graded Asphalt mixture (DGA) is one of those mixes that is usually used in pavement layers such as base, intermediate, and surface layers that subjected to low or moderate truck traffic. The DGA is a composite of well-graded aggregates that have a gradual change in gradation from course to fine aggregates (Texas Asphalt Pavement User Guide, 2017). The DGA mixtures have been used in Texas for more than 50 years and proved a well performance in different applications. Comparing to other asphalt mixes such as Stone Matrix Asphalt (SMA) and Permeable Friction Course (PFC), the dense graded mix has lower initial cost. Also, most contractors and HMA producers are familiar with its production and construction (Smit et al., 2007).

The dense graded mixes are classified for five different types (A, B, C, D, and F) in the TxDOT specifications, Items 340 and 341. Those types were classified based on the nominal aggregate size of each type; type A has a largest nominal aggregate size while type F has the lowest. Each type of the DGA has been determined in the specification to be used for a typical location of pavement layer. Table 4-1 shows the dense graded mix types and their uses (Smit et al., 2007).

Table 4-1 Dense-Graded Asphalt Mix Types (TxDOT specifications)

Mixture Type	Nominal Aggregate Size (in)	Minimum Lift Thickness (in)	Maximum Lift Thickness (in)	Typical location of Pavement layer
Type A	1 1/2	3.0	6.0	Base
Type B	1	2.5	5.0	Base/Intermediate
Type C	3/4	2.0	4.0	Intermediate/Surface
Type D	1/2	1.5	3.0	Surface
Type F	3/8	1.3	2.5	Surface

For this study, it was decided to perform the DST tests on two dense graded asphalt mixes: Type B and D. The Type B was selected in order to assess the modified DST device for measuring the average shear properties of asphalt mixes that contain coarse aggregates with a large nominal aggregate size, whereas the Type D is selected to evaluate the modified device for measuring the average shear properties of asphalt mixes used for surface layers. This is because rutting usually occurs in the upper two to four inches from the pavement surface. The mixes were obtained from the “Austin Bridge and Road” asphalt plant, located in Dallas, Texas.

The mix design data of both mixes are shown in Appendix A. Table 4-2 and 4-3 present the summary of gradation data, type and components percentages of mixes Type B and D respectively. Also, the gradation curves of each mix are illustrated in Figure 4-1 and 4-2.

Table 4-2 Mix Design Summary of Asphalt Mix Type B

Mixture (B)						
Aggregate	Bin No.	1	2	3	8	Total Bin
	Aggregate Source	Limestone-Dolomite	Limestone-Dolomite	Limestone-Dolomite	Fractionated RAP	Total
	Percent of Aggregates (%)	30.0	16.0	29.2	24.8	100.0
	in / #	Cumulative Passing (%)				
	1-1/2"	100.0	100.0	100.0	100.0	**100.0**
	1"	97.0	100.0	100.0	100.0	**99.1**
	3/4"	79.0	100.0	100.0	100.0	**93.7**
	3/8"	30.0	96.0	100.0	96.5	**77.5**
	#4	8.0	37.0	99.3	66.3	**53.8**
	#8	2.5	3.0	86.2	43.6	**37.2**
	#30	2.0	1.5	46.9	27.7	**21.4**
	#50	1.5	1.3	32.1	22.8	**15.7**
	#200	1.5	1.1	5.7	7.0	**4.0**
Asphalt Binder	Origin	Percent (%)	Source & Grade			
	New	4.3	Shell **PG 64-22**			
	Recycled	1.3	RAP			
	Total	**5.6**	N/A			
Additive	Antistripping Agent	**0.4**	Evotherm M1/3G			

Table 4-3 Mix Design Summary of Asphalt Mix Type D

Mixture (D)							
Aggregate	Bin No.	1	2	3	8	9	Total Bin
	Aggregate Source	Limestone-Dolomite	Limestone-Dolomite		Fractionated RAP	RAS	Total
	Percent of Aggregates (%)	46.0	30.6	6.0	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"	97.0	100.0	100.0	96.5	100.0	**98.1**
	#4	38.0	99.0	100.0	66.3	100.0	**66.1**
	#8	6.0	85.0	100.0	43.6	98.7	**43.7**
	#30	2.0	39.5	98.0	27.7	62.0	**24.5**
	#50	2.0	28.0	68.0	22.8	53.5	**18.3**
	#200	2.0	6.0	3.0	7.0	21.7	**4.5**
Asphalt Binder	Origin	Percent (%)	Source & Grade				
	New	5.1	Shell **PG 64-22**				
	Recycled	0.8	RAP				
		0.7	RAS				
	Total	**6.6**	N/A				
Additive	Antistripping Agent	**0.5**	Evotherm M1				

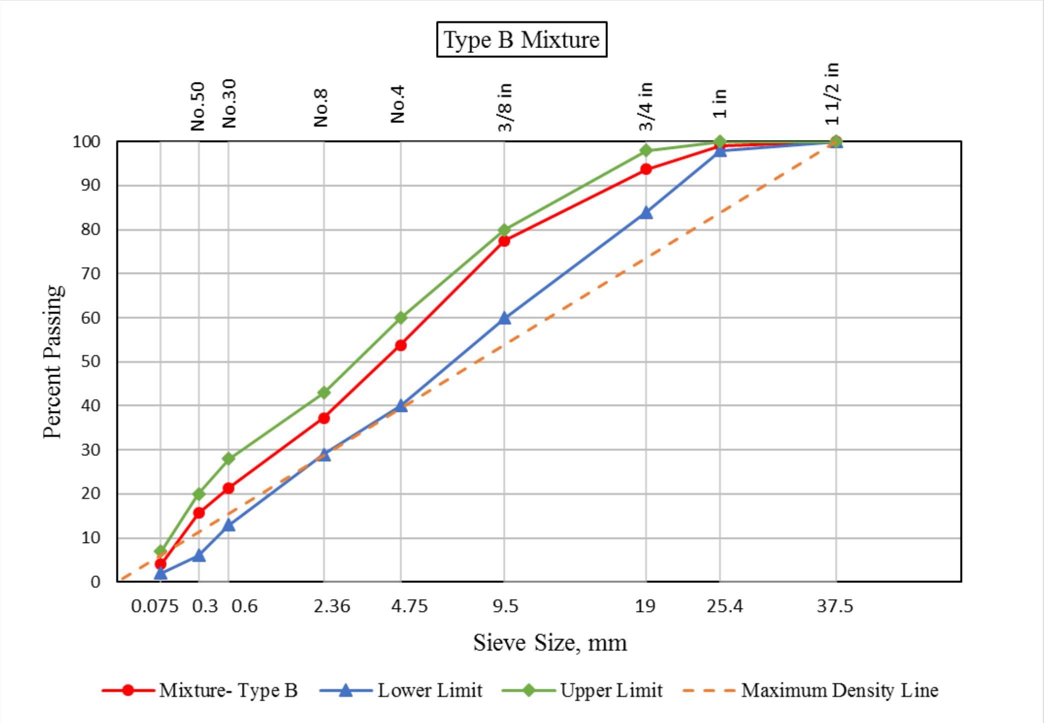


Figure 4-1 Gradation Chart of Mixture Type B

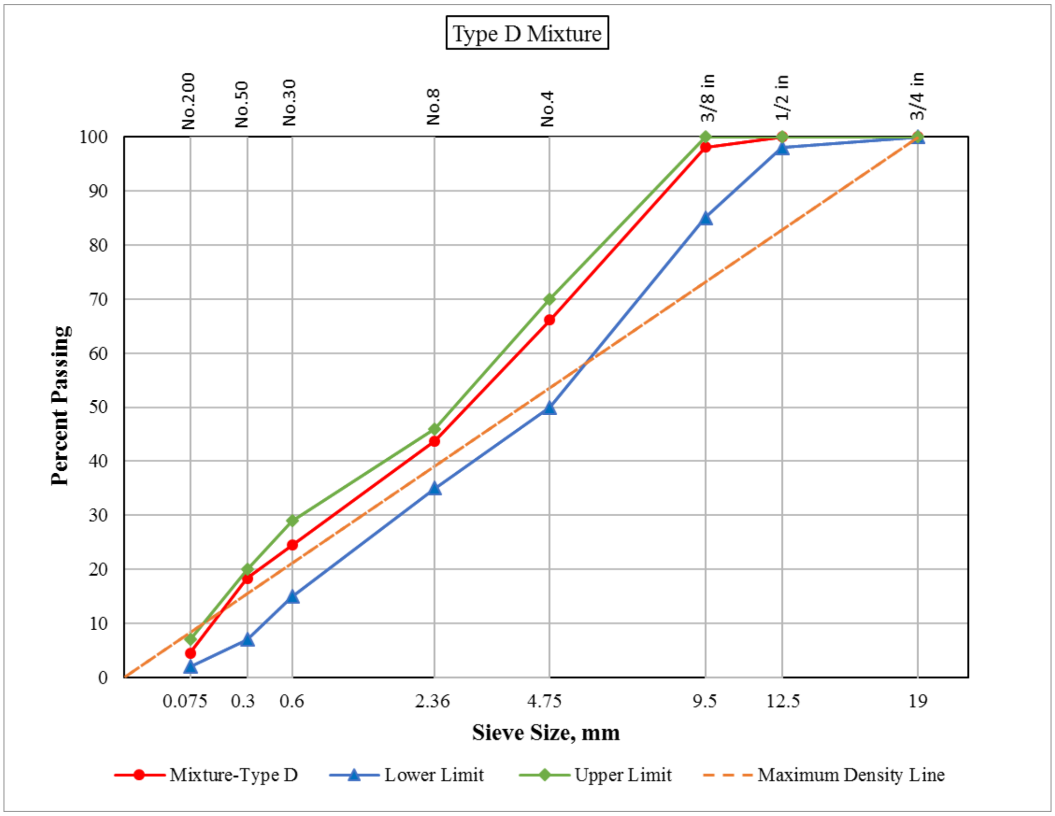


Figure 4-2 Gradation Chart of Mixture Type D

4.2 Sampling and Specimen Preparation

The specimens were fabricated from uniform HMA mixes that were compacted in a Superpave Gyratory Compactor (SGC). As recommended in AASHTO T-320, the specimens should be compacted to a target appropriate air void percentage based on the shear test type, as illustrated previously in Table 2-5. However, the asphalt mix should be compacted to air void percentage higher than the target percentage of the test specimens because the air void content of the test specimen will be reduced after removing the top and bottom ends of the compacted specimen. A 1.0 percent offset is enough to achieve an appropriate percentage of air voids in the test specimen (AASHTO T-320, 2004).

Since the FSCH test is performed theoretically in the linear viscoelastic behavior domain, same DST sets that are used for the FSCH test are used for the RSCH test. Therefore, it was decided in this research to compact all samples at a target air void of 7% to achieve test specimens of around 6% air voids after cutting. Twenty gyratory samples of each mix, Type B and D, were obtained to perform the test specimens. According to Table 3-1, the samples were compacted at 121°C temperature because asphalt with the same PG 64-22 is used in both mixes.

After compaction, gyratory samples of 150 mm diameter and 160 mm height were left to cool at room temperature for one day before cutting. Same procedure of cutting the SST specimens was adopted for cutting the DST specimens by using a wet saw equipped with a 20 inches diamond blade. In order to get the specimens with a uniform air void percentage, each pair of the DST specimens were cut from one gyratory sample, as shown previously in Figure 3-10. For each pair, the air voids percentages and heights of the cut specimens were selected not to differ by more than 1.0 percent and 2.0 millimeters respectively.

To cut the specimens precisely, a special sample holder was fabricated to accommodate a gyratory HMA sample of diameter 150 mm as well as to be placed on the wet saw machine. The holder was provided with three rings to hold the sample firmly while cutting. Each ring consists of a semi-circular mount that welded on the holder base, and an identical semi-circular clamp with two screws on the top, as shown in Figure 4-3. The holder was also provided with a screw attached to a rotated disc to control the thickness of each sliced before cutting. Two straight guides were welded at the bottom of the holder to control the position of the holder while cutting.

By using this holder, a precise DST specimen with height of 50±1 mm and parallel cut-faces can be obtained.

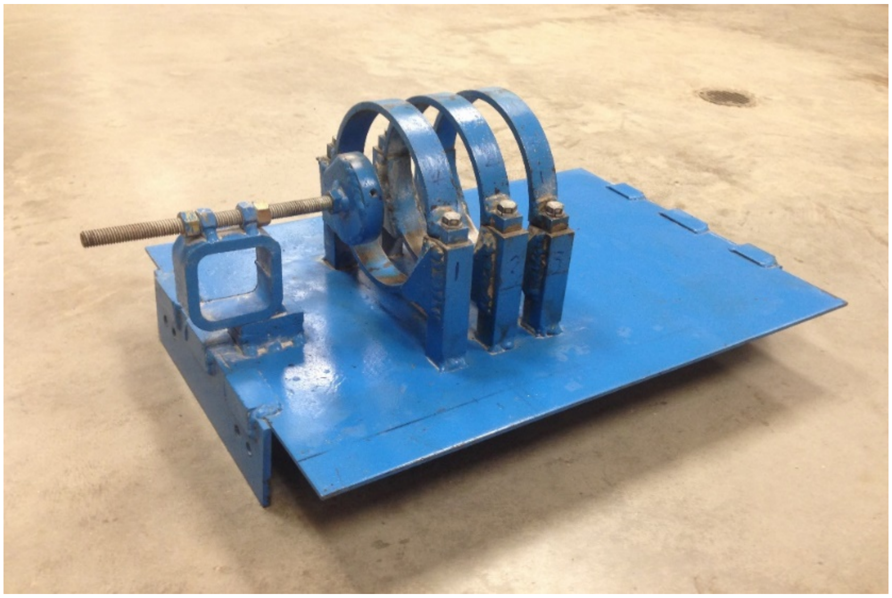


Figure 4-3 Gyratory Sample Holder

Before cutting, it was necessary to set-up the saw machine properly. A saw equipped with a 20 inches diamond asphalt cutting blade was fixed to the side of a rigid rectangular sink of steel, as shown in Figure 4-4. The sink was filled with water so that a motor inside the sink supplies the blade with water during the cut by circulating the water from the sink to the top of the blade. The sink is provided with a portable rectangle table that slides over roller guides located at the top of the sink edges. The table position was then adjusted to be centered with the diamond blade before it fixed by clamps at its corners. The sample holder was then mounted correctly over the table by assuring that the holder guides are matching the table sides. The adjustable screw of the sample holder was then adjusted to provide specimens with 50±1 mm height. This can be done by screwing the holder disc manually till the distance of 50±1 mm is achieved between the exterior edge of the blade and the disc’s edge.

Figure 4-4 Setting up the Wet Saw Machine

To start cutting, a gyratory sample is mounted inside the sample holder. The sample is held firmly at the desired position inside the holder by tightening the holder screws. The first discarded portion of around 25 mm height is cut from the sample. After that, the sawing direction is marked with a vertical red sign before readjusting the position of the sample for the second cutting, as shown in Figure 4-5. To adjust the position of the sample, the holder screws are released partially and the sample is pushed slowly without rotation till it touches the disc face. It should be mentioned that the saw is provided with a foot paddle located under the sink to control the speed of lowering the blade while cutting.

Figure 4-5 Marking and Adjusting the Sample Position for cutting

To obtain the first specimen of a DST pair, a second cut was then performed. The specimen was then taken out by completely releasing the first semi-circular mount. The cut surfaces of the specimen were then checked to be smooth and parallel to each other. Also, the specimen height was checked to be 50±1 mm. Otherwise, the sample should be discarded and the holder disc should be readjusted. To obtain the second specimen of the DST pair, same procedure of marking the cut face, adjusting the position of the sample, cutting, and checking the specimen height were performed again. After that, the remaining end portion from the sample was disregarded off, and the specimens of each pair were marked with the sample’s number. The same procedure was repeated for all gyratory samples. Once the cut is finished, the specimens were kept separately in pairs over dry towels for 24 hours to dry at room temperature, as shown in Figure 4-6.

Figure 4-6 Specimens in Pairs after Cutting

4.3 Volumetric Measurements

Volumetric measurements of each pair of DST specimens were done and recorded one day after the cutting. The volumetric measurements are important to check the uniformity of the specimens in each pair before adopting them for testing. The measurements include measuring the average height and weight of each specimen in order to calculate air voids percentages. The height of specimen is measured with a caliper according to the standard test method ASTM-D3549. Four readings of height were measured for each specimen in order to calculate the average height. According to the standard test method AASHTO T-320, the specimen should be discarded if it has a difference in height more than 2 mm between the largest and smallest height. The weight of each specimen is measured by using a scale.

After measuring the average height and weight of each specimen, the air void percentage of each specimen is calculated. Equation 3-1 is used to calculate the Air void percentage, as required in the standard test method AASHTO T-320. The equation is valid only for calculating the air void percentage of specimens with a 150 mm diameter. The maximum theoretical specific gravity (Gmm) of asphalt mixes are required also for the air void calculations. The Gmm of Type B and D mixes were 2.61 and 2.575 respectively. These values were obtained from the mix design reports, provided by the asphalt mix producer. The Gmm of the mixes are calculated according to the standard test method AASHTO T-209 “Theoretical maximum specific gravity and density of hot-mix asphalt”.

To assure a uniform air void content for each pair, the difference in air void percentage between two specimens of each pair is calculated. The volumetric measurements for the twenty samples of mixes Type B and D are reported in Appendix B. For this study, it was decided to select eight pairs from each mixture for testing. The selected pairs have a difference in average height less than 2 mm and less than 1.0 percent in air voids content. After that, each pair of the selected specimens was kept inside a zip-lock bag to prevent aging. Table 4-4 and 4-5 summarize the selected pairs from mixes Type B and D respectively.

Table 4-4 Selected Pairs of Type B Mixture

Mixture (B)						
Pair #	Top/ Bottom	Height (mm)		Air Void (%)		
		Average	Difference	Content	Average	Difference
B15	T	50.18	0.04	4.73	5.09	0.72
	B	50.22		5.45		
B05	T	50.02	0.06	5.69	5.72	0.07
	B	50.08		5.76		
B18	T	50.41	0.17	5.47	5.61	0.28
	B	50.24		5.75		
B01	T	50.38	0.18	5.49	5.16	0.66
	B	50.21		4.83		
B12	T	49.60	0.20	5.32	5.50	0.35
	B	49.80		5.67		
B08	T	50.21	0.21	4.92	5.31	0.79
	B	50.41		5.71		
B09	T	50.06	0.25	4.96	4.88	0.15
	B	49.80		4.81		
B03	T	50.13	0.25	5.21	5.51	0.59
	B	49.88		5.80		

Table 4-5 Selected Pairs of Type D Mixture

Mixture (D)						
Pair #	Top/Bottom	Height (mm)		Air Void (%)		
		Average	Difference	Content	Average	Difference
D01	T	50.47	0.17	5.72	5.92	0.39
	B	50.30		6.11		
D10	T	49.99	0.19	5.56	5.71	0.29
	B	49.81		5.85		
D04	T	50.51	0.20	6.19	6.33	0.27
	B	50.70		6.46		
D17	T	49.97	0.26	5.51	5.74	0.47
	B	50.23		5.98		
D05	T	50.90	0.27	6.16	6.39	0.47
	B	51.16		6.63		
D18	T	49.70	0.34	5.80	5.85	0.10
	B	50.04		5.90		
D09	T	50.67	0.41	5.93	5.84	0.17
	B	51.08		5.75		
D03	T	50.34	0.53	5.31	5.46	0.30
	B	50.87		5.61		

4.4 Assembling the DST set

After preparing and selecting the specimen pairs of each asphalt mix, the DST sets were assembled for testing. Assembling the DST includes two main steps: gluing the specimens to the DST plates, and tightening the DST sets with threated rods.

4.4.1 Gluing the Specimens to the DST Plates

After the test specimens were dried at room temperature for at least 24 hours, they were glued to the DST plates by using epoxy putty. A Devcon™ Plastic Steel Putty (A) was used for gluing because it satisfies the AASHTO T-320 requirements for a quick adhesive with a minimum hardened stiffness modulus of 2000 Mpa. Resin and Hardener are the two components of this epoxy that need to be mixed in a specific proportion according to the manufacture instructions. Since the epoxy putty needs 45 minutes to get hard, sufficient putty was mixed for gluing one DST sets at a time. A volumetric method is used to proportion the two components of the epoxy putty to provide the sufficient quantity of putty for the four circular surfaces of a DST with no wasting. As specified in the provided technical sheet of the Plastic Steel Putty (A), the appropriate mixing ratio by volume for the resin to the hardener is (2.5/1). So it was determined that mixing 75 cm^3 of the epoxy resin with 30 cm^3 of the epoxy hardener provides a sufficient a quantity of putty to be mixed at a time.

Before preparing the epoxy putty, all steel and aluminum plates were cleaned from dirt or greasy with Acetone and a wire brush. Plate-Specimen Assembly Stand was also placed on a leveled table to be ready for assembling a DST set once the epoxy putty is mixed. Other tools should be available to mix the epoxy components properly and uniformly. Those tools include: a smooth and clean glass board, measuring steel spoons with different sizes, a plastic scraper, and paper towel for cleaning. To mix the epoxy components properly at a time, 75 cm^3 of the resin was measured by a measuring spoon and placed on the glass board, followed by measurement of 30 cm^3 of hardener with another measuring spoon. The hardener should be placed first to the side of the resin on the glass board without mixing. Once the desired quantities of the two components are placed accurately, the plastic scraper is used to mix them uniformly for about 4 minutes, as recommended in the instruction sheet.

Immediately after uniformly mixing the two components, the sequence of the gluing shown in Figure 3-11 were followed. First, as shown in Step 1, a thin layer of the epoxy putty is spread in the depression of the first steel plate. The first specimen of asphalt is then placed in the middle on the steel plate inside the plate groove. The specimen is then pushed and rotated by hand to assure a uniform bonding between the specimen and the plate. In order to assure that the specimens are parallel to each other, it was decided to match the red-signs that marked on the specimen surfaces during cutting between the specimens. Therefore, the sign on the first specimen was directed to the upper side of the steel plate so that the second specimen will be directed in the same way. Then, the first steel plate along with the specimen were placed carefully on the Plate-Specimen Assembly Stand. A level was used to assure the specimen surface is parallel with the steel plate. A rubber mallet was used to achieve the desired level by applying soft strikes as required. Also, to check the center position of the first specimen, the aluminum plate was then placed temporarily without gluing on the assembly stand; the first specimen must be placed into the aluminum plate groove to be centered. Then, the excess epoxy around the specimen edge was removed with a straight edge.

In step 2, a thin layer of the epoxy putty was applied by the scrapper on the aluminum plate groove, followed by inserting the aluminum plate over the first specimen in the assembly stand. The plate was then pushed over the first specimen by hand till the epoxy got out at the specimen edges. Soft strikes were applied with the rubber mallet to assure sufficient bonding between the aluminum plate and first specimen. The process of leveling and removing excess epoxy around the specimen was then repeated similar to that in Step 1. It should be mentioned that before gluing the aluminum plate to the first specimen, the plate should be placed correctly so that the upper side of the aluminum plate that contains a screw hole matches the upper side of the steel plates.

In step 3, a thin layer of the epoxy putty was applied by the scrapper on the upper groove of the aluminum plate. The second specimen of asphalt was then placed over the aluminum plate. The red-sign that marked on the surface of second specimen was directed to the upper side of the aluminum plate same as in Step 1. The second specimen was then pushed by hand till the epoxy got out at the specimen edges. The position of the second specimen was then checked by placing the second steel plate temporarily without gluing over the specimen on the assembly stand same as in Step 1. The same procedure of leveling and removing excess epoxy putty was then performed before moving to the last step.

In Step 4, a thin layer of the epoxy putty was applied by the scrapper on the groove of the second steel plate. The steel plate was then inserted on the assembly stand over the second specimen. The plate was then pushed by hand till the epoxy gets out at the specimen edges. Soft strikes were applied by the rubber mallet to assure sufficient bonding at the interface. The process of leveling and removing excess epoxy around the specimen were then repeated as in the previous steps. Finally, the whole DST device was left on the assembly device for 24 hours at room temperature or until the epoxy was completely cured.

Some practical recommendations should be mentioned to assure proper gluing. The whole process of gluing one DST set should not take more than thirty to forty minutes from the time that the two components of epoxy are mixed since the mixed putty will get hard within 45 minutes. A lubricant substance like a grease or silicon spray should be applied on the assembly stand rods before inserting the plates. The lubricant allows to insert the plates easily with no friction on the assembly stand while gluing, as well as to take out the whole DST set after the curing. Furthermore, beside removing the excess putty after each step of gluing, it is crucial to assure that the two rails attached to the aluminum sides are not spilled with epoxy putty while gluing. Therefore, it is strongly recommended to wipe the rails repeatedly while gluing by using a soft and clean piece of clothes damped with the Acetone.

4.4.2 Tightening the DST sets with Threated Rods

Once the DST set was fully cured, it was removed from the assembly stand to complete its assembly by fixing the four tighten rods along with the grippers. The procedure performed by Khajeh-Hosseini, (2015) for fixing the threated rods were adopted in this study. To fix the threated rods properly without developing axial forces inside the specimens, the nuts were tightened in sequences as shown previously in Figure 3-12. First, the four threaten rods were mounted freely along with nuts on the DST set through the exterior holes of the steel plates. Each threaten rod contains four nuts; two nuts located at the interior sides of the steel plates and the others at the exterior sides. Since the location of the threated rods were adjusted in the new DST device, the threated rods at bottom pass through the grippers. Therefore, the grippers were mounted as a part of assembling the DST sets. The four rods were then tightened firmly by nuts at both sides of one steel plate whereas the nuts on the second steel plate were left loose. After that, each pair of loose nuts on the second plate were tighten by hand. Finally, each pair of nuts on the second plate were tighten firmly by applying same torque on each at the same time.

4.5 Testing Temperatures and Conditioning the Specimens

After assembling the DST sets of each mixture properly, the specimens were conditioned at the desired temperature. In this study, since the objective of performing the tests is to assess the variability of the tests results with the modified DST, it was decided to conduct the tests at the same temperatures selected by Khajeh-Hossein, (2015) in the previous DST tests. Therefore, a 30°C temperature was selected for the FSCH and 50°C for the RSCH test. The same DST sets of each mixture that have been tested for the FSCH were used for the RSCH test as illustrated earlier. The temperature of the UTM-25 chamber should be controlled for at least one hour at the test temperature before launching the test. To monitor and record the test temperature inside the chamber during the tests, a thermometer was inserted inside a dummy asphalt specimen of 4 inches diameter and 6 inches height.

An oven with temperature ranges of 10°C to 204°C (50°F to 400°F) was used to condition the DST sets temperature before performing the tests. The DST sets of each mixture were placed in the oven for overnight at temperature of 30°C (86 °F) for the FSCH test. Next day, the first DST set was transferred to the UTM-25 chamber and reconditioned again at 30°C for at least one hour to stabilize the temperature before starting the test. To minimize the temperature loos, the DST set was fixed properly on the loading frame with the LVDTs in place. Once the FSCH test was performed on the first DST set, the set was returned to the oven and replaced with another set. The process of conditioning, performing the test, and replacing the set was repeated for all sets of each mixture till the FSCH test was completely performed for all sets.

The same DST sets that returned to the oven after performing the FSCH, they were used to perform the RSCH test. To recondition those sets for the RSCH test, the oven temperature was raised up to 50°C (122°F) for overnight. Next day, the first DST set was transferred to the UTM-25 temperature chamber and reconditioned again at 50°C for at least one hour before starting the test. Also, to minimize the temperature loos, the DST set was fixed properly on the loading frame with the LVDTs in place. Once the RSCH test was performed on the first DST set, the set was replaced with another. The same process of conditioning, performing the RSCH test, and replacing the set was repeated for all sets of each mixture.

4.6 Installing the DST on the UTM-25 Device

To install the whole DST device inside the UTM-25 testing equipment, the proper loading attachment depending on the test procedure was fixed into the actuator ram once for the FSCH and another for the RSCH test, as shown in Figure 3-8. The DST supporting plate was then placed on the UTM-25 loading table. The loading table was then lowered enough so that the DST set can be inserted inside the mini-carriages on the supporting plate. The two LVDT mounts were then installed on the top of the steel plates. The LVDT mounts were placed symmetrically in a position that the LVDTs located at 2 inches away from the center of the aluminum plate. The

DST set was then fixed on the supporting plate by screwing the gripper bolts inside the supporting plate.

To start the tests with the FSCH, the supporting table was moved up till the upper edge of the coupling (Piece 1) was lined up with the lower edge of coupling (Piece 2). Piece 1 and 2 were shown previously in Figure 3-8. Once the coupling pieces lined up properly, the table was then moved up till the holes on the coupling pieces were matched. Then the coupling pin was inserted to link the pieces together. The whole DST set along with the supporting plate were then fixed on the loading table of the UTM-25 by two bolts. Finally, the nut at the top of the coupling was tightened while the load level on the actuator was monitored to prevent any excessive stresses to the specimens.

To perform the RSCH test, the proper attachment was fixed in the actuator ram. Then, the supporting table was moved up till the loading attachment got close to the depression on the top of the aluminum plate. The supporting plate was then adjusted to line up with the loading attachment. Then the actuator ram was lowered slowly till the loading attachment touched the surface of the aluminum plate depression. At this stage, the stress level on the actuator was monitored to prevent any excessive stresses to the specimens. Finally, the whole DST set along with the supporting plate were then fixed on the loading table of the UTM-25 by two bolts.

4.7 Executing of the Shear Test Procedures Utilizing the UTM-25

The FSCH and RSCH tests were performed with the modified DST utilizing the UTM-25 testing equipment similar to the previous DST tests done by Khajeh-Hossein, (2015).

4.7.1 Execution of the FSCH test

The FSCH test is performed through a UTS-023 software. This software is usually used to measure the dynamic modulus for mixes under dynamic compressive axial force. However, by modifying some inputs for the specimen diameter and gauge distance, the shear dynamic modulus (G*) of asphalt mixture can be obtained. The input diameter of sample in the software was modified to be 212.13 millimeter while the gauge distance was inserted for each pair as measured in Table 4-4 and Table 4-5. The inserted gauge distance of each pair was the average specimen height.

Before conducting the FSCH test, some data were determined and entered in the UTS-023 program as test parameters. It was required to determine the appropriate level of shear stresses for the HMA mixes at all load frequencies beginning from the highest to lowest frequency. The UTS-023 software can determine these levels by running the "tune condition" which allows to apply a dynamic load to the specimen and measure the parameters. However, the same test template that used by Khajeh-Hossein, (2015) in the previous DST was used for in this study. That template includes the appropriate load levels along with the ten frequencies and load cycle numbers, as illustrated previously in Table 2-4.

Some other levels were monitored and adjusted as required before launching the FSCH tests. Those levels include the UTM-25 actuator position, Load, LVDT ranges and temperature. The levels are monitored through the "Transducer Levels" tab on the UTS-023 software. The actuator position and load were maintained to be zero to prevent any excessive stresses to the specimens, while the LVDTs levels were adjusted to be at the middle of their ranges so that they measured the cyclic strains up and down at each load frequency. The temperature of 30 °C was maintained for the FSCH as illustrated earlier. After that, the test was executed and the shear stress and stain at each frequency were recorded. The average dynamic shear modulus, |G*| and phase angle, (γ) of the DST specimens pair were then calculated and reported at each load frequency by the software.

4.7.2 Execution of the RSCH test

The RSCH test was performed through the UTS-014 software. This software usually used to measure the permanent deformation of asphalt specimens under repeated cyclic pluses or static axial load. The same test template that used by Khajeh-Hossein, (2015) in the previous DST tests was used in this study. The diameter of 212.13 mm and gauge distance were modified also in this software for each DST pair similar to the FSCH test. A seating stress of 3.4 kPa was selected to assure proper seating of the actuator on the aluminum plate as well as to reduce the stress error during the test. The levels of the UTM-25 actuator position, Load, LVDT ranges and temperature were monitored through the "Transducer Levels" tab on the UTS-014 software before starting the test. The actuator position and LVDTs levels were maintained to be set so that it allowed for enough positive movements and deformation measurements during the test. The load level, on the other hand, was maintained to be zero to prevent any excessive stresses to the specimens. After that, the RSCH test was executed and the reading results of shear stresses and strain were recorded and the average shear permanent deformation of specimens was calculated by the UTS-014 software.

4.8 Shear Test Results and Discussion

After conducting the shear tests for all specimen pairs of mixes Type B and D, the results data were extruded from the software in form of tables. Three main parameters were obtained from the data of each mixture. The shear dynamic modulus |G*| and phase angle were obtained from the FSCH tests at 30°C, while the total permanent strain (deformation) in percent was obtained from the RSCH tests at 50°C. The variability of the measured parameters of each mix are evaluated based on the coefficient of variation (COV). The coefficient of variation measures the variability of the measurements relative to the mean value.

4.8.1 Discussion on the FSCH Test Results

The complete FSCH tests results of mixes Type B and D are listed in Table 4-6 and Table 4-7, respectively, while the summaries of the measured dynamic shear modulus and phase angle of both mixes including the mean values and the coefficient of variation are presented in Tables 4-8 and 4-9, respectively.

Table 4-6 FSCH Test Results, Mix Type-B

Mixture- Type B											
Pair #	Frequency (Hz)	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
B15	G* (Mpa)	1386	983	687	498	397	270	201	157	107	80
	Phase Angle (Degrees)	22.92	30.5	34.21	37.04	37.31	32.93	31.34	35.34	36.28	38.78
	Temperature (°C)	30.7	30.6	30.6	30.6	30.6	30.6	30.6	30.5	30.5	30.4
B05	G* (Mpa)	1044	719	476	328	253	162	112	84	52	34
	Phase Angle (Degrees)	29.8	35.11	38.74	41.71	41.22	37.37	36.01	39.61	40.12	42.4
	Temperature (°C)	30.3	30.3	30.2	30.2	30.2	30.1	30.1	30.1	30.2	30.5
B18	G* (Mpa)	1256	904	603	422	320	205	143	106	66	43
	Phase Angle (Degrees)	29.97	34.09	38.57	42.06	41.48	37.81	35.92	39.27	39.71	41.8
	Temperature (°C)	30.4	30.3	30.3	30.2	30.2	30.2	30.2	30.2	30.3	30.4
B01	G* (Mpa)	1256	894	614	441	350	237	175	135	89	62
	Phase Angle (Degrees)	25.56	32.2	35.62	38.39	38.35	33.63	31.53	35.39	36.26	39.03
	Temperature (°C)	30.7	30.7	30.6	30.6	30.5	30.4	30.4	30.3	30.3	30.4
B12	G* (Mpa)	1274	868	574	397	305	194	136	103	66	45
	Phase Angle (Degrees)	29.56	34.09	38.17	41.33	41	37.06	35.64	39.06	39.39	41.6
	Temperature (°C)	30.1	30	30	30	30	30	30.1	30.2	30.3	30.4
B08	G* (Mpa)	1165	824	567	404	319	211	151	115	73	49
	Phase Angle (Degrees)	26.21	31.92	35.64	38.73	38.21	34.77	33.55	37.76	38.79	41.42
	Temperature (°C)	30.6	30.6	30.6	30.5	30.5	30.4	30.3	30.3	30.2	30.3
B09	G* (Mpa)	939	621	413	284	222	145	104	80	53	38
	Phase Angle (Degrees)	24.15	34.66	37.79	40.84	40.45	36.24	34.64	38.93	40.09	42.29
	Temperature (°C)	31	31	31	31	30.9	30.8	30.6	30.4	30.1	29.6
B03	G* (Mpa)	1243	866	601	427	328	211	144	103	60	36
	Phase Angle (Degrees)	22.34	30.64	33.61	36.93	37.96	34.58	33.91	38.8	40.88	43.06
	Temperature (°C)	29.8	29.7	29.7	29.7	29.7	29.8	29.9	30.1	30.3	30.6

Table 4-7 FSCH Test Results, Mix Type-D

Mixture- Type D											
Pair #	Frequency (Hz)	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
D01	G* (Mpa)	995	706	495	362	289	197	145	112	74	52
	Phase Angle (Degrees)	27.4	30.84	33.29	35.69	34.68	30.67	29.89	34.53	35.84	38.78
	Temperature (°C)	30.3	30.3	30.4	30.4	30.4	30.4	30.5	30.5	30.5	30.6
D10	G* (Mpa)	976	718	509	373	298	205	154	122	82	57
	Phase Angle (Degrees)	26.51	29.41	32.11	34.74	34.49	30.1	28.75	33.3	34.67	37.67
	Temperature (°C)	30.3	30.3	30.2	30.2	30.2	30.2	30.2	30.2	30.1	30
D04	G* (Mpa)	893	595	412	297	242	170	128	103	71	51
	Phase Angle (Degrees)	24.09	28.37	30.64	32.9	33.24	29.03	25.66	30.12	30.95	33.69
	Temperature (°C)	30.5	30.6	30.7	30.7	30.8	30.8	30.7	30.7	30.7	30.7
D17	G* (Mpa)	925	668	467	340	274	190	140	110	75	53
	Phase Angle (Degrees)	24.48	27.48	29.73	32.09	32.46	27.26	25.46	30.39	31.35	34.13
	Temperature (°C)	29.9	29.7	29.5	29.4	29.4	29.4	29.4	29.6	29.8	30.1
D05	G* (Mpa)	759	521	359	252	202	138	100	78	51	34
	Phase Angle (Degrees)	23.79	27.93	30.37	32.89	33.17	27.97	26.46	31.15	32.05	35.03
	Temperature (°C)	30.4	30.3	30.3	30.2	30.2	30.2	30.2	30.3	30.4	30.5
D18	G* (Mpa)	897	609	406	280	216	141	99	74	47	31
	Phase Angle (Degrees)	28.02	32.69	35.43	38.35	39.2	34.41	32.97	37.33	38.45	41.4
	Temperature (°C)	30.6	30.8	30.9	30.9	31	31.1	31.2	31.2	31.3	31.4
D09	G* (Mpa)	895	634	457	340	279	199	151	120	83	58
	Phase Angle (Degrees)	22.95	26.35	28.36	30.53	30.44	25.45	23.99	28.89	30.15	33.14
	Temperature (°C)	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3
D03	G* (Mpa)	866	622	449	340	282	204	159	130	93	70
	Phase Angle (Degrees)	24.08	27.56	29.25	30.95	30.61	25.47	23.96	28.72	29.9	32.8
	Temperature (°C)	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.2	30.2	30.2

Table 4-8 Summary of the FSCH Tests Results, Shear Dynamic Modulus

FSCH- Shear Dynamic Modulus |G*| (Mpa)											
Mixture	Frequency (Hz)	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Type-B	Average	1168.14	813.71	549.71	386.14	299.57	195.00	137.86	103.71	65.57	43.86
	STD	119.63	97.46	70.32	53.74	42.02	29.19	22.15	17.17	11.82	8.87
	COV %	**10.2**	**12.0**	**12.8**	**13.9**	**14.0**	**15.0**	**16.1**	**16.6**	**18.0**	**20.2**
Type-D	Average	900.75	634.13	444.25	323.00	260.25	180.50	134.50	106.13	72.00	50.75
	STD	67.58	59.64	46.42	39.46	33.45	25.82	22.04	19.03	14.76	11.93
	COV %	**7.5**	**9.4**	**10.4**	**12.2**	**12.9**	**14.3**	**16.4**	**17.9**	**20.5**	**23.5**

Table 4-9 Summary of the FSCH Tests Results, Phase Angle

FSCH- Phase Angle (Degree)											
Mixture	Frequency (Hz)	10	5	2	1	0.5	0.2	0.1	0.05	0.02	0.01
Type-B	Average	26.80	33.24	36.88	40.00	39.81	35.92	34.46	38.40	39.32	41.66
	STD	2.81	1.54	1.80	1.82	1.45	1.49	1.50	1.34	1.39	1.19
	COV%	**10.50**	**4.62**	**4.88**	**4.56**	**3.64**	**4.13**	**4.34**	**3.49**	**3.53**	**2.86**
Type-D	Average	25.17	28.83	31.15	33.52	33.54	28.80	27.14	31.80	32.92	35.83
	STD	1.75	1.93	2.18	2.45	2.59	2.79	2.95	2.82	2.87	2.91
	COV%	**6.96**	**6.70**	**7.01**	**7.30**	**7.73**	**9.67**	**10.87**	**8.86**	**8.73**	**8.12**

The average values of shear dynamic modulus and phase angle of both mixes have followed in general reasonable decreasing and increasing trends, respectively, as expected with the shear load frequency. The average shear dynamic modulus of mix Type-B decreased from around 1,168 Mpa at 10 Hz shear load frequency to around 44 Mpa at 0.01 Hz. Similarly, for mix Type-D, the average shear modulus decreased from around 900 Mpa to the 50 Mpa at the same frequencies. The average phase angle, on the other hand, increased with the decreasing the shear load frequency. It increased from around 27° degrees at 10Hz to around 42° degrees at 0.01 Hz in mix Type-B and from around 25° degrees to 36 degrees in mix Type-D. Figure 4-7 and 4-8 show the trends of average dynamic shear modulus and phase angle for both mixes, respectively.

The variability of shear dynamic modulus of both mixes have followed almost same pattern of increasing with decreasing the shear load frequency, as shown in Figure 4-9. However, the obtained variabilities of mix Type-B are slightly higher than those for mix Type-D for load frequencies between 10Hz and 0.2 Hz, while the variabilities of both mixes after that have recorded close values for load frequencies 0.1 to 0.01 Hz. The high variabilities of mix Type-B could be justified since the mix contains large aggregate with NMAS of 1 inch, comparing with the NMAS of 0.5 inch for mix Type-D. In general, the coefficient of variation of mix Type-B have increased gradually from 10.2 % at 10 Hz load frequency to 20.2% at 0.01 Hz, while the variabilities of mix Type-D have increased gradually from 7.5% to 23.5% at the same load frequencies.

The variability of phase angles, on the other hand, have shown infrequent changes between mixes across all load frequencies. As shown in Figure 4-10, the coefficient of variation of mix Type-B has dropped from 10.5 % at 10 Hz to fluctuate within the range of 4.9 % to 2.8 % from 5 Hz to 0.01 Hz. The coefficient of variation of mix Type- D has increased gradually from around 7% at 10 Hz up to 11% at 0.1 Hz before it dropped to 8.12% at 0.01 Hz. In general, the measured phase angles of both mixes have recorded COV of less than 11% across all frequencies.

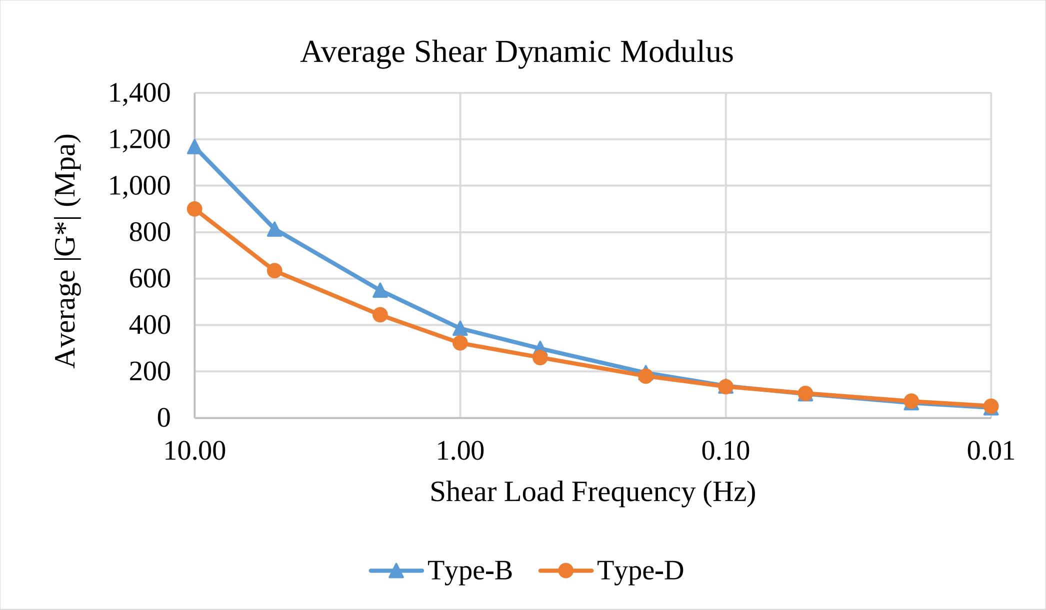


Figure 4-7 Average values of Shear Dynamic Modulus.

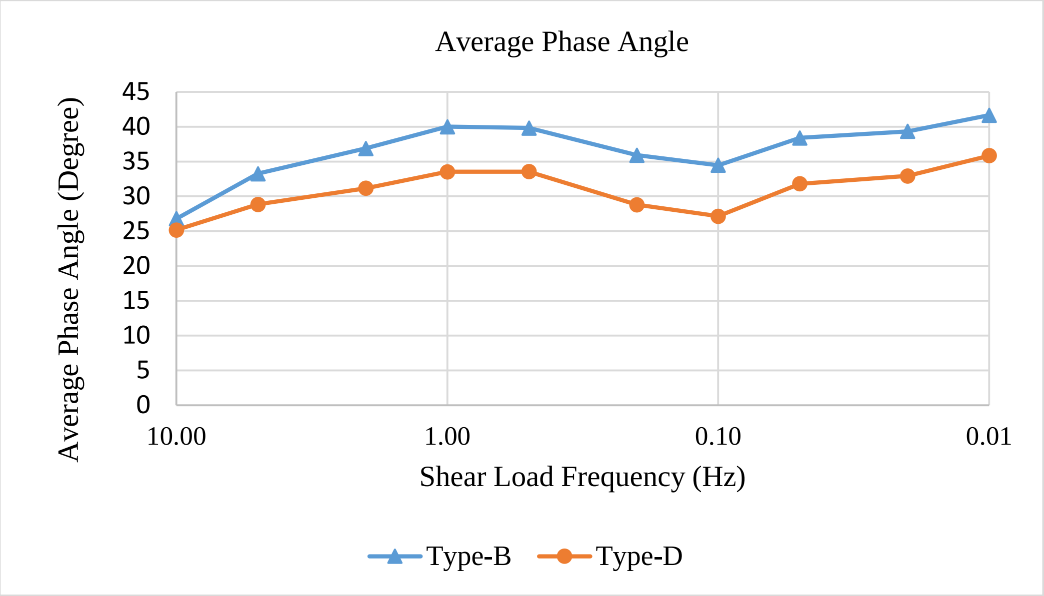


Figure 4-8 Average values of Phase angle.

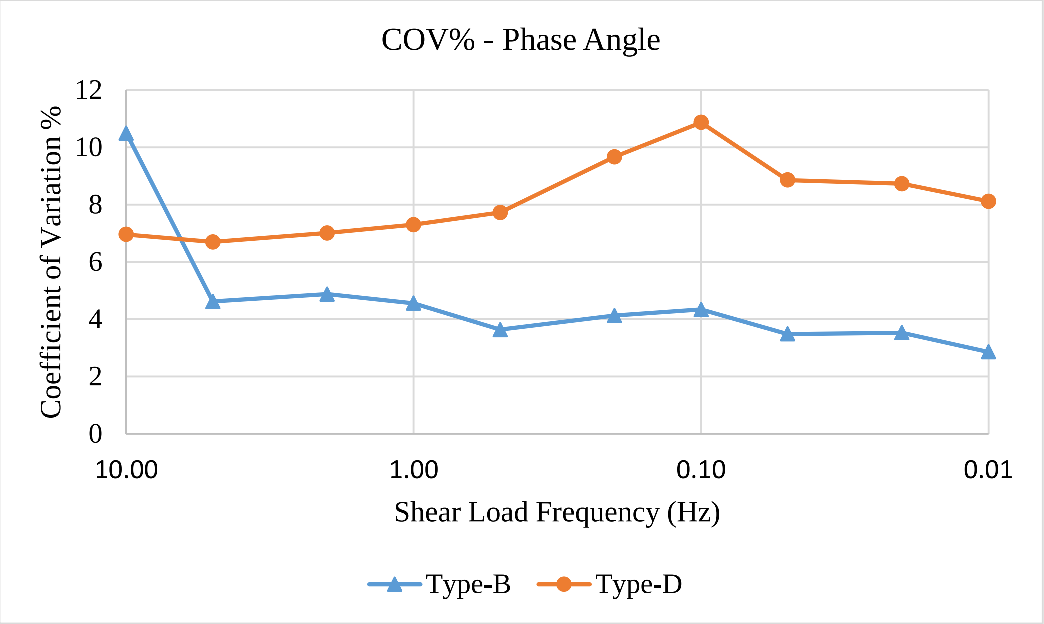


Figure 4-9 Coefficient of Variation for the Shear Dynamic Modulus.

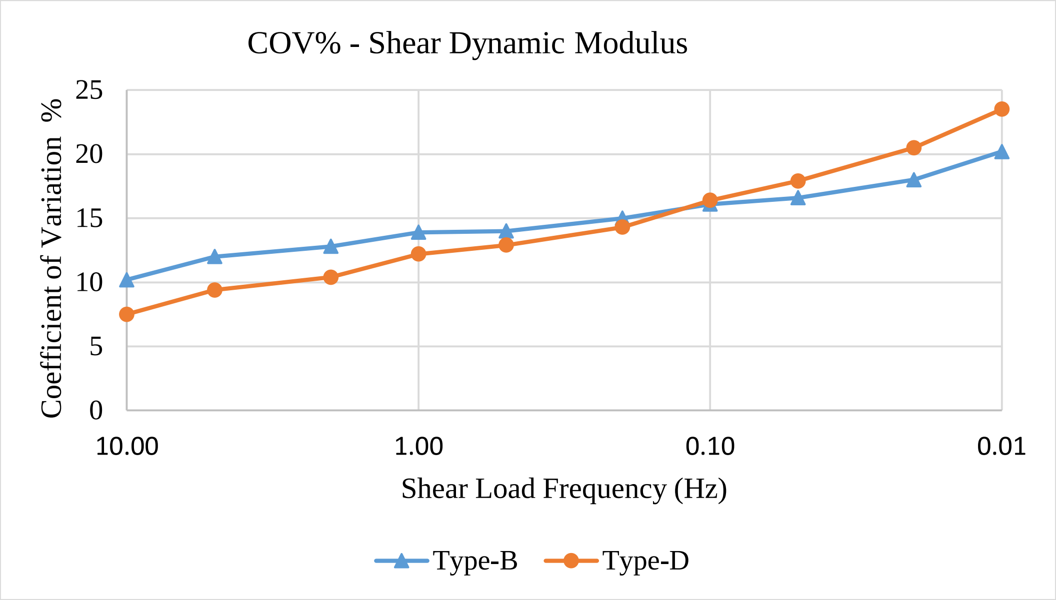


Figure 4-10 Coefficient of Variation for the Phase Angle.

4.8.2 Discussion on the RSCH Test Results

The complete RSCH tests results of both mixes are listed in Table 4-10. The table includes summaries of the measured Permanent Shear Deformation at 5,000 shear load cycles along with the mean values and the coefficient of variation.

Table 4-10 The Permanent Shear Strain (%) at 5,000 load cycles (RSCH Test)

Pair #	Permanent Strain (%)	Temperature (°C)	Pair #	Permanent Strain (%)	Temperature (°C)
B15	0.643	50.6	**D01**	0.538	50.9
B05	0.538	50.8	**D10**	0.371	50.4
B18	0.54	50.1	**D04**	0.637	50.7
B01	0.938	50.4	**D17**	0.698	50.4
B12	0.869	50.2	**D05**	0.552	50.2
B08	0.79	50.1	**D18**	0.51	50.2
B09	0.635	50.2	**D09**	0.541	50.5
B03	0.799	50.1	**D03**	0.356	50.1
Mix-B	Average	0.72	**Mix-D**	Average	0.53
	Standard Deviation	0.14		Standard Deviation	0.11
	COV%	**19.64**		**COV%**	**20.86**

As shown in Table 4-10, the coefficient of variation of the obtained permanent shear deformation of both mixes are of around 20%. Figure 4-11 and 4-12 show the measured total permanent shear deformations as a function with the shear load cycles of all pairs of mixes Type-B and Type-D, respectively. It can be observed that the permanent shear deformation recorded at 5,000 cycles varied from one sample to another for both mixes.

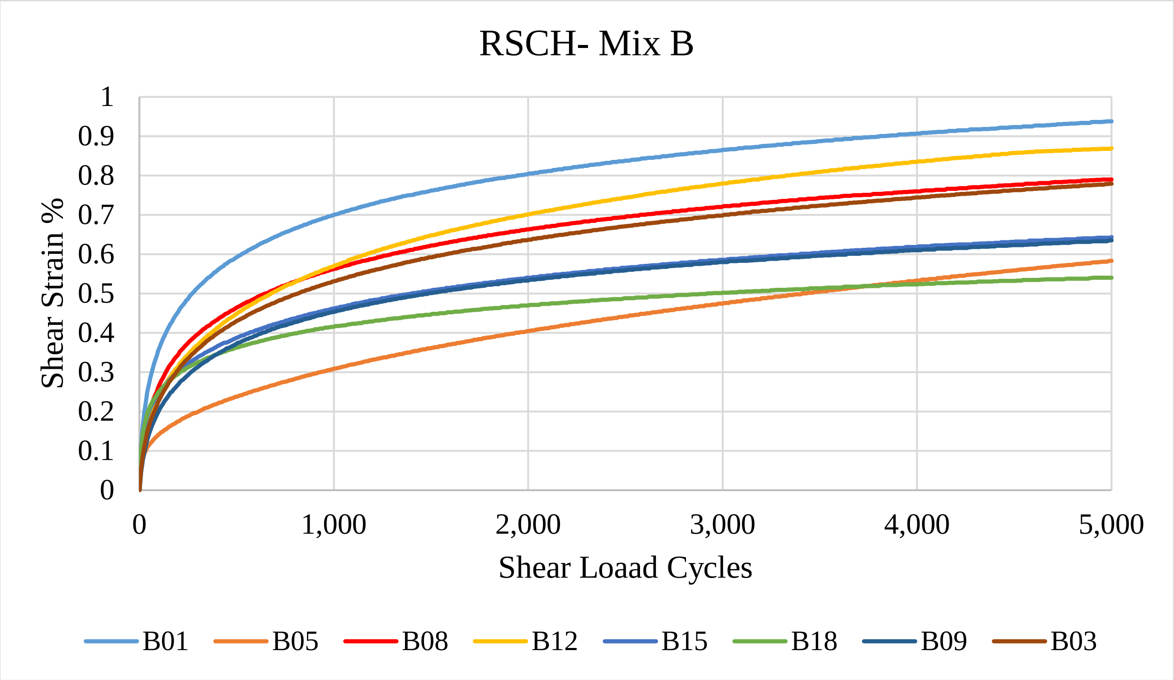


Figure 4-11 Total Permanent Deformation versus Load Cycles of Mix B pairs

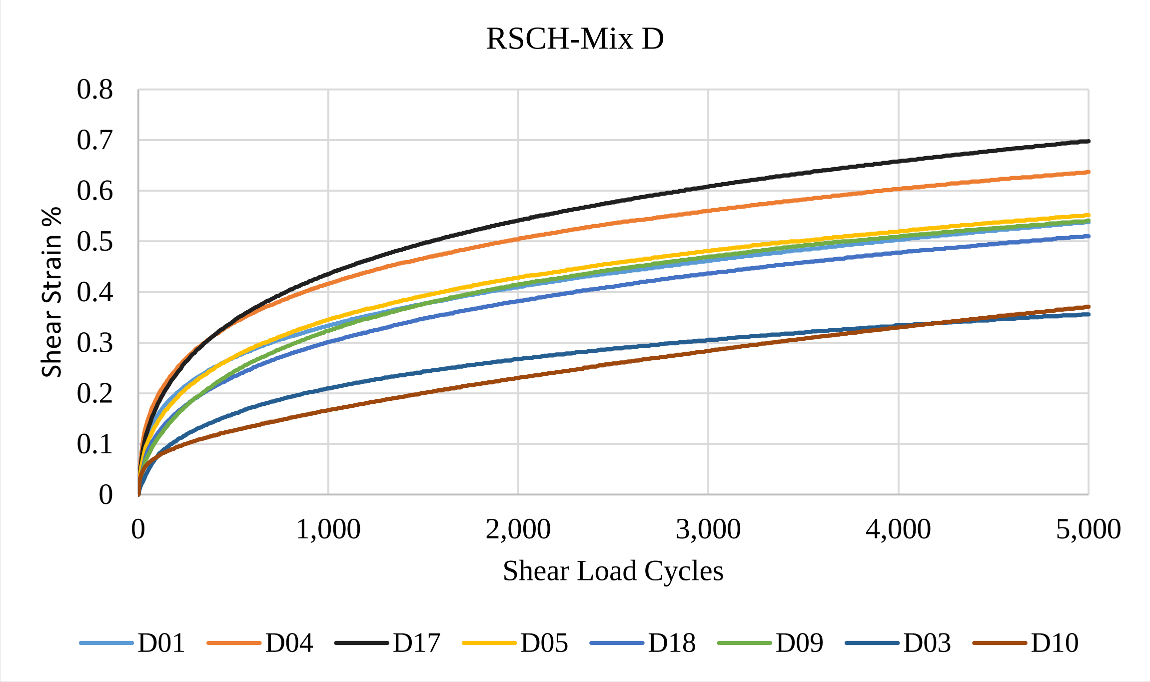


Figure 4-12 Total Permanent Deformation versus Load Cycles of Mix D pairs

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The Duplicate Shear Tester (DST) created at the University of Texas at Arlington can perform the Frequency Sweep at Constant Height (FSCH) and Repeated Shear at Constant Height (RSCH) tests (Khajeh-Hosseini, 2015) accurately and at low cost. The DST has been developed to measure the mechanical shear properties of asphalt concrete in a laboratory. It replicates the loading conditions and constraints of the Superpave Shear Tester (SST) to measure the dynamic shear modulus, phase angle and permanent shear deformation as an average for two asphalt concrete specimens simultaneously. These parameters are inherently related to predict rutting resistance of asphalt mixes.

The first objective of this study was to modify the DST to restrict the vertical movement of the aluminum plate during the tests only in the vertical direction. This was achieved by utilizing a mini linear guides system attached to the aluminum plate. Some adjustments to the DST parts were done to facilitate this system properly with no need to fabricate new parts. The second objective of this study was to assess the variability of the results obtained with the improved device through conducting the two common Superpave Shear Tester (SST) tests: the FSCH and RSCH.

The DST utilized a universal testing machine developed by IPC™ Global since it provides the required components for the shear test system as required by the standard test method AASHTO-T 320. Those components including loading frame, hydraulic pump, control and data acquisition systems as well as a temperature control chamber. In fact, utilizing the universal testing machine adds two major advantages of the DST device:

1- The DST is a simple and inexpensive testing device comparing with the SST device.
2- The DST can be adopted universally in laboratories that have a universal test machine, in which cyclic loading can be provided by one actuator and the testing can be done in a temperature control chamber.

Two dense graded asphalt mixes were tested with the modified DST device. The test results proved the ability of the modified DST device to provide reliable measurements with relatively low coefficient of variations for the measured parameters. According to the FSCH tests results, the coefficient of variability of the measured shear dynamic modulus have increased from 10.2 % to 20.2% and from 7.5% to 23.5% for mixes Type-B and Type-D, respectively, with decreasing the shear load frequencies from 10 Hz to 0.01 Hz. Also, the measured phase angles have recorded general variability less than 11% of both mixes across all frequencies. The results obtained from the RSCH tests, on the other hand, have shown ability of the device to measure the shear permanent deformation of both mixes under cyclic shear loads with a coefficient of variation around 20%. Some of this variation can be attributed to material variability since the mixes were sampled at the asphalt plant from different trucks. Sufficient mix to fabricate six gyratory samples was obtained from a fully loaded asphalt truck leaving the plant. This process was repeated at 3 hour intervals.

The modified DST has successfully satisfied the objectives of a new reliable and simple test device. It provides direct measurements to the fundamental shear properties of asphalt mixes for the rutting prediction at low cost. Moreover, the modified DST can be adopted as a simple performance test equipment for quality control procedure as well as to provide fundamental inputs for developing prediction models to enhance the pavement performance for rutting resistance.

5.2 Recommendations for Future Studies

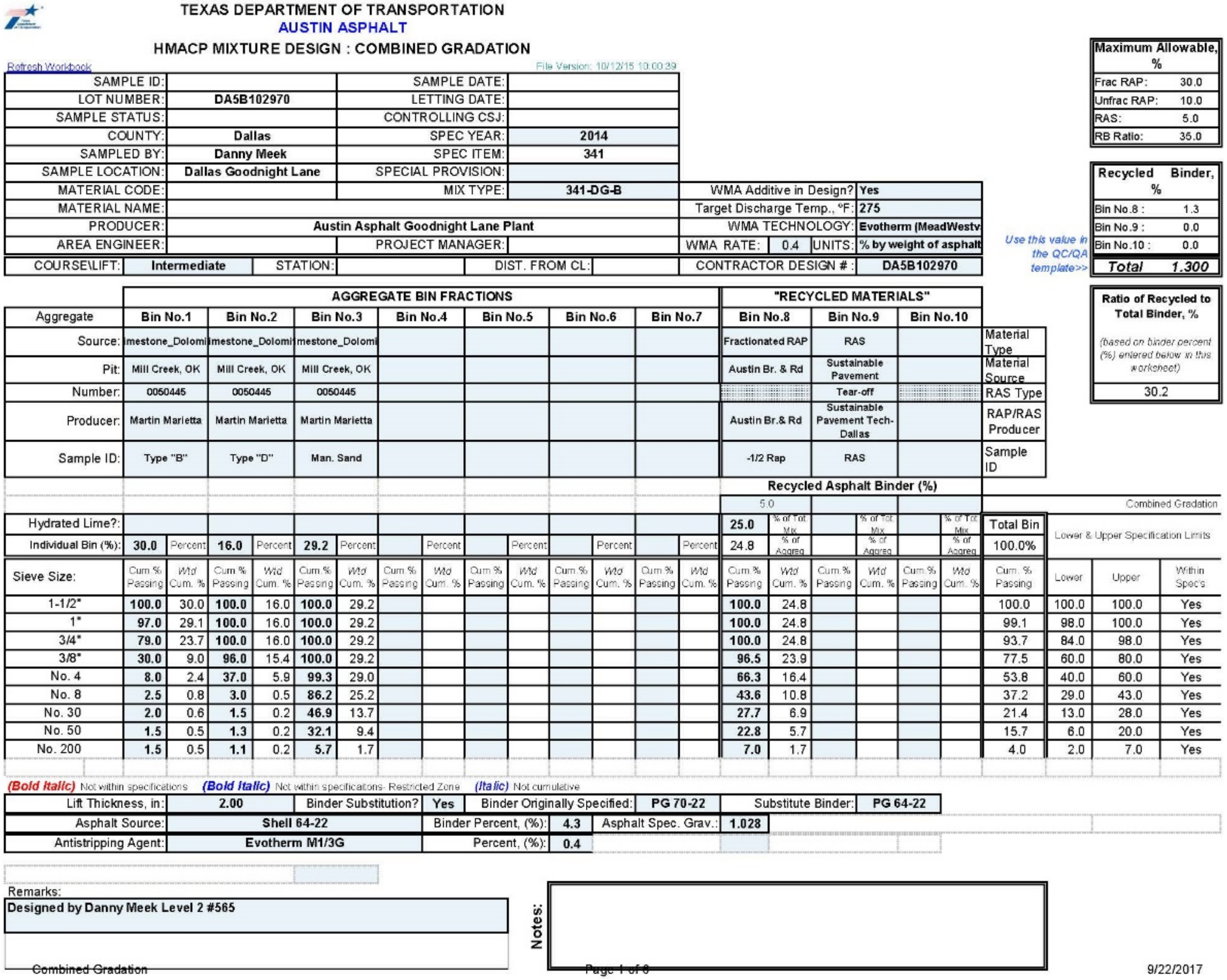
The work conducted to improve the DST device has led to the following recommendations for future work:

- Investigate if the modified DST can be further improved to make the device lighter, to make it easier to handle. The improvements may include replacing the current steel plates with aluminum plates with reduced dimensions.
- Modify the DST to accommodate rectangular asphalt specimens to investigate if testing of rectangular specimens can reduce the variability of results even further.
- Compare the test results obtained on the same mixes with the DST and the SST.

Appendix A

Mix Design Data

Table A-1 Type-B Mix Design Data



TEXAS DEPARTMENT OF TRANSPORTATION
AUSTIN ASPHALT
HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook
File Version: 10/12/15 10:00:39

SAMPLE ID:		SAMPLE DATE:	
LOT NUMBER:	**DA5B102970**	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	**Dallas**	SPEC YEAR:	**2014**
SAMPLED BY:	**Danny Meek**	SPEC ITEM:	**341**
SAMPLE LOCATION:	**Dallas Goodnight Lane**	SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	**341-DG-B**
MATERIAL NAME:			
PRODUCER:	**Austin Asphalt Goodnight Lane Plant**		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	**Intermediate**	STATION:		DIST. FROM CL:	

WMA Additive in Design?	**Yes**
Target Discharge Temp., °F:	**275**
WMA TECHNOLOGY:	**Evotherm (MeadWestv**
WMA RATE: 0.4 UNITS:	**% by weight of asphalt**
CONTRACTOR DESIGN # :	**DA5B102970**

Maximum Allowable, %	
Frac RAP:	30.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	35.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	1.3
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	***1.300***

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

30.2

	AGGREGATE BIN FRACTIONS							**"RECYCLED MATERIALS"**			
Aggregate	**Bin No.1**	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.5**	**Bin No.6**	**Bin No.7**	**Bin No.8**	**Bin No.9**	**Bin No.10**	
Source:	imestone_Dolomi	imestone_Dolomi	mestone_Dolomi					Fractionated RAP	RAS		Material Type
Pit:	Mill Creek, OK	Mill Creek, OK	Mill Creek, OK					Austin Br. & Rd	Sustainable Pavement		Material Source
Number:	0050445	0050445	0050445						Tear-off		RAS Type
Producer:	Martin Marietta	Martin Marietta	Martin Marietta					Austin Br.& Rd	Sustainable Pavement Tech-Dallas		RAP/RAS Producer
Sample ID:	Type "B"	Type "D"	Man. Sand					-1/2 Rap	RAS		Sample ID

Recycled Asphalt Binder (%): Bin No.8 5.0

Combined Gradation

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10			Lower & Upper Specification Limits		
Hydrated Lime?:															25.0	% of Tot Mix		% of Tot Mix		% of Tot Mix	Total Bin			
Individual Bin (%):	**30.0**	Percent	**16.0**	Percent	**29.2**	Percent		Percent		Percent		Percent		Percent	24.8	% of Aggreg		% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum % Passing	*Wtd* Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
1-1/2"	**100.0**	30.0	**100.0**	16.0	**100.0**	29.2									**100.0**	24.8					100.0	100.0	100.0	Yes
1"	**97.0**	29.1	**100.0**	16.0	**100.0**	29.2									**100.0**	24.8					99.1	98.0	100.0	Yes
3/4"	**79.0**	23.7	**100.0**	16.0	**100.0**	29.2									**100.0**	24.8					93.7	84.0	98.0	Yes
3/8"	**30.0**	9.0	**96.0**	15.4	**100.0**	29.2									**96.5**	23.9					77.5	60.0	80.0	Yes
No. 4	**8.0**	2.4	**37.0**	5.9	**99.3**	29.0									**66.3**	16.4					53.8	40.0	60.0	Yes
No. 8	**2.5**	0.8	**3.0**	0.5	**86.2**	25.2									**43.6**	10.8					37.2	29.0	43.0	Yes
No. 30	**2.0**	0.6	**1.5**	0.2	**46.9**	13.7									**27.7**	6.9					21.4	13.0	28.0	Yes
No. 50	**1.5**	0.5	**1.3**	0.2	**32.1**	9.4									**22.8**	5.7					15.7	6.0	20.0	Yes
No. 200	**1.5**	0.5	**1.1**	0.2	**5.7**	1.7									**7.0**	1.7					4.0	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificatons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	**2.00**	Binder Substitution?	**Yes**	Binder Originally Specified:	**PG 70-22**	Substitute Binder:	**PG 64-22**
Asphalt Source:	**Shell 64-22**	Binder Percent, (%):	**4.3**	Asphalt Spec. Grav.:	**1.028**		
Antistripping Agent:	**Evotherm M1/3G**	Percent, (%):	**0.4**				

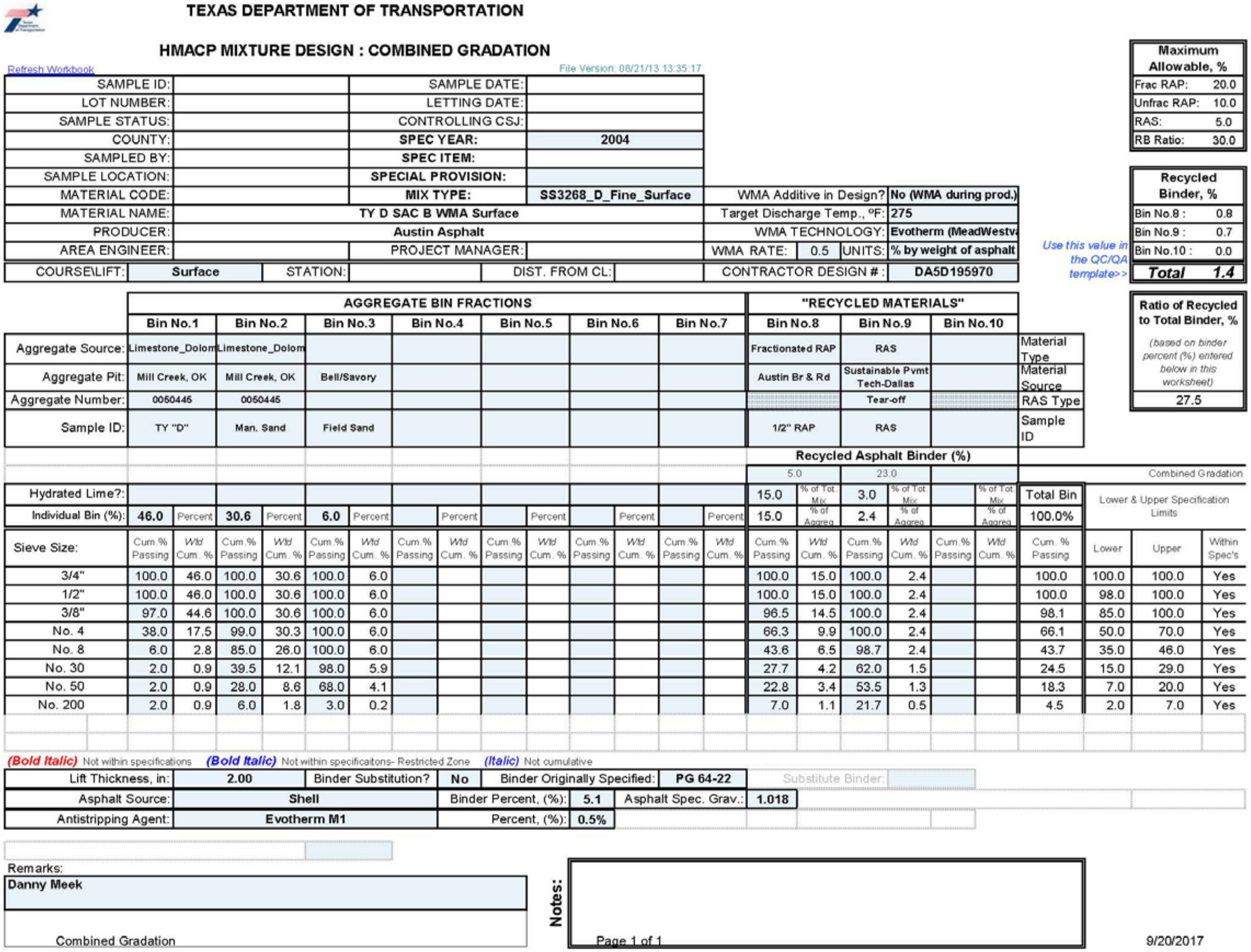
Remarks:

Designed by Danny Meek Level 2 #565

Notes:

Combined Gradation Page 1 of 6 9/22/2017

Table A-2 Type-D Mix Design Data



TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook

File Version: 08/21/13 13:35:17

SAMPLE ID:		SAMPLE DATE:	
LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:		**SPEC YEAR:**	**2004**
SAMPLED BY:		**SPEC ITEM:**	
SAMPLE LOCATION:		**SPECIAL PROVISION:**	
MATERIAL CODE:		**MIX TYPE:**	**SS3268_D_Fine_Surface**
MATERIAL NAME:	**TY D SAC B WMA Surface**		
PRODUCER:	**Austin Asphalt**		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	**Surface**	STATION:		DIST. FROM CL:	

WMA Additive in Design?	**No (WMA during prod.)**		
Target Discharge Temp., ºF:	**275**		
WMA TECHNOLOGY:	**Evotherm (MeadWestv**		
WMA RATE:	0.5	UNITS:	**% by weight of asphalt**
CONTRACTOR DESIGN # :	**DA5D195970**		

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	30.0

Use this value in the QC/QA template>>

Recycled Binder, %	
Bin No.8 :	0.8
Bin No.9 :	0.7
Bin No.10 :	0.0
Total	***1.4***

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

27.5

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Aggregate Source:	Limestone_Dolom	Limestone_Dolom						Fractionated RAP	RAS		Material Type
Aggregate Pit:	Mill Creek, OK	Mill Creek, OK	Bell/Savory					Austin Br & Rd	Sustainable Pvmt Tech-Dallas		Material Source
Aggregate Number:	0050445	0050445							Tear-off		RAS Type
Sample ID:	TY "D"	Man. Sand	Field Sand					1/2" RAP	RAS		Sample ID

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10					
Recycled Asphalt Binder (%)															5.0		23.0				Combined Gradation			
Hydrated Lime?:															15.0	% of Tot. Mix	3.0	% of Tot. Mix		% of Tot. Mix	Total Bin	Lower & Upper Specification Limits		
Individual Bin (%):	**46.0**	Percent	**30.6**	Percent	**6.0**	Percent		Percent		Percent		Percent		Percent	15.0	% of Aggreg	2.4	% of Aggreg		% of Aggreg	100.0%			
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's
3/4"	100.0	46.0	100.0	30.6	100.0	6.0									100.0	15.0	100.0	2.4			100.0	100.0	100.0	Yes
1/2"	100.0	46.0	100.0	30.6	100.0	6.0									100.0	15.0	100.0	2.4			100.0	98.0	100.0	Yes
3/8"	97.0	44.6	100.0	30.6	100.0	6.0									96.5	14.5	100.0	2.4			98.1	85.0	100.0	Yes
No. 4	38.0	17.5	99.0	30.3	100.0	6.0									66.3	9.9	100.0	2.4			66.1	50.0	70.0	Yes
No. 8	6.0	2.8	85.0	26.0	100.0	6.0									43.6	6.5	98.7	2.4			43.7	35.0	46.0	Yes
No. 30	2.0	0.9	39.5	12.1	98.0	5.9									27.7	4.2	62.0	1.5			24.5	15.0	29.0	Yes
No. 50	2.0	0.9	28.0	8.6	68.0	4.1									22.8	3.4	53.5	1.3			18.3	7.0	20.0	Yes
No. 200	2.0	0.9	6.0	1.8	3.0	0.2									7.0	1.1	21.7	0.5			4.5	2.0	7.0	Yes

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:	**2.00**	Binder Substitution?	**No**	Binder Originally Specified:	**PG 64-22**	Substitute Binder:	
Asphalt Source:	**Shell**			Binder Percent, (%):	**5.1**	Asphalt Spec. Grav.:	**1.018**
Antistripping Agent:	**Evotherm M1**			Percent, (%):	**0.5%**		

Remarks:

Danny Meek

Notes:

Combined Gradation

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9/20/2017

Appendix B

Volumetric Measurements

Table B-1 Volumetric Measurements of Mix Type- B Specimen Pairs

Mixture (B)											
Pair	T/B	Height Measurements (mm)						Weight (g)	Air Void (%)		
		H1	H2	H3	H4	Average	Difference		Content	Average	Difference
B01	T	50.17	50.33	50.53	50.50	**50.38**	0.18	2196.2	5.49	**5.16**	0.66
	B	50.02	50.10	50.45	50.26	**50.21**		2203.8	4.83		
B02	T	50.12	50.21	50.40	50.71	**50.36**	0.54	2208	4.94	**5.32**	0.77
	B	49.78	49.96	49.87	49.65	**49.82**		2166.4	5.71		
B03	T	50.09	50.17	50.25	50.02	**50.13**	0.25	2191.6	5.21	**5.51**	0.59
	B	49.80	49.78	50.00	49.95	**49.88**		2167.2	5.80		
B04	T	50.12	50.50	50.25	50.65	**50.38**	0.14	2183.8	6.02	**5.88**	0.27
	B	50.30	50.25	50.70	50.85	**50.53**		2196.4	5.75		
B05	T	49.82	50.23	50.11	49.91	**50.02**	0.06	2175.7	5.69	**5.72**	0.07
	B	49.83	49.95	50.25	50.30	**50.08**		2176.8	5.76		
B06	T	49.98	49.96	50.25	50.40	**50.15**	0.48	2197.2	5.00	**5.40**	0.79
	B	49.71	49.50	49.73	49.75	**49.67**		2158.2	5.79		
B07	T	50.00	50.26	50.42	50.49	**50.29**	0.18	2199	5.20	**5.03**	0.34
	B	49.95	50.03	50.16	50.32	**50.12**		2199	4.86		
B08	T	50.15	50.35	50.19	50.13	**50.21**	0.21	2201.6	4.92	**5.31**	0.79
	B	50.17	50.72	50.50	50.26	**50.41**		2192.4	5.71		
B09	T	49.98	50.25	50.05	49.95	**50.06**	0.25	2194.2	4.96	**4.88**	0.15
	B	49.71	49.85	49.90	49.75	**49.80**		2186.5	4.81		
B10	T	49.66	49.98	49.97	49.65	**49.82**	0.03	2177.7	5.22	**5.29**	0.15
	B	49.44	49.80	50.09	49.81	**49.79**		2173	5.36		
B11	T	49.20	49.44	50.01	49.82	**49.62**	0.56	2147.5	6.16	**5.56**	1.19
	B	49.89	49.90	50.50	50.42	**50.18**		2199.3	4.97		
B12	T	49.75	49.66	49.45	49.53	**49.60**	0.20	2165.7	5.32	**5.50**	0.35
	B	49.64	49.55	50.02	50.00	**49.80**		2166.7	5.67		
B13	T	49.90	49.75	50.12	50.20	**49.99**	0.29	2172.4	5.78	**5.58**	0.41
	B	49.98	50.32	50.60	50.22	**50.28**		2194.4	5.37		
B14	T	50.48	50.61	50.40	50.85	**50.59**	0.43	2205.4	5.47	**5.39**	0.17
	B	49.80	50.32	50.50	50.00	**50.16**		2190.6	5.30		
B15	T	50.00	50.06	50.41	50.26	**50.18**	0.04	2205.1	4.73	**5.09**	0.72
	B	50.02	50.50	50.26	50.11	**50.22**		2190.2	5.45		
B16	T	49.41	49.70	49.81	49.80	**49.68**	0.39	2173.2	5.15	**5.29**	0.28
	B	49.84	50.20	50.23	50.03	**50.08**		2184.1	5.43		
B17	T	50.04	50.06	49.98	50.21	**50.07**	0.42	2185	5.39	**5.54**	0.31
	B	50.02	50.41	51.12	50.43	**50.50**		2196.2	5.70		
B18	T	50.20	50.50	50.60	50.35	**50.41**	0.17	2198	5.47	**5.61**	0.28
	B	50.27	50.11	50.13	50.45	**50.24**		2184	5.75		
B19	T	49.93	50.13	50.63	50.25	**50.24**	0.00	2186.1	5.65	**5.35**	0.60
	B	50.30	50.25	50.20	50.20	**50.24**		2200	5.05		
B20	T	50.15	50.45	50.92	50.20	**50.43**	0.01	2207.7	5.08	**5.59**	1.02
	B	50.20	50.62	50.75	50.11	**50.42**		2183.5	6.10		

Table B-2 Volumetric Measurements of Mix Type-D Specimen Pairs

Mixture (D)											
Pair	T/B	Height Measurements (mm)						Weight (g)	Air Void (%)		
		H1	H2	H3	H4	Average	Difference		Content	Average	Difference
D01	T	50.55	50.22	50.40	50.70	**50.47**	0.17	2165	5.72	**5.92**	0.39
	B	50.36	50.32	50.21	50.29	**50.30**		2148.7	6.11		
D02	T	50.44	50.73	50.65	50.57	**50.60**	0.00	2165.1	5.96	**5.98**	0.05
	B	50.25	50.53	50.80	50.82	**50.60**		2164.1	6.01		
D03	T	50.24	50.30	50.35	50.46	**50.34**	0.53	2168.9	5.31	**5.46**	0.30
	B	50.77	50.61	50.79	51.30	**50.87**		2184.7	5.61		
D04	T	50.60	50.41	50.50	50.51	**50.51**	0.20	2155.8	6.19	**6.33**	0.27
	B	50.61	50.68	50.66	50.85	**50.70**		2158	6.46		
D05	T	51.01	50.70	50.85	51.02	**50.90**	0.27	2173.3	6.16	**6.39**	0.47
	B	51.32	51.18	51.09	51.06	**51.16**		2173.8	6.63		
D06	T	50.91	50.50	50.71	50.95	**50.77**	0.03	2178.2	5.71	**5.85**	0.29
	B	50.60	50.71	50.92	50.72	**50.74**		2170.2	6.00		
D07	T	50.80	50.50	50.65	50.80	**50.69**	0.07	2187.1	5.17	**5.69**	1.04
	B	50.55	50.57	50.90	51.01	**50.76**		2166.1	6.21		
D08	T	50.61	50.79	50.56	50.35	**50.58**	0.13	2175.8	5.46	**5.43**	0.06
	B	50.45	50.81	50.76	50.80	**50.71**		2182.6	5.40		
D09	T	50.56	50.78	50.84	50.50	**50.67**	0.41	2169	5.93	**5.84**	0.17
	B	50.90	51.14	51.12	51.16	**51.08**		2190.6	5.75		
D10	T	49.82	50.01	50.06	50.07	**49.99**	0.19	2148.1	5.56	**5.71**	0.29
	B	49.50	49.76	49.95	50.01	**49.81**		2133.6	5.85		
D11	T	49.50	49.61	49.88	49.92	**49.73**	0.15	2141.5	5.36	**5.49**	0.27
	B	49.61	49.72	49.94	50.23	**49.88**		2141.8	5.62		
D12	T	49.62	49.90	50.30	49.92	**49.94**	0.02	2138.5	5.88	**5.86**	0.04
	B	49.71	49.75	50.12	50.09	**49.92**		2138.7	5.84		
D13	T	50.82	50.24	50.70	51.41	**50.79**	0.75	2174.1	5.93	**5.93**	0.00
	B	51.07	51.06	51.80	52.22	**51.54**		2205.9	5.94		
D14	T	49.50	49.61	49.90	49.89	**49.73**	0.05	2128.2	5.94	**5.98**	0.08
	B	49.78	49.66	49.60	49.65	**49.67**		2124.2	6.02		
D15	T	49.54	49.60	50.21	50.01	**49.84**	0.17	2135.2	5.85	**6.05**	0.41
	B	50.06	49.40	49.36	49.85	**49.67**		2118.6	6.26		
D16	T	49.52	49.08	49.09	49.50	**49.30**	0.73	2117.9	5.58	**5.82**	0.48
	B	49.85	49.78	50.11	50.36	**50.03**		2138.3	6.06		
D17	T	49.76	49.65	50.12	50.33	**49.97**	0.26	2148.3	5.51	**5.74**	0.47
	B	49.86	49.94	50.45	50.65	**50.23**		2148.8	5.98		
D18	T	49.67	49.51	49.72	49.90	**49.70**	0.34	2130.3	5.80	**5.85**	0.10
	B	50.02	49.96	50.07	50.12	**50.04**		2142.8	5.90		
D19	T	49.85	49.81	50.01	50.02	**49.92**	0.14	2150.5	5.33	**5.50**	0.34
	B	49.70	49.51	49.89	50.04	**49.79**		2136.8	5.67		
D20	T	49.23	49.28	49.31	49.20	**49.26**	0.81	2108.9	5.90	**6.01**	0.21
	B	50.02	49.61	50.19	50.42	**50.06**		2138.6	6.11		

References

AASHTO T-320. (2004). Standard Method of Test for Determining the Permanent Shear Strain and Dtiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST). In Standard Specification for Transportation Materials and Methods of Sampling and Testing (Vol. Part 2B). American Association of State Highway and Transportation Officials AASHTO.

ASTM-D7175-05. (2005). Standard Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer. In Annual Book of ASTM Standards (Vol. 4.03). West Conshohocken, PA, United States: ASTM International.

ASTM-D7552-09. (2009). Standard Test Method for Determining the Complex Shear Modulus (G*) of Bituminous Mixtures Using Dynamic Shear Rheometer. In Annual Book of ASTM Standard (Vol. 4.03). West Conshohocken, PA, United States: ASTM International.

André de Fortier Smit, Jorge Prozzi, Vivek Tandon, Magdy Mikhail. (2007). TexSys: Guide for Selecting HMA for Texas Flexible Pavements. El Paso, Texas. Center for Transportation Infrastructure Systems The University of Texas at El Paso.

Brown, E. R., & Cross, S. A. (1992). A National Study of Rutting in Hot Mix (HMA) Pavements. National Center for Asphalt Technology (No. NCAT 92-5).

Brown, E. R., Kandhal, P. S., & Zhang, J. (2001). Performance Testing For Hot Mix Asphalt. National Center for Asphalt Technology (No. NCAT 01-05).

Chowdhury, A., & Button, J. (2002). Evaluation of Superpave Shear Test Protocols. Texas Transportation Institute (No. FHWA/TX-02/1819-1).

Christensen, D. W., Bonaquist, R. F., & Handojo, T. (2002). Field Shear Test for Hot Mix Asphalt. Transportaion Research Board (TRB), National Cooperative Highway Research Program (NCHRP). Transportation Research Board National Research Council.

Christensen, D. W. (2003, June). Sensitivity Evaluation of Field Shear Test using Improved Protocol and Indirect Tension Strength Test. National Cooperative Highway Research Program.

Cominsky, R. J., Killingsworth, B. M., Anderson, R. M., Anderson, D. A., & Crockford, W. W. (1998). Quality Control and Acceptance of Superpave-Designed Hot Mix Asphalt. Transportation Research Board (TRB), National Cooperative Highway Research Program (No. Project D9-7 FY'93). Washington: Transportation Research Board.

El Halim, A. A. (2007). Design, Development and Validation of an Advanced In-Situ Shear Stiffness Test Facility for Asphalt Concrete Pavements. Highway IDEA Project 55. Transportation Research Board of the National Academies.

Goodman, S. (2000). Design, Development and Validation of the In-Situ Shear Stiffness Test (InSiSST™) for Asphalt Concrete Pavements. Ottawa, Canada: Carleton University.

Gamut. (2017, September 8). Retrieved from Profile Rail Sleeve Bearing Linear Guides: https://www.gamut.com/c/power-transmission/profile-rail-sleeve-bearing-linear-guides?q=Linear+Sleeve+Bearing+Carriage

Kennedy, T. W., Huber, G. A., Harrigan, E. T., Cominsky, R. J., Hughes, C. S., Quintus, H. V., et al. (1994). Superior Performing Asphalt Pavements (Superpave): The Product of the SHRP

Asphalt Research Program. National Research Council. Washington: Strategic Highway Research Program.

Khajeh Hosseini, M. (2015). Development of the duplicate shear test for asphalt mixtures Civil & Environmental Engineering.

NHI. (2000). Superpave Fundamentals Reference Manual (NHI Course #131053). Federal Highway Administration - FHWA, National Highway Intitute. U.S. Department of Transportation.

Pavement Interactive. (2011, April 21). Dynamic Shear Rheometer. Retrieved July 15, 2017, from http://www.pavementinteractive.org

http://www.pavementinteractive.org/article/dynamic-shear-rheometer/

Pavement Interactive. (2008, January 1). Superpave Shear Tester. Retrieved August 6, 2017, from http://www.pavementinteractive.org:

http://www.pavementinteractive.org/article/superpave-shear-tester/

Pbclinear. (2017, September 8). Retrieved from Mini-Rail® Miniature Linear Guide - Gliding Surface Technology: http://www.pbclinear.com/Mini-Rail-Miniature-Linear-Guide

Reinke, G., & Glidden, S. (2004). Development of Mixture Creep Performance Tests Using a Dynamic Shear Rheometer. Transportation Research E-Circular, E-C068.

Sousa, J. B., Craus, J., & Monismith, C. L. (1991). Summary Report on Permanent Deformation in Asphalt Concrete. Washington: Strategic Highway Research Program (No. SHRP-A-318).

Texas Asphalt Pavement User Guide. (2017, September 27). TXAPA User Guide. Retrieved from Texas Asphalt Pavement Association:

http://www.texasasphalt.org/files/Texas%20Asphalt%20User%20Guide.pdf

White, T. D., Haddock, J. E., Hand, A. J., & Fang, H. (2002). Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements. NCHRP Report, 468. National Research Conuncil. Washington: Transportation Research Board.

Witczak, M. W., Kaloush, K., Pellinen, T., El-Basyouny, M., & Quintus, H. V. (2002). Simple Performance Test for Superpave Mix Design. National Cooperative Highway Research Program (NCHRP). Transportation Research Board.

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Yazeed Suleiman Jweihan was born in Jordan at 1989. He received his Bachelor degree in Civil Engineering from Mutah University, Jordan in August 2011. During his study, he achieved a distinguished academic record by listing his name on the Dean's list for four times and once on the University list. He was also awarded the University shield for excellence. He worked in Jordan as a QC engineer in the field of pipeline and service road construction for three years. In 2015, he received a full scholarship from Muta'h University to continue his Master's and PhD studies in Civil Engineering in the USA. In January 2016, he started his Master of Science program in Civil Engineering at the University of Texas at Arlington.

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