EVALUTATION OF BOND STRENGTH AT ASPHALT INTERFACES

by

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Abstract

The primary objective of this research project was to evaluate the shear behavior of three asphalt-to-asphalt mix interfaces. To accomplish this objective, a special attachment and loading mechanism was designed and built to facilitate the measurement of the dynamic shear reaction modulus and shear strength of the asphalt-to-asphalt interfaces when shear and normal forces are acting simultaneously and they are proportional. Two tests were conducted on 4-inch diameter cylindrical samples cored from an asphalt concrete pad where three types of asphalt-to- asphalt interfaces were built. For each interface, four tack-coat quantities were sprayed. On each sample, the Dynamic Shear Reaction Modulus test was conducted first. Then the Shear Strength test was conducted until the sample failed in shear at the interface. The experiments suggest that the shear strength of the interface is affected neither by the interface type nor by the tack-coat application rate. However, the dynamic shear reaction modulus was affected by both interface type and by the tack-coat application rate. The lowest moduli were recorded for the interface between two fine graded asphalt mixes. With very few exceptions, the highest moduli were obtained for the tack-coat application rate recommended by the construction specification.

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CHAPTER 1 - Introduction

In the United States pavements play a major role in the daily lives of the people. The transportation cost's in the US contributes 11% of the Nation's gross domestic product, totaling around $950 billion. The average total cost of transportation (including the cost of vehicles) for a household in the US is about 19% of total spending (Transportation, 2007).

There are more than 4.7 trillion passenger miles and more than 3.7 trillion ton miles that are transported in the US each year on its road networks (Transportation, 2007). Due to this significant volume, the road networks construction and maintenance costs account for more than half of the total funds spent on all highway expenditures. Therefore more durable and more economical ways of designing and constructing pavements is necessary. The more advances that are made in pavement design the more reliable the pavement infrastructure will become. Thus, advances in this engineering area have the potential to lead to significant monetary savings.

A proper pavement design is essential to a successful and long lasting pavement structure. The design process typically includes the selection and design of materials, determination of layer thickness depending on traffic volumes and environmental conditions, pavement configuration, and drainage design. All of these components must be considered for a long lasting, low maintenance, and well performing pavement structure (Romanoschi, 1999).

Pavement structures are designed using empirical methods or mechanistic-empirical methods (Romanoschi, 1999). In the empirical methods, the relationship between the design inputs (layer thickness, material properties, traffic and environmental conditions) and pavement performance are determined through experience or experimentation. There are limitations to using this approach but as long as they are recognized as reasonable, these methods can be used with confidence (HAPI, 2007).

The mechanistic-empirical methods are more advanced than the purely empirical method. The mechanistic part of this approach estimates pavement response (stresses, strains, deflections) considering the type of vehicle loads and material properties of the pavement structure and environmental conditions based on the fundamental laws of physics and mechanics of materials (Romanoschi, 1999). The relationship between loading conditions and pavement response are usually described using mathematical models. The empirical part of the mechanistic-empirical methods estimates pavement distresses (cracking, rutting, joint faulting, roughness of the longitudinal profile), and thus pavement performance, from the pavement response (HAPI, 2007).

One assumption in the structural response model for flexible pavements is that the asphalt layers are completely bonded to each other, when in all reality they may not be. There is no widely accepted test method for measuring the degree of bonding between pavement layers. Without proper modeling of the bond between layers, the calculation of pavement response, and thus the design of the flexible pavement structures, cannot be accurate.

Asphalt pavement layers cannot be constructed in one single lift if the layer thickness is higher than 2.5 to 3.0 inches because thicker lifts cannot be compacted efficiently with the currently used equipment. Therefore, asphalt concrete layers are typically constructed in lifts with a maximum thickness of 2 to 2.5 inches. Therefore, the construction of interfaces between layers cannot be avoided.

To achieve a good bond between layers tack coat is usually sprayed in between asphalt pavement layers. The material can play a large role in the successful bonding of asphalt layers. The tack material can be asphalt emulsions (slow, medium, and fast setting), cutback asphalts, high float emulsions, polymer modified asphalt emulsions, and paving grade asphalt cements. The most commonly used tack material is asphalt emulsion. Another factor to consider when applying tack coat is the application rate. Too much or to little tack coat can result in a poor bond. Also, before the tack coat is sprayed, the surface where asphalt is to be placed it must be clean and debris free. Dirt and fine dust can significantly inhibit bonding of the layers. The surface is most commonly cleaned with a power broom (West, 2005).

The tack coat is only used if the next of pavement is placed more than two days after the underlying lift. So if the lifts are placed sooner than two days, no tack coat is typically used between the layers. The reason for this is that after two days the tack coat is needed to improve the bond strength between the layers. The bonding between the layers is also improved if the surface is cleaned before placing the next lift of pavement.

Poor bonding between pavement layers can cause many distresses. One of the most common distress is slippage failure, which usually occurs where heavy vehicles are often accelerating, decelerating, or turning. The vehicles load creates dynamic normal and tangential stresses in the pavement interfaces from horizontal and vertical loads. With the vehicles load being transferred to each underlying layer of asphalt, the interface between the layers is vital to the pavements integrity. Slippage failure develops when the pavement layers begin to slide on one another usually with the top layer separating from the lower layer. This is caused by a lack of bond and a high enough horizontal force to cause the two layers to begin to separate (Hachiya, 1997). Other pavement problems that have been linked to poor bond strength between pavement layers include premature fatigue, top down cracking, potholes, and surface layer delamination (NAPA, 2000).

As stated before poor bonding can result in slippage failure, delamination, top down cracking, potholes, and premature fatigue. With the presence of anyone of these, the pavement structure's integrity is compromised and pavements begin to fail quickly. With pavement layer bonding being so important to the integrity of the structure, improvements to the design process by incorporating interface models are necessary. This will more than likely lead to lower maintenance and rehabilitation costs (Romanoschi, 1999).

Objective

The objective of this research project is to evaluate the shear behavior of three asphalt-to-asphalt mix interfaces, with different quantities of tack coat. This will include determining the dynamic shear reaction modulus and strength of the interfaces.

The first phase of this study is to conduct a literature search. The purpose of this literature review is to gather information on previous studies on interfaces between materials and on laboratory tests for the determination of mechanical properties of interfaces.

The next phase of the study is to conduct laboratory tests on layer interfaces constructed in the field. Four-inch diameter cylindrical specimens will be made in the field and cored. From there they will be brought into the laboratory for testing. To conduct the laboratory tests, a special attachment and loading mechanism will be built to fit the IPC UTM machine in the Advanced Asphalt Laboratory of Kansas State University. Three asphalt-to-asphalt mix interfaces with different quantities of tack coat will be tested under dynamic shear test with a normal load to measure the dynamic shear reaction modulus and strength of the interfaces. These tests will be performed at several loading magnitudes and frequencies.

Graphical plots of the test results will be developed to determine the influence of the characteristics of the interface material on the mechanical properties of the interface.

A report will be written that will give detailed information on the development of laboratory tests and the findings of the analysis. Also included in this report will be recommendations for further research.

CHAPTER 2 - LITERATURE REVIEW

When dealing with most flexible pavements, the pavement structure is typically constructed using more than one lift (depending on thickness). The bonding at the interfaces of the individual layers is very important to the structural performance. If the pavement layers are not fully bonded, the magnitude and location of critical strain will be different than when the layers were completely bonded (Romanoschi, 1999). For this reason it is important to ensure a proper bond so that pavement performance can be maximized and predicted. Several studies have been done to study the effects of tack coat and bonding. The studies have included varying temperatures, tack coat application rate, tack coat material and loading conditions.

A world wide survey done in 1999 by the Bitumen Emulsion Federation was conducted to determine the most common type of tack material used, the rates at which they were applied, curing time, test methods, and construction methods. The survey concluded that the most common type of tack material used was cationic emulsions. The average rate of application was found to be from 0.026 to 0.088 gal/sq.yd, which was based on residual asphalt (West, 2005).

When a proper bond has not formed, the most common failure of the pavement is slippage cracking. Slippage cracking occurs where vehicles are usually decelerating, accelerating, or turning. The top layer will begin to slide and separate from the layer beneath it and will result in a half moon shaped crack opening away from the direction of movement an example of this can be seen in Figure 2.1 (Romanoschi, 1999).

Figure 2.1- Slippage Cracking in Hawaii (HAPI, 2007)

2.1 Interface Tests

Many studies have been done to analyze the behavior interfaces of asphalt pavements. Of these studies some were inconclusive and some lead to significant findings. One study with inconclusive findings was conducted by Korkmaz (2003). This study was to evaluate a laboratory testing procedure for analyzing tack materials used at asphalt interfaces. The tack coat performance was to be evaluated using the Hamburg wheel tracking device and simple shear tests on laboratory samples. In this particular study the performance of thin asphalt concrete overlays on concrete pavements was evaluated. Four variables were considered: tack coat type, mix type, application rate, and trafficking. The shear test applied a shear load at a constant rate of 50 mm/min and was conducted at 20°C. The Hamburg wheel tests were conducted at 50°C. It was found the trafficking improved the shear strength of the interfaces at 5,000 cycles. For this reason it was recommended to repeat the experiment at a higher number of cycles at a lower temperature and up to 20,000 cycles (Korkmaz, 2003).

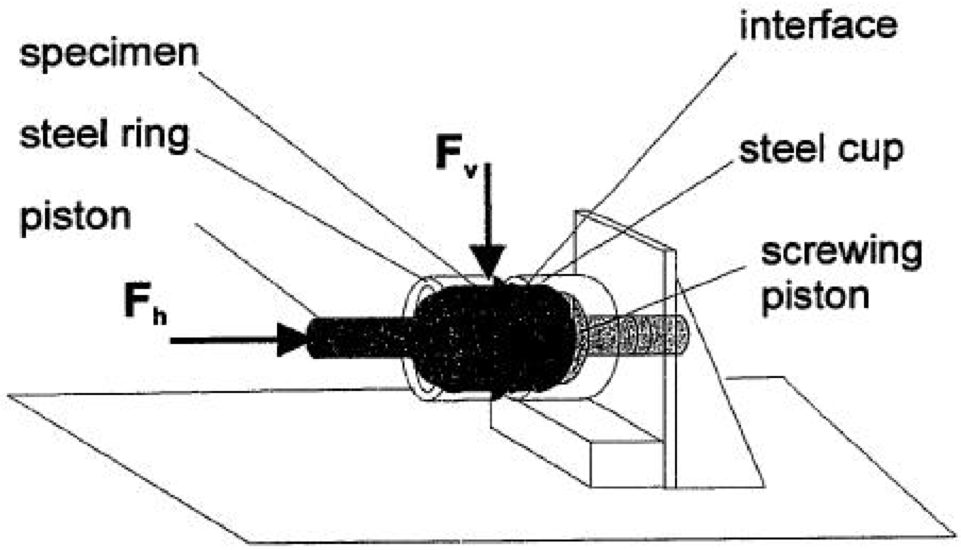
A specific apparatus was developed for this study to hold the specimens during the testing. This was developed specifically to induce failure at the asphalt interfaces. The specimen holders were 150 mm in diameter and 50.8 mm deep. The testing of these samples used this apparatus and the Superpave Shear Tester (SST). At the end of the study it was concluded that the addition of a tack material at the interfaces does add shear strength. The tack material that was found to perform the best was CRS 2P with an optimum application rate of 0.02 gal/sq.yd.

A study conducted at Delft University of Technology (Molenaar, 1986) used a simple shear test to determine the shear resistance at the interface between asphalt layers. The shear resistance test was done on interfaces with and without a tack coat. This particular device held the bottom part of the compacted cylinder and a shear load was applied perpendicular to the axis of the cylinder of the top layer. The load was transferred to the interface of the asphalt layers and the resistance could then be measured. The device was used in conjunction with a standard Marshall stability loading press, which applied a load at a rate of 0.85 mm/sec. Their findings were that at, 15^{o}C, there was no significant difference between the interfaces with and without a tack coat (West, 2005).

A testing method that is currently being used in the UK involves testing in the field. This test is simply referred to as an in-situ torque test. A core is drilled in the asphalt and the core is left in place. Then a plate is attached to the top of the core at the surface of the asphalt and a torque is applied. The torque is applied with a torque wrench so that the force can be recorded. The torque is applied to the core until it fails and the final torque applied is recorded (West, 2005). No other detailed information about this test was found.

Romanoschi (1999) conducted direct shear tests at a constant normal load on asphalt-to-asphalt interfaces to study the mechanical behavior of the interface. It included tests on interfaces with and without tack coat, three temperature levels (15^{o}C, 25^{o}C, and 35^{o}C), and different normal stresses at the interface of approximately 138, 276, 414, and 552 kPa. In this test, the asphalt core sample was fixed in a split steel ring with the interface at the end of the steel ring. Then the half that is sticking out is fixed in a steel cup that is welded to a vertical plate. A vertical actuator then pushes on top of the split steel ring, which puts a shearing force at the interface while a horizontal actuator applies a constant, normal stress at the interface. The maximum shear stress that could be applied (because of equipment limitations) was 663 kPa (Romanoschi, 1999).

Figure 2.2- Schematic of Direct Shear Test with Normal Load (Romanoschi, 1999)



In the same study, Romanoschi (1999) performed interface fatigue test using a device to hold cored specimens with the axis at an angle with the direction of load application. The asphalt specimens were placed in two metal cups spaced at 5 mm. The device was designed such that adjustments could be made so that the asphalt interface could always be in between the two cups. The cups holding the specimens were attached to metal angle pieces so that the cups were at angle of 25.5 degrees with the direction of the applied force. This angle was chosen because at this angle the shear pressure at the interface is half to the normal pressure. This is important because this is the average ratio between the vertical and horizontal forces applied at the interfaces between asphalt layers under the passing of wheel loads. An actuator placed on the top of the metal angle that was holding the cup applied a vertical force, which was then transferred by the device holding the specimen to asphalt interface. A schematic of this testing device is shown in Figure 2.3 (Romanoschi, 1999).

Figure 2.3- Schematic of the Shear Fatigue Test (Romanoschi, 1999)

There are several test methods that are in use today to evaluate asphalt interfaces of different layers of asphalt layers. These tests include: NCAT Shear test, Torque Bond Test, Superpave Shear Tester (SST), FDOT Shear Tester, and ASTRA from Italy.

The NCAT Shear test is a shear type test. The loading can be applied using a Marshall press or a universal loading machine. This test has had many improvements over the years. One of the main improvements that it has under gone over the years was the added ability to apply a horizontal load. Similar to other methods this is a device that is placed in an MTS machine to test core samples. It is loaded at a rate of 2 in/min (50.8 mm/min) and is tested at a constant temperature, which is maintained in the testing chamber. A schematic is given in Figure 2.4 (West, 2005).

Figure 2.4- Schematic of the NCAT Shear Testing Device (West, 2005)

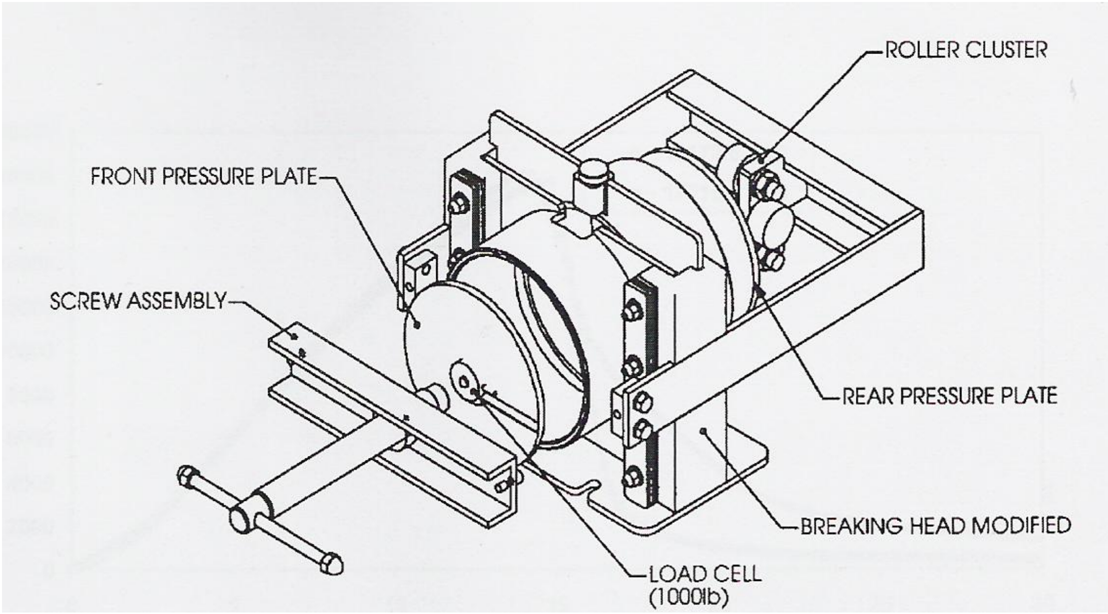
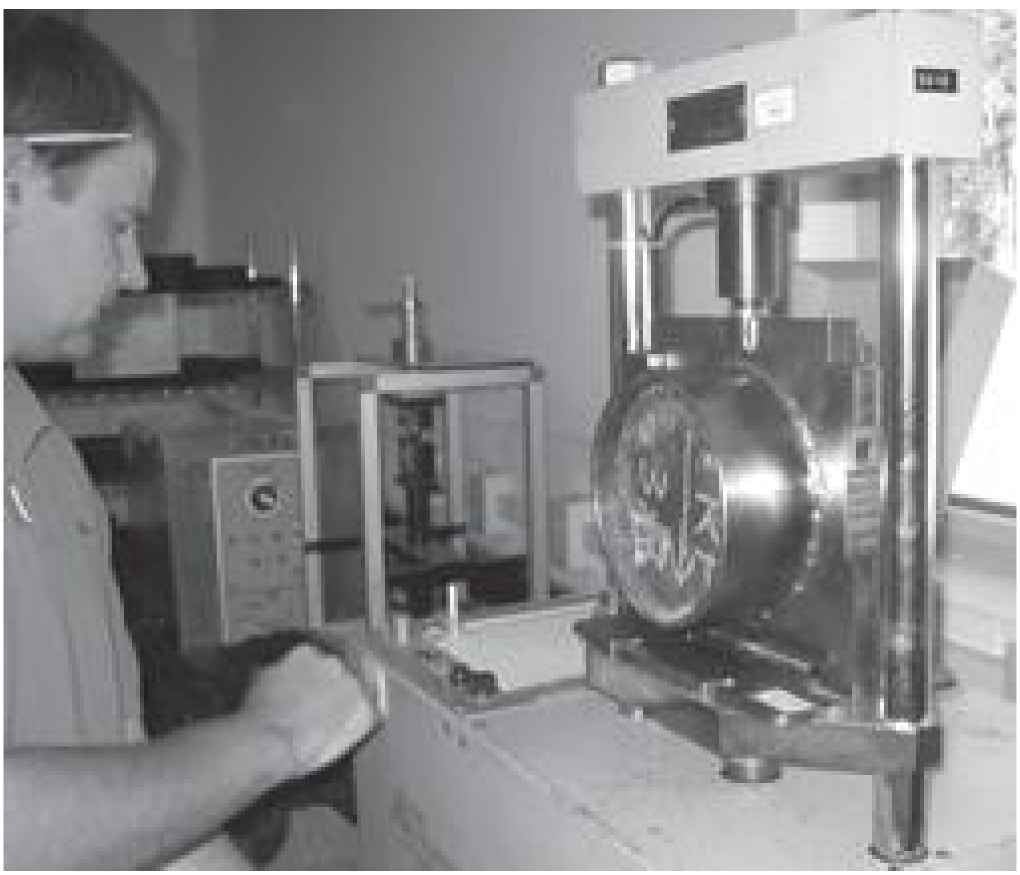


Figure 2.5- NCAT Shear Testing Device (West, 2005)



The Torque Bond Test was developed in Sweden for in-situ testing of asphalt interfaces. In this relatively simple test, the asphalt concrete is cored to a depth that is deeper than the interface in question and the core is then left in place. Then a metal plate is glued to the top of the specimen and from there a torque is applied to the top of the core until failure occurs. The torque that was required to cause the shear failure will then indicate the tack coat strength. This test is generally used on interfaces between thin surfacing and its underlying layer. There have also been laboratory studies with this procedure, which is fundamentally the same procedure except that the core is removed and placed in a clamping device (Figure 2.6). The clamping device holds the bottom layer below the interface while the torque is applied to the top of the core. The major findings of this study were that the interfaces on milled sections of pavement had significantly higher shear strength when compared to those of non-milled sections. It was also found that curing time doesn't influence the strength at the interface, and that for the milled surfaces tack coat made a significant difference in strength as opposed to using no tack-coat (Tashman, 2006).

Figure 2.6- Torque Bond Testing Device and Procedure (Tashman, 2006)

A study conducted by Mohammad et al. (2002) using the Superpave Shear Tester aimed to determine the optimum tack coat type and the optimum application rate. The Superpave Shear Tester (SST) can apply axial loads, shear loads, confinement pressures to asphalt specimens with controlled temperatures. This machine is a closed-loop feedback, servo-hydraulic system and has six main components: testing chamber, test control system, environmental system, hydraulic system, air pressurization system, and measurement transducers. This machine usually tests specimens that have a height of 50 mm and a diameter of 150 mm although it can accommodate specimens with heights and diameters up to 200 mm. When determining the shear strength of the tack coat, the specimen is placed on the shear table inside the testing chamber and the temperature is then stabilized. The machine will then apply shear and normal forces to the interface. A picture of the testing chamber with a specimen in it is shown in Figure 2.6. This machine is preprogrammed to perform several different tests: volumetric uniaxial strain, repeated shear at constant height, repeated shear at constant stress ratio, simple shear at constant height, and frequency sweep at constant height.

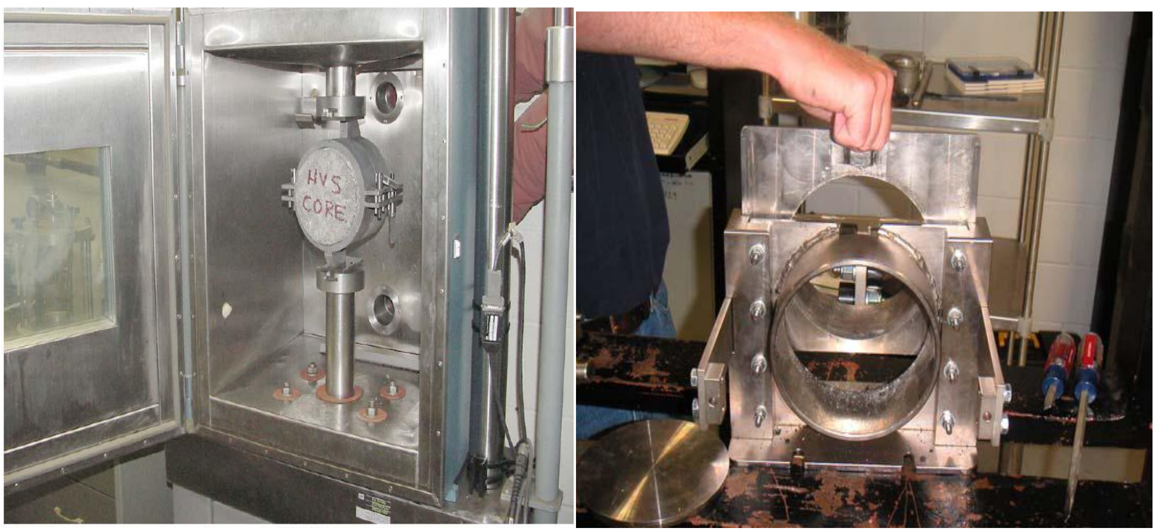
The objective of the study by Mohammad et al. (2002) was to evaluate the practice of using tack materials on asphalt interfaces. To accomplish this several tack materials were considered. The tack materials included two types of asphalt cements, PG 64-22 and PG 76-22M and four types of emulsions, CRS-2P, SS-1, CSS-1, and SS-1h. Five rates of application were considered: no tack material, 0.02 gal/sq.yd, 0.05 gal/sq.yd, 0.10 gal/sq.yd, and 0.2 gal/sq.yd. This study was conducted at two temperatures 77°F and 131°F (25°C and 55°C) to determine the effect of temperature on the tack materials shear strength. The results of this test showed that the tests at 25°C yielded approximately 5 times the shear strengths at 55°C. Also, it was found that the tests at 25°C distinguish better the different tack coat application rates (West, 2005).

Figure 2.7- Superpave Shear Tester (SST) with Test Sample (Tashman, 2006)

The Florida DOT Shear Tester was developed in 2003 to address the need for a test to evaluate tack coat strength. This tester makes use of the standard universal testing machine MTS. This tester is basically an attachment, which fits inside the universal machine. This device uses 6-inch diameter cores and the interface is placed in between the gap of the two ring sets. The gap between the two rings should be 3/16 inch. The specimen is brought to a temperature of 25^{o}C plus or minus 1^{o}C for a minimum of two hours before testing. When the core is placed in the ring sets it is placed so that the direction of load on the core is parallel the shear direction. The test is strain controlled and will load at a rate of 2-in/min until failure. From there the shear strength can be calculated. Also, in this study water was sprayed on two sections with tack coat on them to simulate rain. Their findings were that water significantly reduces the bond strength. Also concluded from this study was that all interfaces gained bond strength with time (West, 2005).

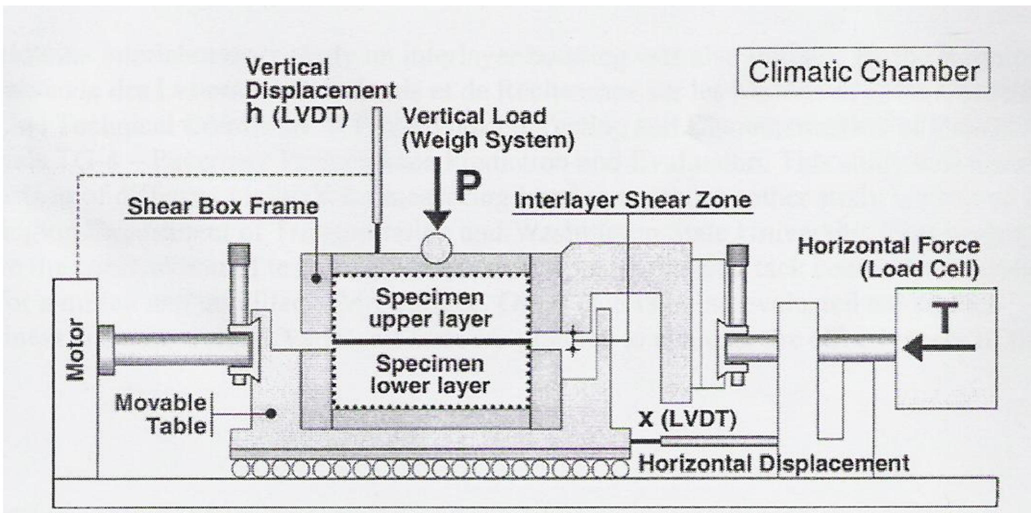
Another study conducted by the Washington Center for Asphalt Technology using the Florida DOT Shear Tester found that milled sections of pavements had a significantly higher shear strength than the non-milled sections, that the shear strength at the interface was not affected by the location of the load, and that tack coat did not have an impact of the performance of the non-milled sections while it greatly affected the milled sections (Tashman, 2006). This method is now used by the Florida DOT to evaluate the bonding of an interface if there is a question of bond integrity (West, 2005).

Figure 2.8- FDOT Shear Tester in use and attachment device (Tashman, 2006)



In Italy a device called the Ancona Shear Testing Research and Analysis (ASTRA) is used to determine the bond strength of tack coats. This device had many improvements since it was first developed more than ten years ago. This device operates by applying a normal load to the specimen while in shear. The specimen is sheared at a rate of 0.1 in/min (2.5 mm/min). A schematic of this device can be seen below.

Figure 2.9- Schematic of the Ancona Shear Testing Research and Analysis (Tashman, 2006)



2.2 Tack Coat Tests

In addition to the tests developed to evaluate the mechanical properties of interfaces, several other tests have been developed to evaluate the tack coat by itself. Two of those tests are the Texas DOT UTEP Pull-Off Test and the ATACKER Device that was developed by Instrotek.

The Texas DOT UTEP Pull-Off Test was developed at the University of Texas at El Paso (Tashman, 2006). This device measures the bond strength of the tack material. The pivoting feet shown in Figure 2.10 are used to level the device before the test begins. This device is placed on the pavement after the tack coat has been placed and then it is leveled. The contact plate is then lowered until it is contact with the tack coat. A 40 lb load is placed on top and then the contact plate is allowed to set for 10 minutes to set the contact plate. After 10 minutes, the load is removed and the torque wrench is rotated counter clockwise until the contact plate has broken away from the tack coat material. The force that was needed to remove the contact plate from the tack material is recorded. The reading from the torque wrench is then converted to the strength of the tack material using a calibration factor. The equation used to find the UTEP Pull-Off Strength is UTEP Pull-Off Strength= overall mean + effect due to Surface Condition + effect of Residual Rate within the Surface Condition + effect due to testing time + random errors. A study conducted by the Washington Center for Asphalt Technology involved the UTEP Pull-Off Strength test at different surface conditions. The study was able to conclude that milled sections of pavement had a lower tensile strength than the non-milled road surfaces. They speculated this is due to lesser contact area. Another finding from this study is that the bond strength decreases with time (Tashman, 2006).

Figure 2.10- Texas DOT UTEP Pull-Off Testing device (Tashman, 2006)

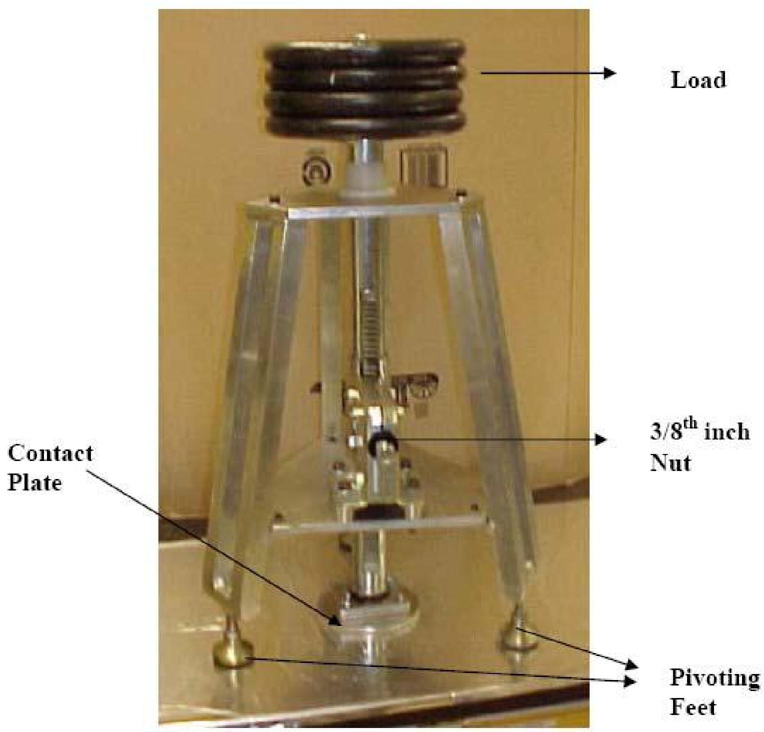


Figure 2.11- Texas DOT UTEP Pull-Off Testing device in the field (Tashman, 2006)

The Attacker device is also a machine used to evaluate the bond strength of tack coats. It was developed by Instrotek, Inc and can be seen in Figure 2.12. The tack coat material can be applied to a metal plate, a pavement surface, or a hot-mix-asphalt (HMA) sample and then a metal disc will lower to make contact with whatever surface has the tack coat material applied to it. This machine can measure the bond strength of the tack material in two ways: tensile or torsion mode (West, 2005).

Figure 2.12- The ATACKER Device Developed by Instrotek (West, 2005)

2.3 Summary

The performance of pavements currently in service today proves that bonding between pavement layers is critical. The bonding of the layers affects how stresses and strains are distributed throughout the pavement, which ultimately affects the overall performance of the pavement structure. There are many different tests that attempt to measure the bonding at the interface and also the strength of the bonding material. With the rising cost of pavements more testing is needed to develop more realistic models for pavement structures. These tests should replicate as close as possible the same conditions that the pavement is subjected in the field. Thus, a normal load should be applied simultaneously with a shear force.

CHAPTER 3 - METHODOLOGY

This chapter discusses the experimental work. To start, details on how the specimens were prepared will be discussed from planning to construction. This chapter will include details of sample identification numbers, how the asphalt pad was constructed, including the tack coat application process, and the coring process. Once the samples were brought to the laboratory from the field, a wet saw was used to make a smooth flat surface on the bottom. The testing configuration for the attachment that fits within the UTM machine will be discussed. Then once the samples are loaded into the apparatus and securely fastened they are ready to be tested. Two tests that will be conducted on each sample once they are loaded into the apparatus are the Dynamic Modulus Test and the Stress-Strain Test (Strength Test).

3.1. Preparation of Test Specimens

To begin this research the Shilling Asphalt Company in Manhattan, Kansas was first contacted so that a work plan could be discussed. Three asphalt interfaces were built: a coarse-coarse mix interface, coarse-fine mix interface, and fine-fine mix interface (Figure 3.1). Each of these asphalt combinations was divided into four equal parts and different amounts of tack quantities sprayed on each section: no tack coat, 1/2 specification (11 grams per square foot), specification (21 grams per square foot), and 1.5 specification (approx. 32 grams per square foot), making a total of 12 different combinations. The layout of the pavement construction is shown in Figure 3.1. The individual combinations were then labeled as shown in Table 3.1.

Some coordination was necessary because the asphalt plant usually makes one type of mix at a time. In mid July, Shilling Construction laid an approximately 6.1 meter section about 4 inches thick of a 12.5A (see appendix A for mix design) mix at the KSU research facility CISL. In late July, Shilling returned and laid an approximately 4.6 meter section about four-inches thick of a BM1 (see appendix A for mix design) mix, BM1 is coarse mix, and 12.5A is fine mix. Now with the base course laid, the next step was to apply the tack coat.

Table 3.1- Definition of Sample Labels

Asphalt Mixture Combinations			
Tack Quantities	Coarse-Coarse	Coarse-Fine	Fine-Fine
No Tack Coat	4	8	12
½ Specification	3	7	11
Specification	2	6	10
1 ½ Specification	1	5	9

Figure 3.1- Schematic layout of the asphalt pad constructed by the Shilling Asphalt Company

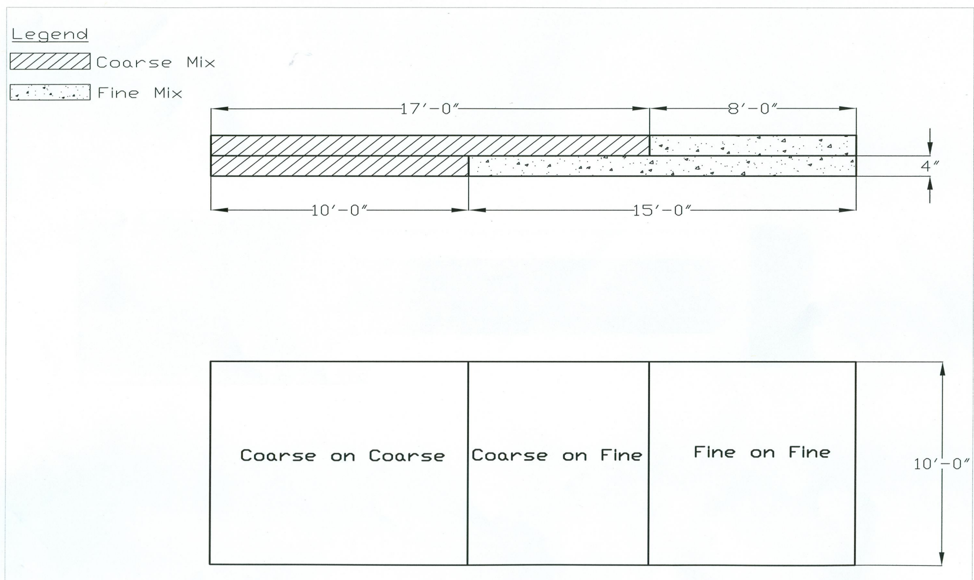


Figure 3.2- Laid Base Coarse

The tack coat was applied with an industrial form oil sprayer (Chapin - model 1949). To measure the amount of tack coat being applied several 30.5 cm by 30.5 cm (12 in by 12 in) square boards were cut and tack coat was sprayed on them at the same application rate as on the asphalt pad. The weight of the boards was then measured before and after the tack coat was applied on them. This way the rate of tack coat application was measured.

Four quantities of tack coat were sprayed:

- No tack at all,
- Half of the specification rate (approximately 11 grams per square foot),
- Specification rate (approximately 21 grams per square foot),
- 1.5 times the specification rate (approximately 32 grams per square foot).

Figure 3.3-(Left) Application of the Tack Coat. (Right) The Form Oil Sprayer used to Apply the Tack

The next lift of asphalt mix was then placed. A coarse-graded mix was laid across approximately 3 meters of the fine-graded mix and 3 meters of the coarse mix. This resulted in the coarse-coarse and coarse-fine mix interface. Next a fine-graded mix was laid was laid on the fine-graded mix base coarse, to obtain the fine-fine mix interface. This process can be seen in Figure 3.4.

Figure 3.4- (Left) Placing and (Right) Leveling the Asphalt Layer on Top of Coarse Base

Figure 3.5- Asphalt is almost completely leveled out and ready to be compacted

Figure 3.6- Compaction of the second asphalt concrete lift

After the second lifts of asphalt concrete had been placed it was allowed to set for a few days before taking the core samples. A coring machine was used to take 100 mm diameter core samples as shown in Figure 3.7.

Figure 3.7- Coring Machine used for 4-inch Diameter Core Samples

Figure 3.8- The Core Samples

When coring the samples with coarse-fine mix interface with no tack coat (specimen # 8), all samples separated at the interface before they could be removed from the hole. This failure may be attributed to a weak bond between layers at the interface. Also when coring the samples for the fine-fine asphalt mix interface with no tack coat, several samples separated before being removed from the hole so multiple cores had to be cut to obtain enough intact samples. The two layers of asphalt separated during coring because the layers did not bond well enough to withstand the shear force exerted at the interface.

After coring, the bottom of the samples was cut with a wet saw. This was necessary because, due to the way the samples were constructed, the bottoms were rough and uneven. This would cause uneven load distribution when the interfaces are tested in shear with normal load.

Figure 3.9- Wet Saw for Sample Cutting

3.2. Test Configuration Construction

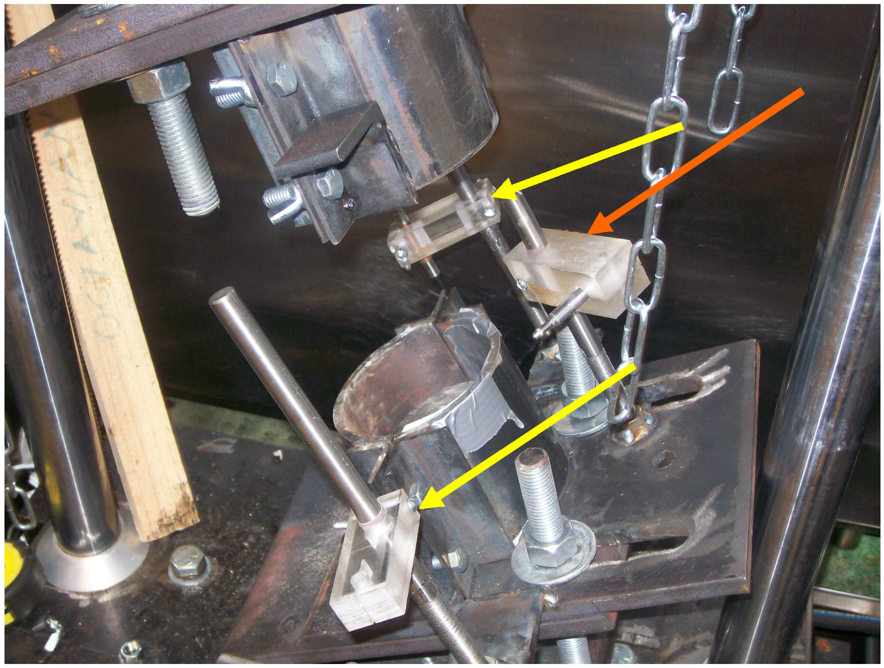
After saw cutting the samples they were ready to be tested. Before testing could begin, two attachments for the Universal Testing Machine (UTM) of the Advanced Asphalt Laboratory machine had to be built. The steel attachments were fabricated at Express Steel located in Shawnee, Kansas and then finished in the shop at KSU. Each attachment weighs 252.66 Newtons. With the asphalt cores (4 inches in diameter) supporting the weight of the top attachment, a preloading stress of 31 kPa is applied at the interface due to the weight of the steel attachment alone. The individual attachments can be viewed and the attachments in working setup can be viewed in Figure 3.11.

Figure 3.10- The Attachments in the UTM Machine

Figure 3.11- The Attachments Placed in the UTM Machine and Ready for Testing

Special holders for the LVDT's were constructed out of plexi-glass. Three LVDT's were used to measure displacement: two were set up to measure normal displacement and one LVDT to measure radial displacement, as shown in Figure 3.12. (the yellow arrows are pointing to the axial LVDT holders and the red arrow is pointing to the radial LVDT holder).

Figure 3.12- The LVDT's and the LVDT Holders



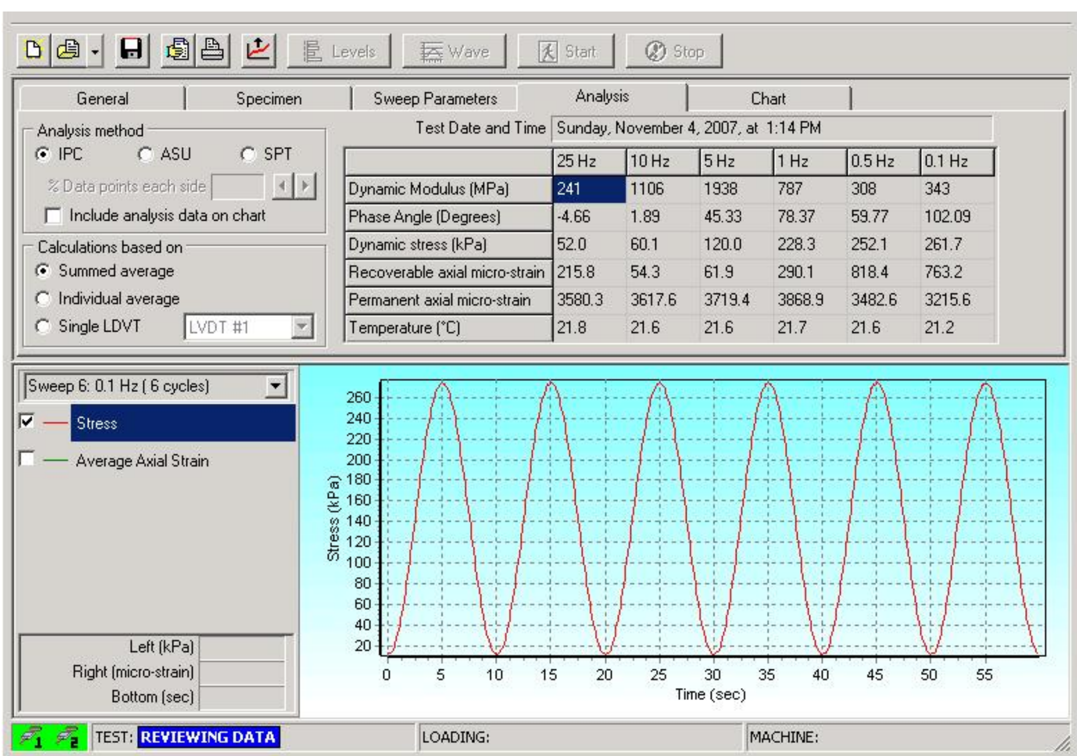
3.3. Testing

At the beginning of the test, the core samples were placed into the lower attachment and secured tightly. Then the lower attachment was raised up to meet the upper attachment. After the core was placed into the cup on the upper attachment, the bolts were tightened to securely fasten the core in the cup of the upper attachment. After the table holding the attachments was raised to meet the actuator or the actuator was lowered to meet the attachments. The actuator came down to meet a circular piece of metal with a notch cut in it for the actuator to sit in. This circular plate then sat on a ball bearing plate to allow the top attachment to move freely in the horizontal direction without applying any horizontal forces to the actuator. This can be seen in Figure 3.11 with the yellow arrow identifying these pieces.

Now with the core securely fastened and the actuator in place, the Dynamic Shear Reaction Modulus test was run first. In this test the actuator applies a vertical pulsating force on the interface at several different frequencies. These frequencies are 25, 10, 5, 1, 0.5, and 0.1 Hz. The readings during this test were taken from the 3 LVDT's installed on the attachments. The two different angles that the specimens were tested at were an angle of 20^{o} and 30^{o}. To begin this test you must open the program specifically for the Dynamic Modulus test. There is some information that must be input such as core diameter, length, sample identification, and comments if desired. Once all the information is input and the testing options have been selected the LVDT's must be set. A screen will come up with showing the LVDT's readings, so that the LVDT's could be adjusted to have the initial reading at their midpoint range. Once the program is started, the test commences first with the loading at 25Hz frequency and continues with the loading at the remaining frequencies, in decreasing order; the last loading frequency is 0.1 Hz. This test took approximately 5 minutes from start to finish.

Figure 3.13 shows the typical output from the Dynamic Modulus Test. As mentioned before, the test is run at several frequencies starting with 25 Hz and stopping at 0.1 Hz. The test records the data in columns for each frequency, which includes dynamic modulus, phase angle, dynamic stress, recoverable axial micro-strain, permanent axial micro-strain, and the temperature of the sample at the time it was tested. The data shown in this case is based on the summed average, which can be changed via options on the left side of the Figure. The graph shown in Figure 3.13 displays the stress (kPa) vs. time (sec).

Figure 3.13- A typical Output and Graph of a Dynamic Modulus Test



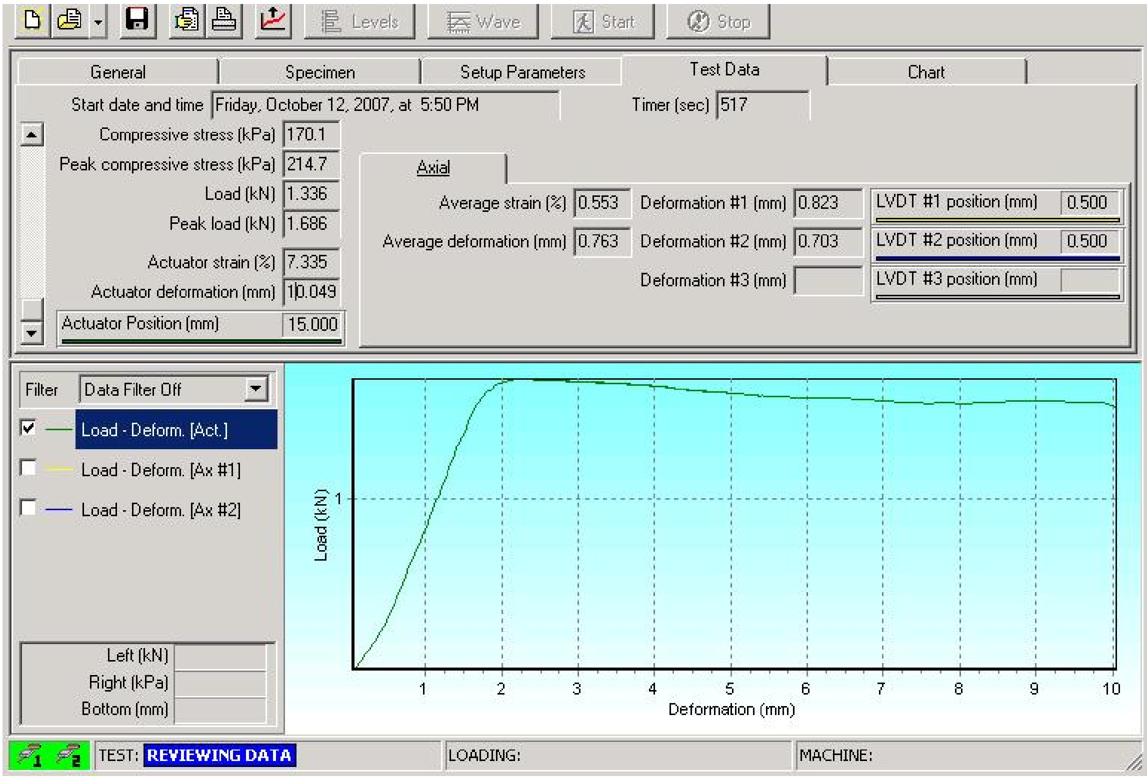
A Shear Strength test was run on the sample after the Dynamic Modulus test was finished. This test was performed to determine the shear strength of the interfaces. The on-specimen mounted LVDT's were removed to avoid their deterioration when the interface fails. So the actuator displacement was used to measure the displacement in this test. A maximum displacement of 10 mm and the displacement rate of 0.05 mm/sec of the vertical actuator were used in the Shear Strength test.

This test was performed for two angles between the normal direction to the interface and the direction of the applied load: 20^o and 30^o. This test was conducted immediately after the Dynamic Shear Reaction Modulus test, because the samples were already fastened and put in place.

Another program specifically for the Shear Strength tests was used for this test. Once the program is open, the required information is keyed in: core length, core diameter, core identification number, the displacement rate, and the maximum displacement of the actuator.

Figure 3.14 shows a typical screen capture during the shear strength test, with the vertical load vs. shear deformation at the interface during the test. It can be observed that the deformation increases with the applied load until the maximum load is reached. At that point, the interface fails and the two layers at the interface continue to move relative to each other, but under lesser stress. The relative information shown in Figure 3.14 is the compressive stress, which multiplied by the sine of the angle, at which the sample was being tested to find the shear stress and the actuator deformation, which was also multiplied, by the sine of the angle at which the sample was being tested to find the shear displacement.

Figure 3.14- Typical Output and Graph of a Stress-Strain Test



CHAPTER 4 - RESULTS

In general, all interfaces tested with varying tack coat application rates had roughly the same shape of strength curves. Also, in general the ultimate strength values were all very close to each other, only varying 3 to 4 kPa. These findings would suggest that the tack coat application rate does not have an effect on the ultimate strength of the bonding of the asphalt layers when they are under a normal load. However, when not subjected to a normal load this could be different because there were a few problems with cores separating while they were being cut. All samples with no tack coat with the coarse-fine interface separated during the coring process and several of the fine-fine interfaces with no tack coat did as well.

The first round of tests was conducted with the apparatus set at an angle of 30 degrees and at a temperature of 20°C. This seemed to work fine for both the Dynamic Modulus tests and the Strength tests. The weight of the upper attachment did, however, break some samples before they could be tested: two of the #12 samples and one of the #10 samples.

After this, it was attempted to test at 45 degrees angle between the actuator and the interface and at the temperature of 20°C. At this angle, the shear component of the dead weight of the upper attachment sheared the sample at the interface of all samples before testing could begin. Thus, the 45-degree angle was found to be too large, so the testing was continued for the angle between the actuator and the normal to the interface of 20 degrees.

At this new angle, the Dynamic Shear Reaction Modulus Tests were conducted first. However, when the strength test was performed, it was found that, for this reduced angle, the normal stress at the interface was too high, and failure of the interface in shear was not induced anymore; the samples were failing in compression. Therefore, no strength tests were performed for the 20-degree angle.

4.1- Strength Tests

The final results of the strength tests are shown in Table 4.1. This table shows the ultimate stress level at which each sample was subjected to and its corresponding displacement at that stress level. Once the ultimate stress level was reached it took lower and lower shear stress to cause more and more deformation.

Table 4.1- Shear Strength Test Results at 30-degree Angle

Coarse-Coarse Interface		
Sample Label	Maximum Shear Stress (kPa)	Corresponding Displacement (mm)
1.1	105.68	1.249
1.2	106.95	1.102
2.1	106.62	1.093
2.2	107.30	1.120
3.1	108.47	1.073
3.2	107.66	1.874
4.1	108.13	67.115
4.2	108.45	97.269
Coarse-Fine Interface		
5.1	107.66	4.261
5.2	105.62	1.350
6.1	108.26	1.045
6.2	107.80	1.075
7.1	107.33	1.343
7.2	104.97	1.249
8.1	N/A	N/A
8.2	N/A	N/A
Fine-Fine Interface		
9.1	102.69	1.528
9.2	105.61	1.419
10.1	106.29	1.249
10.2	N/A	N/A
11.1	106.60	1.277
11.2	105.52	2.232
12.1	N/A	N/A
12.2	N/A	N/A

Figure 4.1- Interface Shear Strength of Each Sample Tested

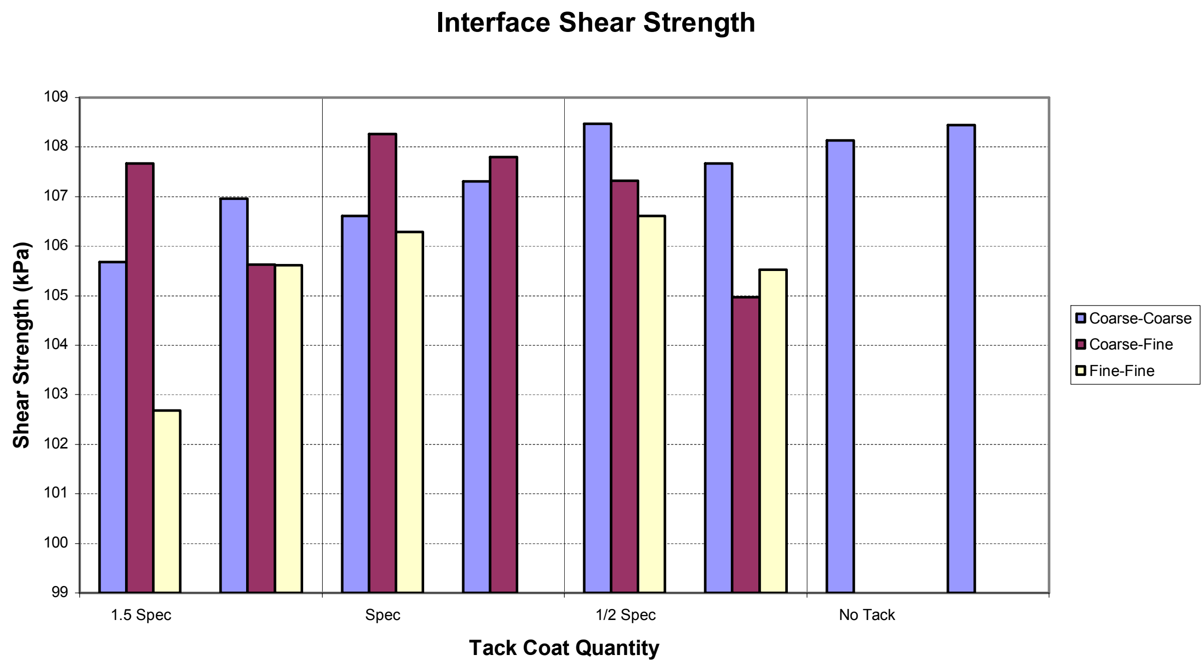


Figure 4.1 suggests that the ultimate shear strength of the interface does not depend significantly on the quantity of tack coat for any of the three interfaces. All samples except one had an ultimate strength between 105 kPa and 109 kPa. This is not really a significant difference. For the coarse-coarse mixes interface, the shear strength decreases when the applied tack coat quantity increases.

The results of the strength tests have been plotted next to each other to aid in comparing the results. The data has been grouped in two ways. One way the data was grouped to compare was the effect of the rate of tack-coat application for interface type (Figures 4.2 to 4.4). The second grouping was done to compare the effect of the three-interface types, for the same tack-coat application rate.

Figure 4.2- Shear Stress-Displacement Curves for the Coarse-Coarse Interface

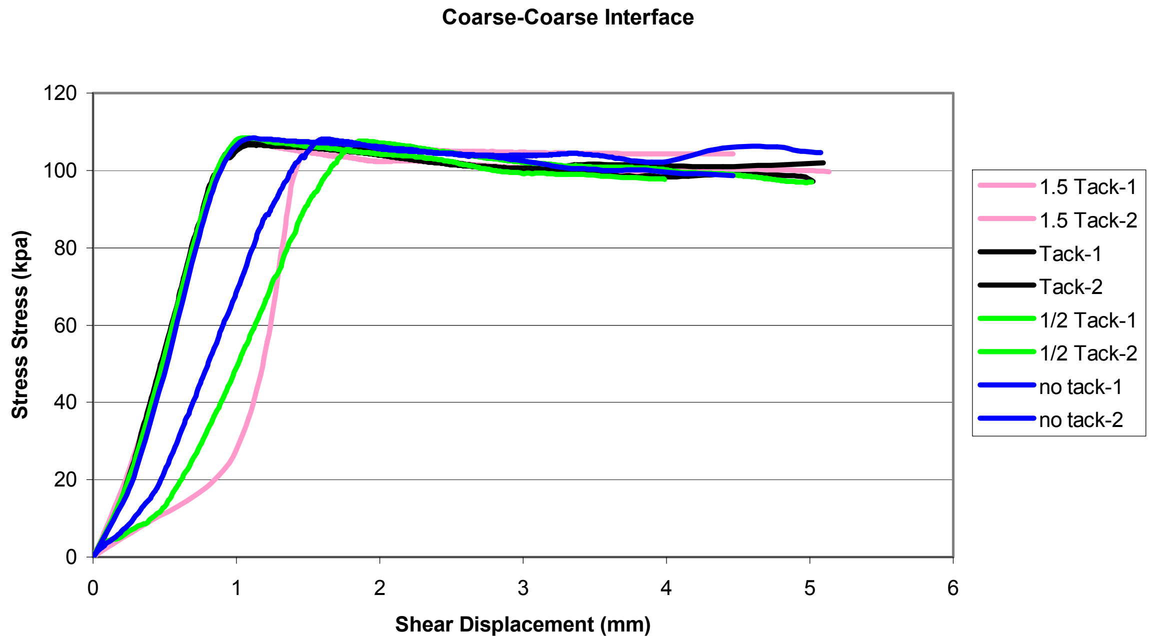


Figure 4.3- Shear Stress-Displacement Curves for the Coarse-Fine Interface

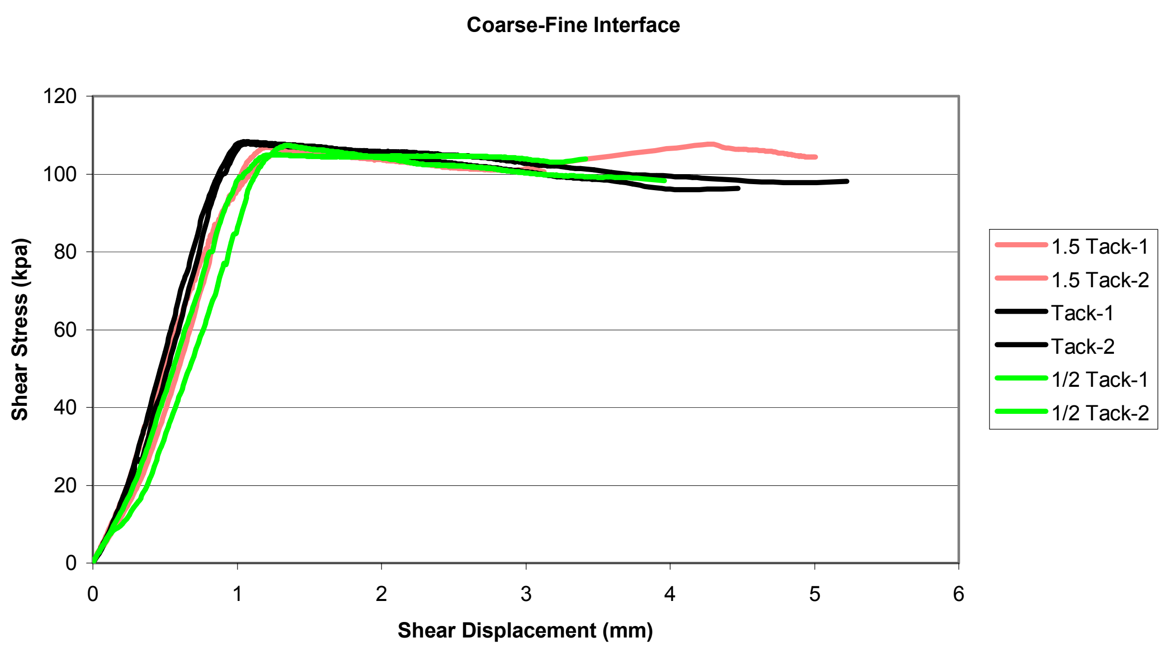


Figure 4.4- Shear Stress-Displacement Curves for the Fine-Fine Interface

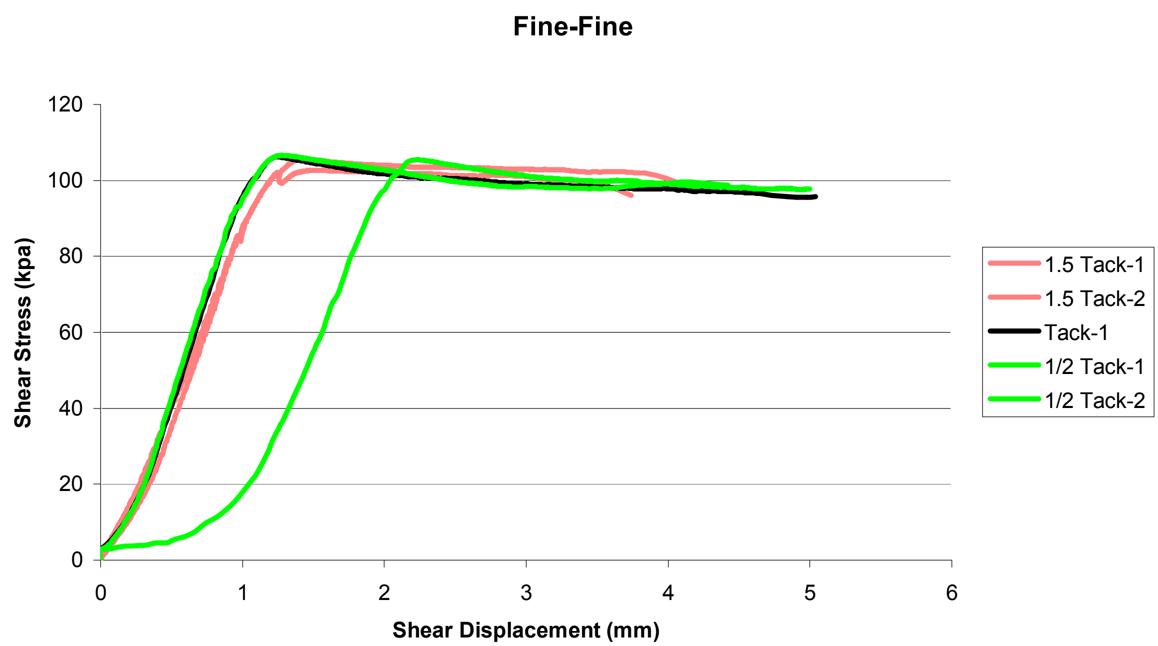


Figure 4.5- Shear Stress-Displacement Curves for Interfaces with No Tack Coat

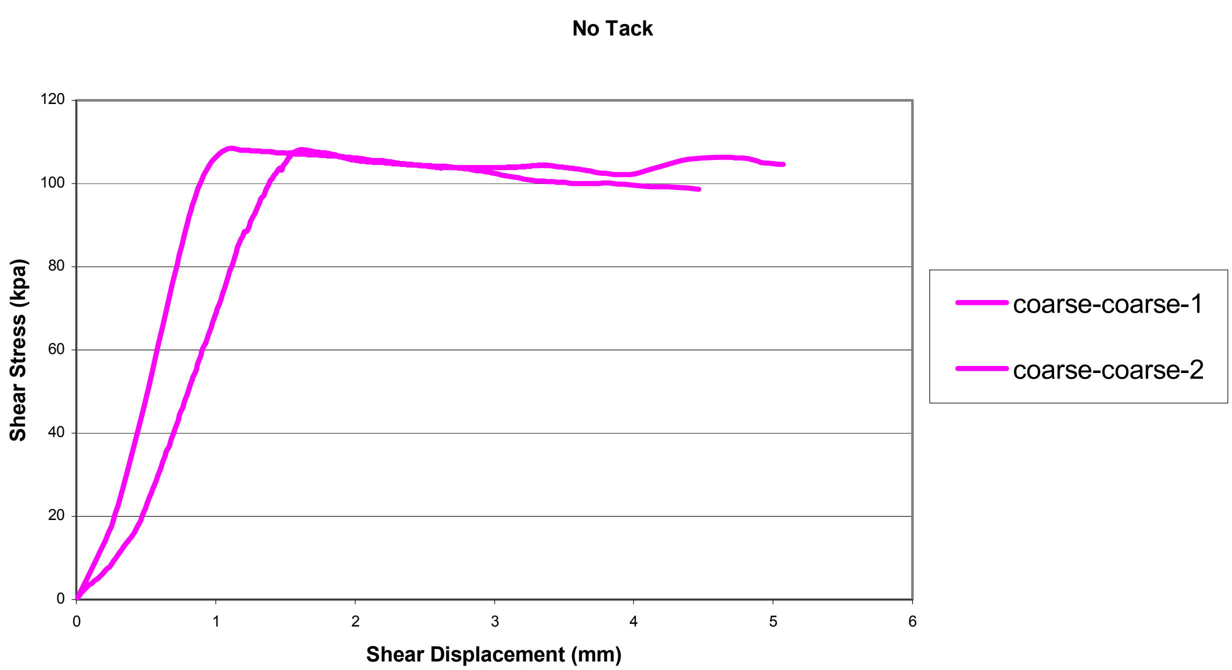


Figure 4.6- Shear Stress-Displacement Curves for Interfaces with 1/2 Specification Tack Coat

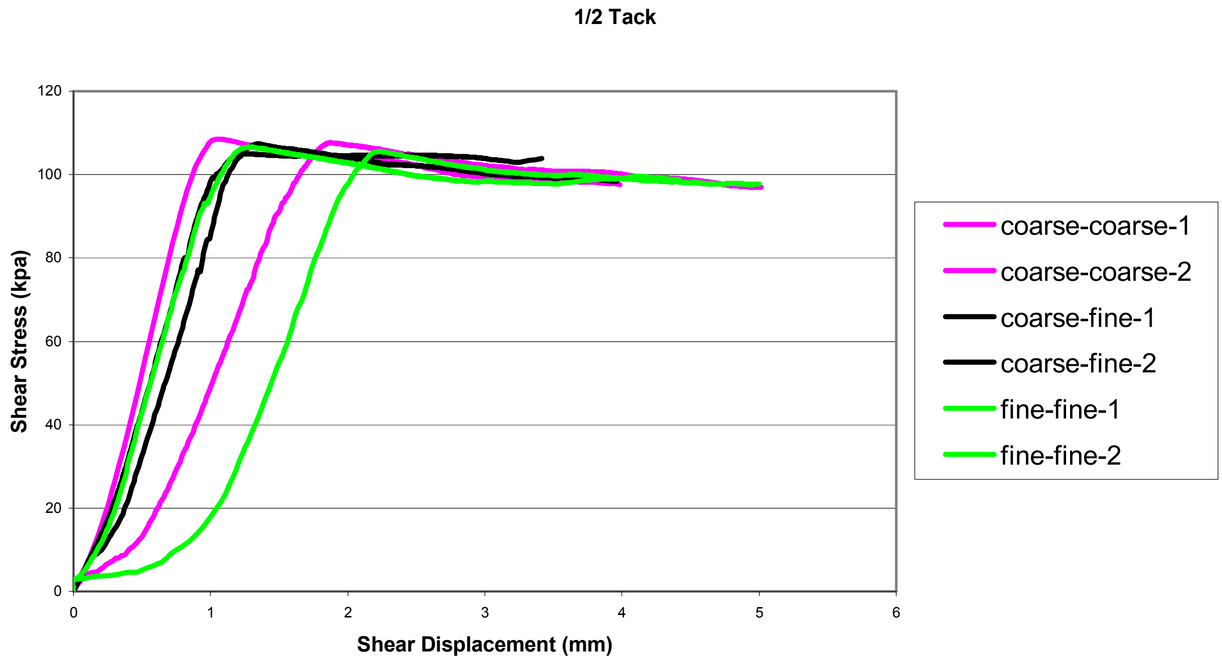


Figure 4.7- Shear Stress-Displacement Curves for Interfaces with Specification Tack Coat

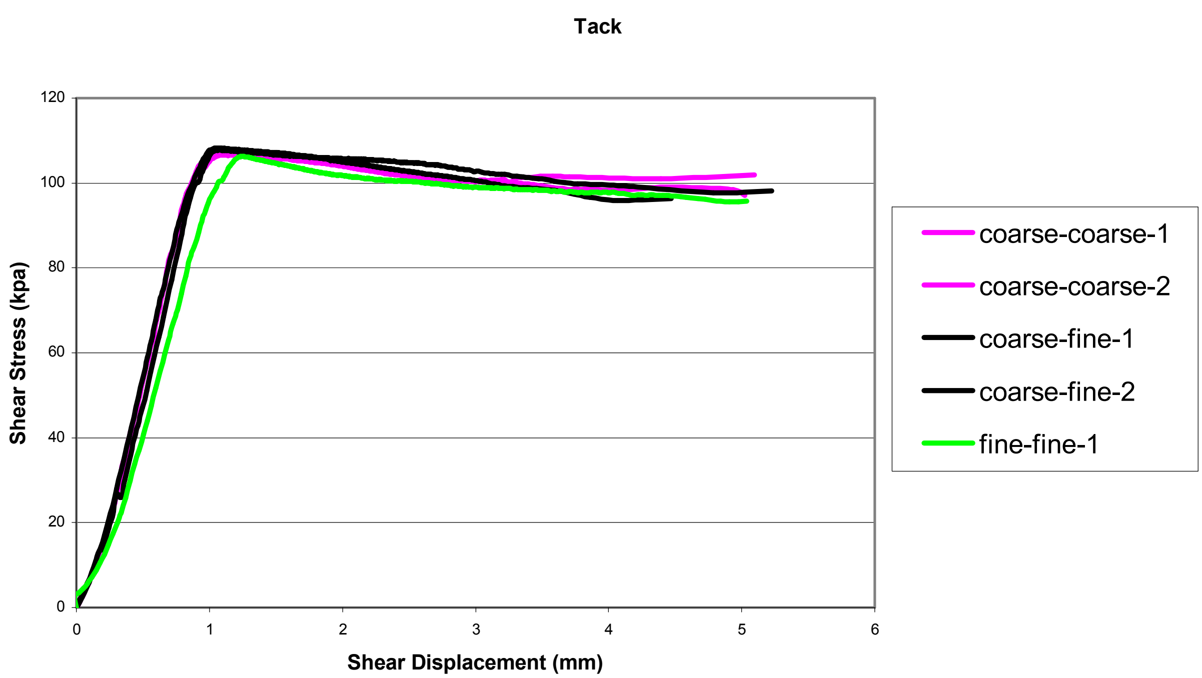
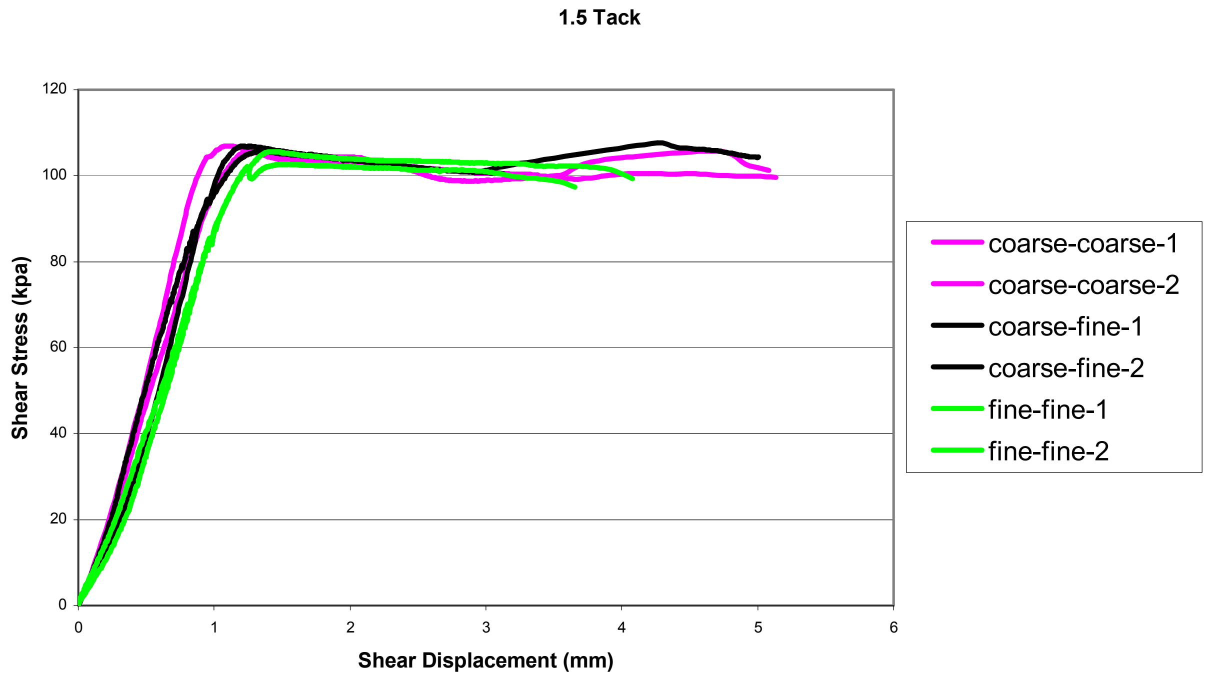


Figure 4.8- Shear Stress-Displacement Curves for Interfaces with 1.5 Specification Tack Coat



Figures 4.2 through 4.8 show a definite trend. The maximum shear stress typically occurred between 1 and 2 mm of deformation. All of the maximum shear stresses were also between 100 and 120 kPa. There was an increase of the shear stress with the shear displacement up to a maximum shear stress after which the shear stress stabilized. These graphs would also suggest that under simultaneous, proportional normal and shear loads; the tack coat application rate does not significantly affect the shear strength of the interface.

4.2-Dynamic Modulus Tests

Table 4.2 shows a summary of the dynamic modulus test results for all interfaces. Data in Table 4.2 shows that the dynamic modulus tends to be higher for the samples when they are tested at an angle of 30 degrees. The importance of testing samples at multiple frequencies is that the different frequencies simulate a vehicle moving over the pavement at different speeds (i.e. 10 Hz simulates a vehicle moving at approximately 40 mph).

Table 4.2- Dynamic Shear Reaction Modulus Test Results

Sample ID	Angle	Interface	Dynamic Modulus (MPa)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
1.1-20d	20	1	69	322	307	277	267	266
1.1-20d	20	1	69	289	266	198	196	222
2.1-20d	20	2	41	355	332	206	200	216
2.2-20d	20	2	73	327	286	240	231	240
3.1-20d	20	3	58	423	399	293	290	304
3.2-20d	20	3	48	223	207	177	175	611
4.1-20d	20	4	43	282	266	233	225	237
4.2-20d	20	4	49	270	258	197	192	208
5.1-20d	20	5	44	267	283	233	214	222
6.1-20d	20	6	54	239	219	190	184	184
6.2-20d	20	6	48	257	229	192	185	179
7.1-20d	20	7	40	269	261	227	219	227
7.2-20d	20	7	45	281	273	234	225	225
9.1-20d	20	9	39	239	257	208	197	190
9.2-20d	20	9	43	280	241	219	213	228
10.1-20d	20	10	94	400	355	265	252	258
10.2-20d	20	10	74	282	319	247	243	252
11.1-20d	20	11	100	321	293	225	213	214
11.2-20d	20	11	67	283	270	204	196	206
12.1-20d	20	12	105	333	306	238	224	230
12.2-20d	20	12	114	361	329	268	257	262
1.1-30d	30	1	186	300	286	232	238	262
1.1-30d	30	1	111	183	192	189	190	187
2.1-30d	30	2	91	658	933	899	668	454
2.2-30d	30	2	104	460	1002	796	643	471
3.1-30d	30	3	110	300	464	576	521	467
3.2-30d	30	3	158	278	318	323	271	224
4.1-30d	30	4	81	919	1086	594	846	374
4.2-30d	30	4	92	527	565	477	470	383
5.1-30d	30	5	83	631	990	789	0	0
5.2-30d	30	5	92	600	927	240	158	131
6.1-30d	30	6	93	527	1012	785	305	245
6.2-30d	30	6	78	1174	1467	591	227	178
7.1-30d	30	7	87	408	572	539	405	302
7.2-30d	30	7	114	301	343	454	316	254
9.1-30d	30	9	117	278	310	341	389	360
9.2-30d	30	9	96	336	363	329	372	350
10.1-30d	30	10	68	476	529	478	484	457
10.2-30d	30	10	95	352	423	462	567	470
11.1-30d	30	11	106	256	302	287	294	297
11.2-30d	30	11	105	308	337	326	358	368
12.1-30d	30	12	n/a	n/a	n/a	n/a	n/a	n/a
12.2-30d	30	12	n/a	n/a	n/a	n/a	n/a	n/a

Table 4.3- Phase Angle Test Results

Sample ID	Angle	Interface	Phase Angle (Degrees)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
1.1-20d	20	1	104.15	6.76	11.43	10.9	12.46	11.51
1.1-20d	20	1	129.17	7.23	11.55	12.44	13.32	14.66
2.1-20d	20	2	94.75	-1.15	16.03	10.18	12	14.26
2.2-20d	20	2	57.97	2.07	11.38	11.08	12.93	13.63
3.1-20d	20	3	-30.81	-5.17	12.53	13.54	14.32	13.84
3.2-20d	20	3	120.7	9.64	11.76	11.75	12.11	-47.87
4.1-20d	20	4	105.67	3.94	10.03	12.36	13.88	13.77
4.2-20d	20	4	117.84	3.38	10.23	12.21	13.73	14.08
5.1-20d	20	5	125.59	7.52	12.06	10.95	11.54	13.11
6.1-20d	20	6	133.73	5.49	9.51	8	9.36	10.33
6.2-20d	20	6	109.91	9.8	10.14	8.18	9.76	10.56
7.1-20d	20	7	81.9	5.95	10.99	9.96	11.44	12.01
7.2-20d	20	7	75.35	6.32	13.09	9.65	10.99	11.39
9.1-20d	20	9	91.85	2.7	7.99	9.52	11.61	12.7
9.2-20d	20	9	105.39	6.44	9.49	9.88	11.24	11.14
10.1-20d	20	10	21.38	1.5	16.98	13.74	13.67	13.74
10.2-20d	20	10	118.96	5.69	10.68	13.08	13.62	13.29
11.1-20d	20	11	30.04	3.14	8.11	9.61	11.47	11.47
11.2-20d	20	11	45.41	3.71	7.48	11.17	12.64	13.88
12.1-20d	20	12	29.31	5.88	9.78	13.6	15.26	16.15
12.2-20d	20	12	41.01	4.29	9.65	12.73	13.97	13.93
1.1-30d	30	1	17.58	3.56	1.79	4.8	5.47	1.15
1.1-30d	30	1	8.2	1.68	1.32	2.18	4.19	6.4
2.1-30d	30	2	-18.81	0.37	-18.87	-42.12	106.88	121.26
2.2-30d	30	2	-6.47	1.06	-24.41	-32.99	106.96	-4.42
3.1-30d	30	3	-9.27	3.34	-3.24	-29.8	-21.63	-14.37
3.2-30d	30	3	-18.33	8.57	5.4	7.63	9.39	16.31
4.1-30d	30	4	-19.64	33.93	7.07	22.79	3.31	-46.18
4.2-30d	30	4	-22.11	13.9	14.36	12.96	-155.55	-156.4
5.1-30d	30	5	-5.99	-7.24	-62.57	69.71	0	0
5.2-30d	30	5	-12.94	-0.16	-122.85	24.77	37.7	29.02
6.1-30d	30	6	-8.44	4.89	-18.03	44.14	41.62	44.77
6.2-30d	30	6	-6.52	-10.82	39.5	21.52	24.93	41
7.1-30d	30	7	-5.99	1.8	-19.56	-42.7	86.95	67.15
7.2-30d	30	7	-13.93	3.39	-2.17	-38.63	68.32	66.4
9.1-30d	30	9	-22.1	3.85	0.68	3.42	4.66	-2.48
9.2-30d	30	9	155.04	6.97	2.63	4.87	4.42	1.98
10.1-30d	30	10	99.52	7.31	4	2.61	1.18	-2.12
10.2-30d	30	10	-34.91	10.23	1.71	-7.24	157.45	156.39
11.1-30d	30	11	-28.45	8.55	4.26	7.17	9.77	11.45
11.2-30d	30	11	-31.39	7.3	5.74	6.92	7.68	7.97
12.1-30d	30	12	n/a	n/a	n/a	n/a	n/a	n/a
12.2-30d	30	12	n/a	n/a	n/a	n/a	n/a	n/a

Figures 4.9 through 4.15 compare the Dynamic Shear Reaction Modulus of different interfaces. These figures compare each interface tested at the same angle to the varying tack coat application rates. Figure 4.15 compares the Dynamic Shear Reaction Modulus of the different interfaces and varying tack coat application rates at 10 Hz, which is significant because it simulates traffic on the pavement at approximately 40 mph.

Figure 4.9- Dynamic Shear Modulus of Coarse-Coarse Interface at 20-degree Angle

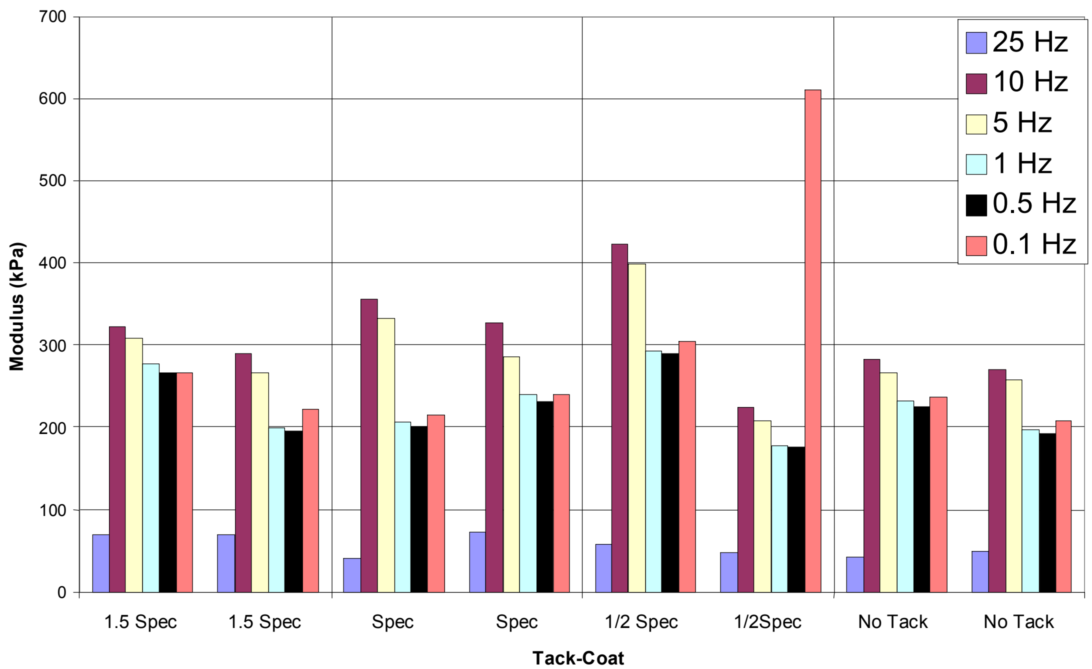


Figure 4.10- Dynamic Shear Modulus of Coarse-Fine Interface at 20-degree Angle

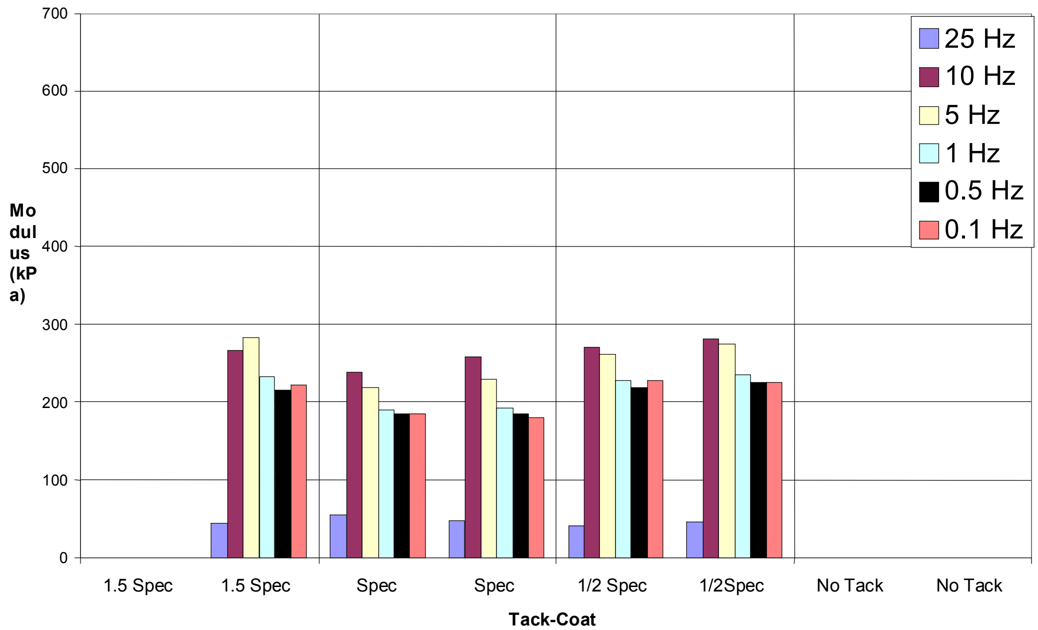


Figure 4.11- Dynamic Shear Modulus of Fine-Fine Interface at 20-degree Angle

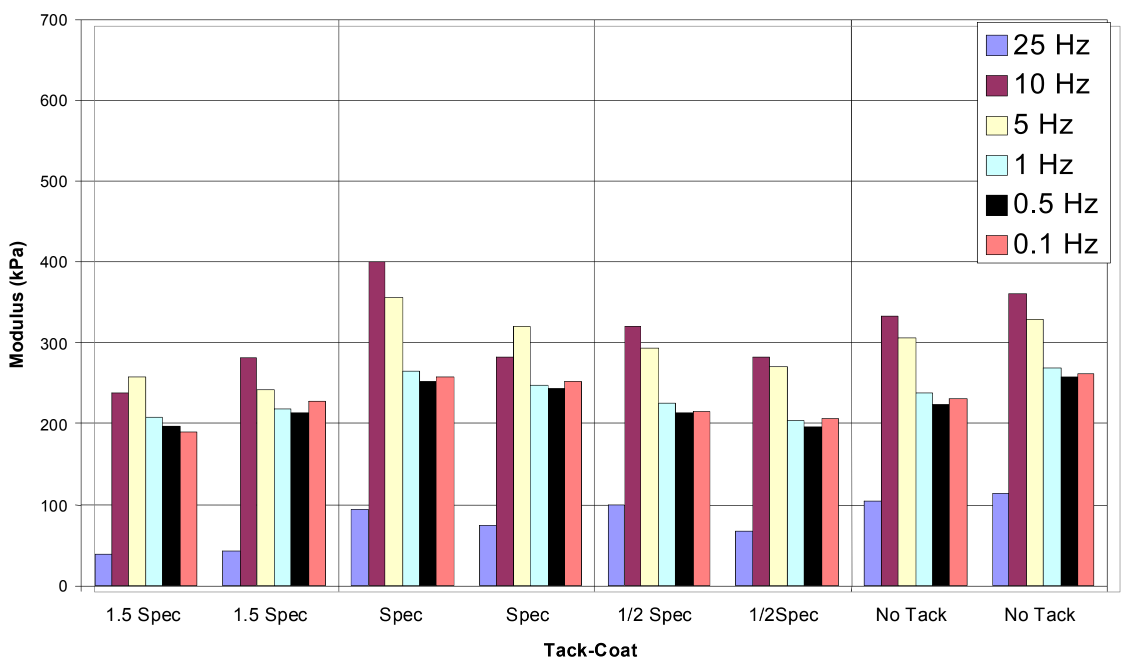


Figure 4.12- Dynamic Shear Modulus of Coarse-Coarse Interface at 30-degree Angle

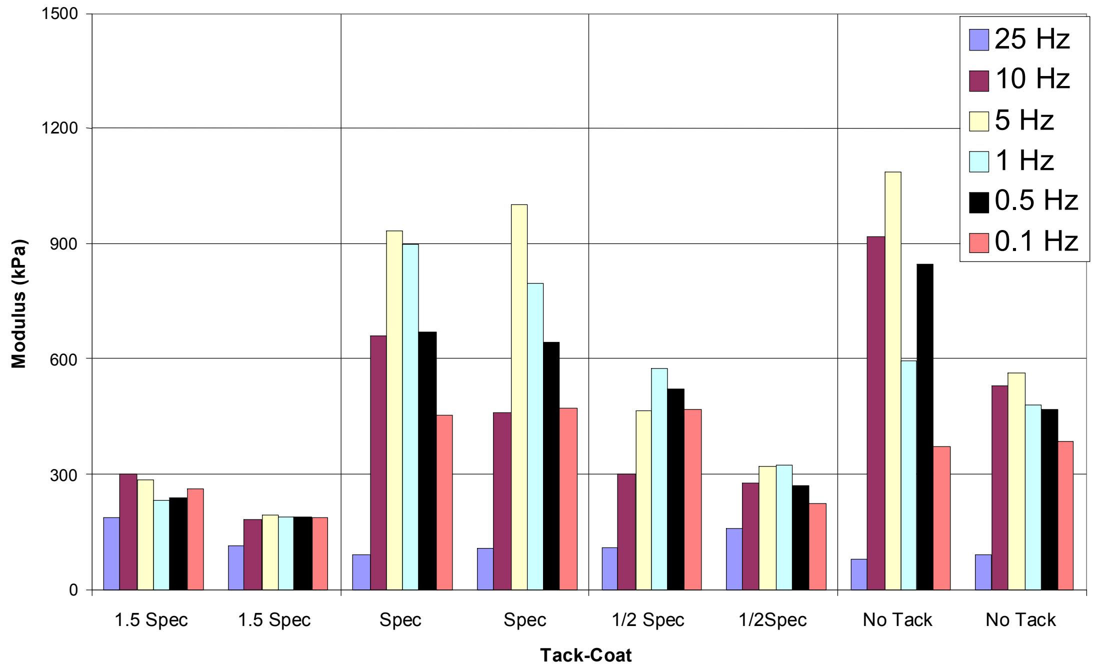


Figure 4.13- Dynamic Shear Modulus of Coarse-Fine Interface at 30-degree Angle

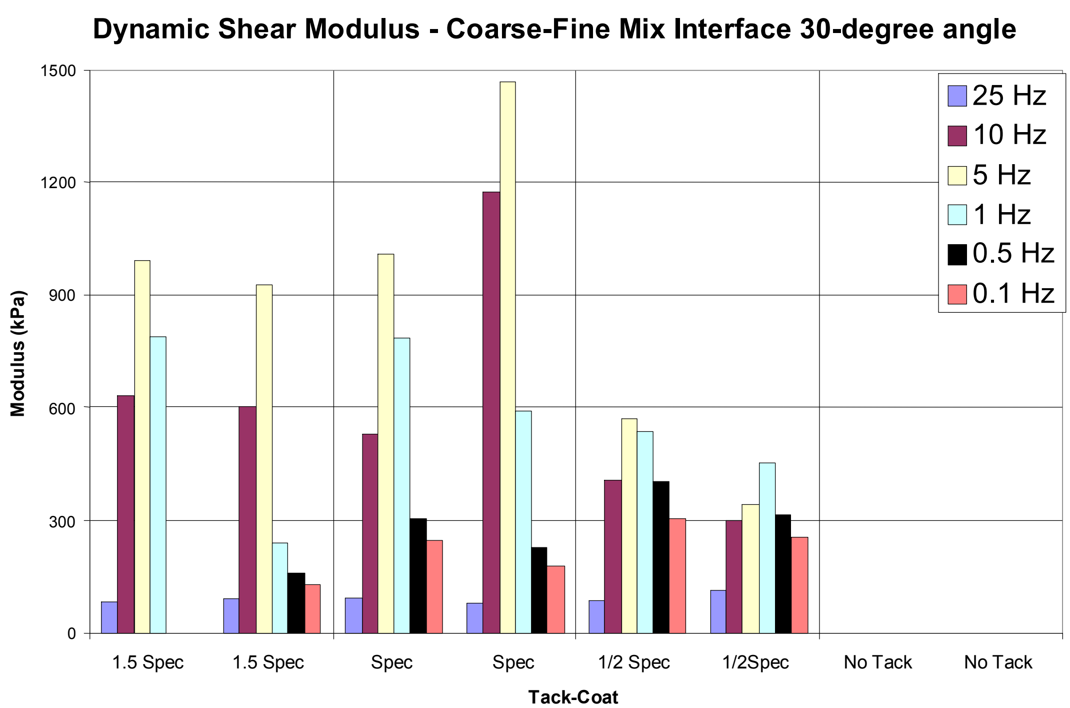


Figure 4.14- Dynamic Shear Modulus of Fine-Fine Interface at 30-degree Angle

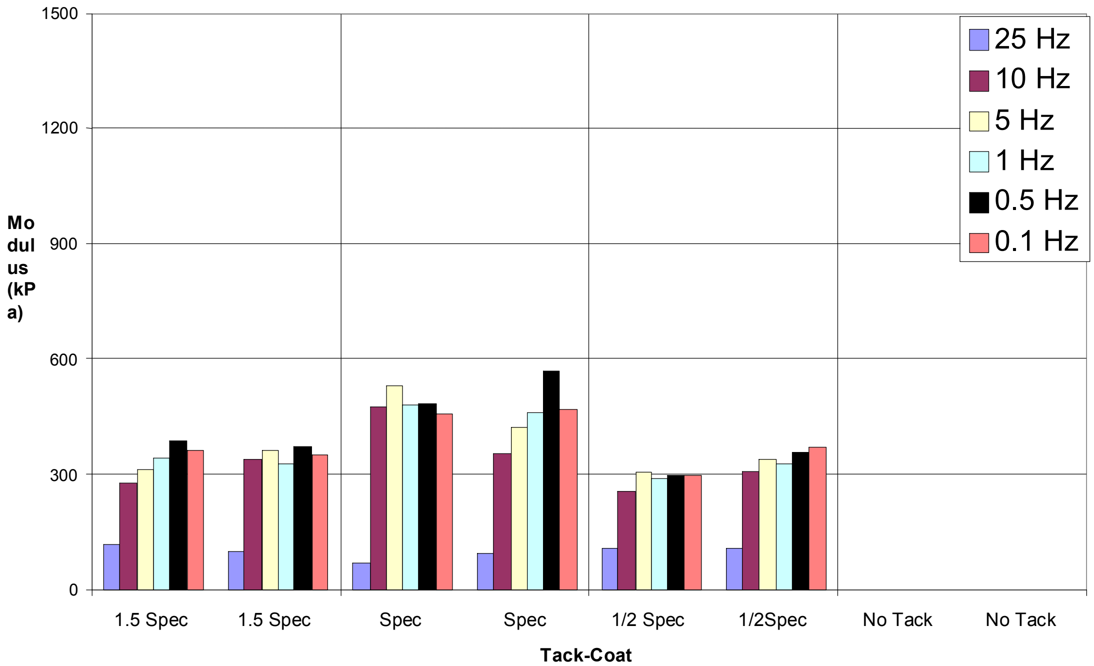
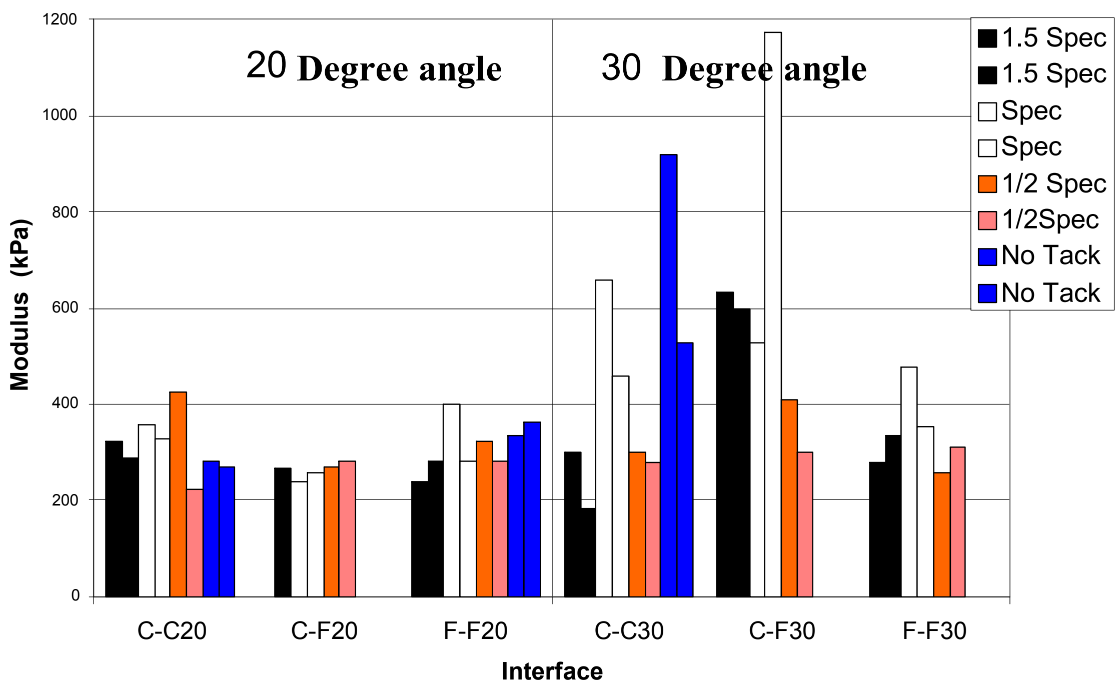


Figure 4.15- Dynamic Shear Modulus at 10 Hz at Different Angles



For the 20-degree angle, the shear modulus ranged between 200 and 300 kPa. The lowest variability of the modulus was obtained for the interface with the specification rate application of tack coat. For the other two interface types, the lower variability of shear modulus was also obtained for the specification rate of tack-coat application.

For the Coarse-Fine Interface the optimum tack coat application rate was found to be ½ specification rate (11gm/sq.ft) of tack coat application; the shear moduli were the highest measured and very similar values were obtained for both samples. It is important to note that the modulus obtained for the specification rate for tack coat was not much lower than that obtained for the ½ specification rate. For the coarse-coarse and fine-fine mix interfaces the optimum tack coat application rate was the specification rate.

For the 30-degree loading angle, the highest shear modulus was obtained for the specification rate of tack-coat application rate for all interfaces. The coarse-coarse interface has the most repeatable values for the dynamic shear reaction modulus and higher values than any other interfaces. Even very consistent, the shear modulus was the lowest for the fine-fine mix interface when compared to the values for the other two interfaces.

The shear modulus results obtained for the loading frequency of 10 Hz are of more interest, since this frequency simulates the loading under the passing of a vehicle at moderate speed (40 mph). When comparing the dynamic shear reaction modulus values of all the different interfaces at this frequency, the highest modulus was obtained for the coarse-fine interface with the specification tack-coat application rate at the 30-degree angle. However, for the 20-degree angle, this interface had the lowest modulus; the coarse-coarse mix interface and the fine-fine mix interface had very similar shear modulus values.

In general, the higher dynamic shear reaction modulus values were obtained for the 30-degree angle. This contradicts the common assumption that the shear modulus is higher when the normal stress at the interface is higher. When the samples were tested at an angle of 20-degrees, the interface type and application rate did not seem to make as big as a difference as it did at 30 degrees.

CHAPTER 5 - CONCLUSIONS AND RECOMENDATIONS

The purpose of this research was to evaluate the mechanical properties of asphalt-to-asphalt interfaces using tests in which the interface is subjected simultaneously to a normal and shear stresses. This loading was applied to simulate the corresponding stress condition developed at the interfaces between asphalt layers when a vehicle rolls on a flexible pavement structure. The core samples were obtained from the pavement layers built at the Civil Infrastructure Systems Laboratory (CISL) of Kansas State University with conventional methods. The core samples were tested at the Civil Engineering Advanced Asphalts Laboratory at Kansas State University. Three different asphalt-to-asphalt interfaces were constructed (coarse-coarse mixes, coarse-fine mixes and fine-fine mixes), each with four different tack coat application rates (no tack coat, ½ specification, specification, and 1 ½ specification tack coat). This resulted in twelve different combinations of asphalt interface types and tack coat application rates.

The testing attachments were built to allow testing of the specimens at different angles from 0 to 45 degrees. The experiments were conducted for two angles (20 and 30 degrees) between the normal direction to the interface and the direction of the applied force.

At the beginning of the laboratory tests, the sample was secured into the top and bottom attachments and then the actuator was set into place on top of the upper attachment. The Dynamic Modulus software was then opened and the sample specifications were entered (length, diameter, volume, sample number). Once the LVDT's were adjusted and the temperature was allowed to stabilize the program was started. The Stress-Strain test program was then run to measure the shear strength of the interfaces. Once it was open the sample specifications were entered (length, diameter, volume, sample number. The program was run at a rate of deformation of 0.05mm/sec and continued to run until a total deformation of 10mm was reached. When testing at the angle of 30 degrees a few of the specimens were sheared apart at the interface before testing could begin. This was due to the weight of the upper apparatus. Also, when testing at 20 degrees, the interface did not fail in shear; the samples failed in compression.

The results of the laboratory experiments led to the following conclusions:

- The interface shear strength was about the same, between 105 and 109 kPa for all interface types and tack-coat application rates. Since no effect of tack-coat application rate or interface type on the shear strength were observed, the strength tests should not be used to optimize the tack coat application.
- The Dynamic Shear Reaction Modulus of the fine-on-fine interface was lower than the moduli of the coarse-coarse or coarse-fine interfaces.
- When the specimens were tested at an angle of 20-degrees, the interface type did not affect the Dynamic Shear Reaction Modulus nearly as much as at 30-degrees.
- When considering the no tack-coat application rate, the interface that seemed to work best was the coarse-on-coarse interface. It yielded much higher Dynamic Shear Reaction Moduli than the other two interfaces did when only considering the no tack application rate.

The following recommendations were drawn from this study:

- When dealing with the coarse-on-coarse interfaces, the best tack coat application rate is the current specification rate. It produced the highest dynamic modulus results for that interface.
- The coarse-fine and fine-fine interfaces have the highest Dynamic Shear reaction Moduli at the specification rate of tack coat application. This suggests that the current practice is the optimum method for constructing these interfaces.
- The Dynamic Shear Modulus tests should be used to determine the optimum tack-coat application rate in lieu of the shear strength test. The shear strength tests cannot distinguish the effect of tack-coat application rate or interface type on the shear strength.
- For further studies the apparatus should be constructed of lighter material to reduce the initial stress put on the sample. It should also be taken into account that this study did not include the stress on the sample before testing began. The pre-loading stress on the samples was approximately 31 kPa.

CHAPTER 6 - REFERENCES

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Appendix A - Mix Designs

Table 6.1- Single Point gradation of Base Mix # 1

Base Mix #1 (Top Lift)												
Sieve	1 ½	1	¾	½	3/8	#4	#8	#16	#30	#50	#100	#200
Single Point	0	0	0	0	2	24	41	60	75	86	92	94.5
Binder Grade	PG 64-22											
Binder Content	5.25%											

Table 6.2-Single Point gradation of Base Mix # 2

Base Mix #2 (Base Coarse)												
Sieve	1 ½	1	¾	½	3/8	#4	#8	#16	#30	#50	#100	#200
Single Point	0	0	0	9	17	34	48	60	74	86	93	96
Binder Grade	PG 64-22											
Binder Content												

Table 6.3- Single Point gradation of Fine Mix (SR-12.5A)

Fine Mix (SR-12.5A)												
Sieve	1 ½	1	¾	½	3/8	#4	#8	#16	#30	#50	#100	#200
Single Point	0	0	0	7	13	23	42	64	78	88	94	96.2
Binder Grade	PG 64-22											
Binder Content	5.40%											