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Evaluation of Bond Strength Between Paving Layers for Hot-Mix Asphalt

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by

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Evaluation of Bond Strength Between Paving Layers for Hot-Mix Asphalt

EXECUTIVE SUMMARY

Poor adhesion between paving layers results in premature pavement distress, and ultimately causes pavement failure. Early detection of bond-related problems through good quality control and quality assurance help prevent expensive rehabilitation efforts. The bonding strength of two tack coat materials was investigated at three application rates, two temperatures, and three mix type combinations. All factors showed a significant effect on bond strength, with temperature exhibiting the greatest effect. While application rate showed an effect on strength, it is demonstrated that an application rate of 0.02 gal/yd^2 is sufficient to develop bond between all pavement type combinations studied – and with both tack coat materials. It is recommended that laboratory results from this study be validated using field cores taken from construction projects; further, it is recommended that an additional study of long-term strength be conducted to assess the variation of bond strength over time.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

A flexible pavement consists of surface course, base course and occasionally subbase course. The surface course provides the maximum strength to the pavement structure and consists of hot mix asphalt (HMA). During construction, a prime coat may be applied on the base course to fill the surface voids, stabilize the fines, and protect the subbase from weather deterioration. Once the base course is treated with prime coat, the surface course is constructed. The surface course may consist of multiple layers, including (a) wearing course (b) binder course and (c) asphalt base. To achieve a good bonding between the lifts of the surface course, tack coat is applied. Tack coat is a thin bituminous asphalt layer, and is applied prior to the construction of subgrade layers. In the case of pavement rehabilitation project, tack coat is applied to the existing pavement surface before placing a new asphalt overlay.

In all cases, the purpose of tack coat is to improve the bonding between the lifts of HMA. The bonding between the lifts of HMA is crucial for pavement performance. Loss of bond between HMA lifts causes the layers of HMA act individually, and fails to support repeated traffic, which imposes bending stress.

Pavements with good bonding between layers perform better and last longer. Application of tack coat is simple and inexpensive compared to the total cost of the project (*1*). For this reason, less importance is given to the tack coat application, and, consequently, several pavement failures like rutting, slippage, as shown in Figure 1, and corrugations arise and cause cracking. These cracks allow water to enter into the pavement layers and accelerate the pavement deterioration. The failure is prominent at traffic signals, small radius curves, heavily trafficked roads, and roads with steep gradient.

FIGURE 1 Slippage Cracks *(14)*

Variables like type, temperature, and application rate of tack coat contribute to the performance of a tack coat and to the longevity of the pavement life. Attention to tack coat application significantly reduces premature pavement failure.

1.2 OBJECTIVES

The overall objective of this project is to evaluate the bond strength between HMA layers. Specific objectives include:

- Evaluate the effects of tack coat material, application rate, testing temperature and normal stress between two HMA layers in the laboratory samples.
- Validate the laboratory results using the field-cored samples.
- Recommend guidelines for tack coat selection, application rate and bond strength tests.

1.3 SCOPE

Poor adhesion results in premature pavement distress, and ultimately causes pavement failure. Early detection of problems through good quality control and quality assurance help prevent expensive rehabilitation efforts. Debonding of pavement layers is one of the factors affecting pavement performance, which can be controlled.

Results of this research will be a catalog for engineers and site inspectors to ensure adequate bonding. This research will also encompass the following:

- Recommendations for tack materials.
- Optimum application rates for the recommended tack coat.

CHAPTER 2 LITERATURE REVIEW

2.1 TACK COAT IN ASPHALT PAVEMENT

A tack coat is a thin or light application of asphalt emulsion or paving asphalt on an existing pavement surface. As per ASTM D 8-02, tack coat is defined as "an application of bituminous material to an existing relatively non absorptive surface to provide a thorough bond between old and new surfacing" (*2*).

Tack coat is used to ensure a strong bond between the existing pavement surface and the new asphalt concrete overlay and between the lifts of the asphalt concrete (*3*). Tack coat acts as an adhesive between two HMA layers and helps to eliminate the possibility of slipping (*4*). Thus, it allows the lifts of HMA to perform as a monolithic structure.

Tack coat is in the form of asphalt emulsion or liquid asphalt (*5*). Tack coats such as cutback asphalt are used currently. The simple mechanism of tack coat bonding involves the hot mixture placed on the tack coat softening the tack coat layer so that it can fill the surface voids in the HMA. Therefore, after compaction, it partially interlocks with the hotmix layer thus creating a bond (*6*).

2.2 TYPES OF TACK COAT

There are two primary types of tack coats: asphalt emulsion and cutback asphalt binder. Asphalt emulsion is a stable, homogenous mixture of minute asphalt droplets suspended in a continuous water phase. The stability of oil and water dispersion is brought about by a colloidal mill, which shears the asphalt into tiny droplets. Cutback asphalt is a combination of asphalt and petroleum products. After the application of cut back asphalt, the petroleum product evaporates leaving behind the asphalt. Chemical surfactants in the water phase stabilize the system by imparting a charge to the asphalt particles. The emulsions are characterized by the nature of this charge as cationic, anionic or nonionic (*7*).

The letter “C” in front of the classification denotes the cationic (positively charged), while the absence of the letter denotes anionic (negatively charged). For example, SS1 is anionic and CSS1 is cationic. The principal difference between the two is that, cationic emulsions give up their water faster than anionic emulsions. In addition, emulsions are best used with aggregates carrying opposite charge (*3*).

Emulsions are classified based on how fast the asphalt droplets will break and set-up. The terms slow setting (SS), rapid setting (RS), medium setting (MS), and quick setting (QS) are used to classify the emulsions (*7*).

SS 1, SS 1-h (Anionic slow-set, hard base), CSS 1, and CSS 1-h (Cationic slow-set, hard base) are slow setting emulsions used as tack coat. The original slow setting emulsions contain a maximum of 43% water and are diluted by adding an equal amount of water. However, slow setting emulsions take longer to break than rapid setting emulsions. Therefore, slow setting emulsions are not recommended for construction in cool weather, night construction, or when there is a short construction window. Because cationic slow set emulsions are less sensitive to moisture and temperature, they can be used in areas with damp pavements such as coastal areas (*3*).

Rapid setting grades of emulsion include polymer-modified emulsion. Tack coats of this type are RS1, RS2, CRS1, CRS2, PMRS2, PMRS2h, PMCRS2 and

PMCRS2h. The letter “PM” in the rapid-setting emulsions denotes polymer-modified emulsion. The rapid setting emulsions contain a maximum of 35% water and must not be diluted with additional water (*3*).

Asphalt emulsions consist of three basic ingredients: paving asphalt, water, and emulsifying agent (*3*). Asphalt emulsions are more common than asphalt binder because asphalt emulsions under go a mechanism known as “breaking” (*8*). Breaking is a process in which water evaporates, leaving behind only the asphalt. In the state of Arkansas, rapid curing cutback or emulsified asphalt is used (*9*).

A survey done by Paul and Sherocman(*10*) showed that slow set emulsions such as anionic slow set (SS-1), cationic slow set (CSS-1) and harder base-asphalt versions (SS-1h and CSS-1h) are most commonly used throughout USA for both new pavements as well as rehabilitation pavements. A few states use rapid-set emulsions like CRS-1, CRS-2 and RS-1. Two states specify using asphalt binder as tack coat. The survey was sent out to all of the DOTs, and 42 states responded. Details of the survey are shown in Appendix A.

Chaignon and Roffe (*11*), along with International Bitumen Emulsion Federation, conducted a survey to investigate the following:

- Tack coat type.
- Application rate.
- Set time.
- Existing standards and specifications.
- Applicable tests.
- Inspection techniques and

- Application methods.

The outcome of the survey showed that most common tack coats are cationic emulsion followed by anionic emulsion. Setting time varied from 20 min for a broken binder to several hours for a dry binder.

A research done by Trevino (*4*) for the Texas Department of Transportation tested the strength of three tack coats (SS-1, CSS-1h and AC-10). Testing was done with a Humberg wheel tracking and later subjected to shearing. AC-10 provided the highest shear strength, and next best option was SS-1.

A study was conducted by Mohammad (*12*) to investigate the suitability of four emulsions (CRS-2P, SS-1, CSS-1 and SS-1h) and two PG grade binder (PG 64-22 and PG 76-22M) when used as tack coats. The Superpave Shear Tester (SST) was used for testing with a uniform load of 50 lb/min. The testing temperatures were 77^{o}F and 131^{o}F. From the test results, it was concluded that CRS-2P emulsion was the best tack coat.

NCAT (*13*) conducted tests using tack coat materials CRS-2, CSS-1 and PG 64-22. From the study it was concluded that PG 64-22 provides higher bond strength than CRS-2 and CSS-1, especially for fine graded mixtures tested at higher temperature.

The Arkansas State highway and Transportation Department's *Standard Specification for Highway Construction* limits the materials used for tack coat to rapid curing cutback or emulsified asphalt (9).

2.3 APPLICATION RATE

Table 1 illustrates the common application rates used by various researchers and agencies.

TABLE 1 Application Rates

Research	**AHTD** gal/yd^2 (9)	**Paul & Sherocman** gal/yd^2 (*10*)	**Chaignon and Roffe** lb/ft^2 (*11*)	**Mohammad** gal/yd^2 (*12*)	**Trevino** gal/yd^2 (*4*)	**NCAT** gal/yd^2 (*13*)
Application rate	0.03	0.07	0.025	0	0.04	0.02
	0.10	0.11	0.082	0.2	0.08	0.05
	-	-	-	-	0.12	0.08

The Arkansas State highway and Transportation Department's *Standard Specification for Highway Construction* (9) specifies that the application rates should be between 0.03gal/yd^2 and 0.10gal/yd^2

The survey done by Paul & Sherocman (*10*) showed that common application rates are 0.03 L/m^2 (0.07 gal/yd^2) to 0.52 L/m^2 (0.11 gal/yd^2).

Chaignon and Roffe (*11*), along with the International Bitumen Emulsion Federation, conducted a worldwide survey for application rates. Responses from the United States showed that an application rate of 0.12 kg/m^2 (0.025 lb/ft^2) to 0.4 kg/m^2 (0.082 lb/ft^2) is common.

Mohammad (*12*) found that the application rates vary from 0.0 gal/yd^2 to 0.2 gal/yd^2 . From this range, he concluded that 0.02 gal/yd^2 is the optimum application rate.

In a study done by Trevino for the Texas Department of Transportation (*4*), tack coat applications of 0.04 gal/yd^2 (0.22 L/m^2), 0.08 gal/yd^2 (0.43 L/m^2) and 0.12 gal/yd^2 (0.65 L/m^2) were used. Test results showed that higher tack coat application rates result in significantly higher shear strengths.

NCAT (*13*) conducted tests using application rates of 0.02 gal/yd^2, 0.05 gal/yd^2, 0.08 gal/yd^2. Interestingly, the test results showed that lower application rates provided higher bond strength for fine graded HMA. Varied application rates for coarse graded did not have any effect.

2.4 QUALITY CONTROL OF TACK COAT APPLICATION

Any project has a design phase and construction phase; if proper quality control is not followed, the result could vary regardless of the design. As a rule of thumb, the engineer at the job site should check the capability of the distributor to maintain the required temperature, pressure, distribution spray bar height, and nozzle angle. Spray bar height should be checked frequently because as the tack coat is emptied from the tank of the distributor, the distributor becomes lighter and the distributor rises up, thus increasing the spray bar height. Thus, the tack coat only partially covers the pavement. Figure 2 shows a tack coat distributor.

FIGURE 2 Tack Coat Distributor (*3*)

The distributor must maintain the application temperature of the tack coat to ensure that there is an adequate flow of the material. Spraying temperature of 75°F and 130°F are suggested for slow setting asphalt emulsion such as SS-1h (*14*). Excessive heating should be avoided because high temperatures may induce breaking (*8*) while in the distributor.

Distributors must have developed sufficient pressure to force the bituminous materials through the spray bar nozzles in order to create a fan shape as the material comes out of the nozzle, as shown in Figure 3 (*14*). For slow setting emulsified asphalt materials, dilution will facilitate this operation by reducing the material's viscosity. It is important to adjust the application rate after the dilution so that sufficient bituminous material is deposited on the pavement (*14*).

The distribution spray bar should be at a sufficient height to ensure that a fan shaped spray is developed. A fully developed fan will provide overlap of the material placed by the adjacent nozzles as shown in Figure 3. The double lap, or in some cases triple lap, ensures the desired application of 90% coverage of the pavement. The distributors should be equipped to maintain a constant height of the spray bar to prevent a non-uniform spread of bituminous material (*14*).

To ensure a uniform coating of material on the pavement, all spray bar nozzles should be open and set at the same angle. The angle is measured from the axis of the spray bar, which is typically 15° to 30°, (*14*). Figures 4 and 5 show the nozzle angle settings.

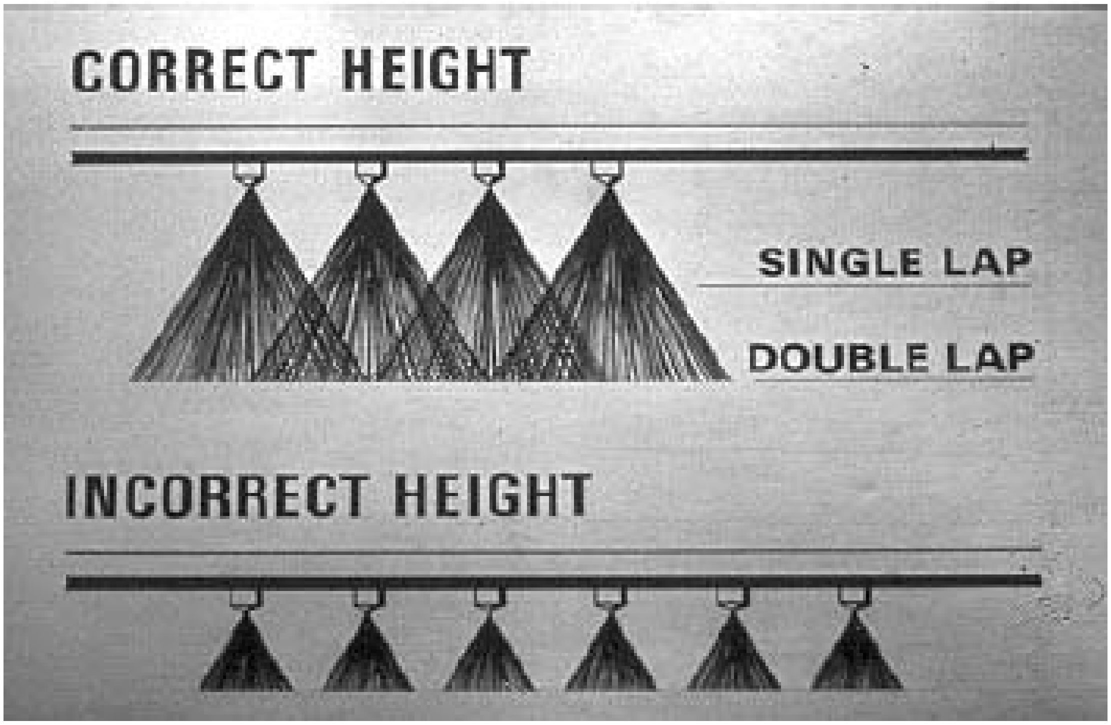


FIGURE 3 Spray Bar Height To Obtain Desired Coverage (*9*)

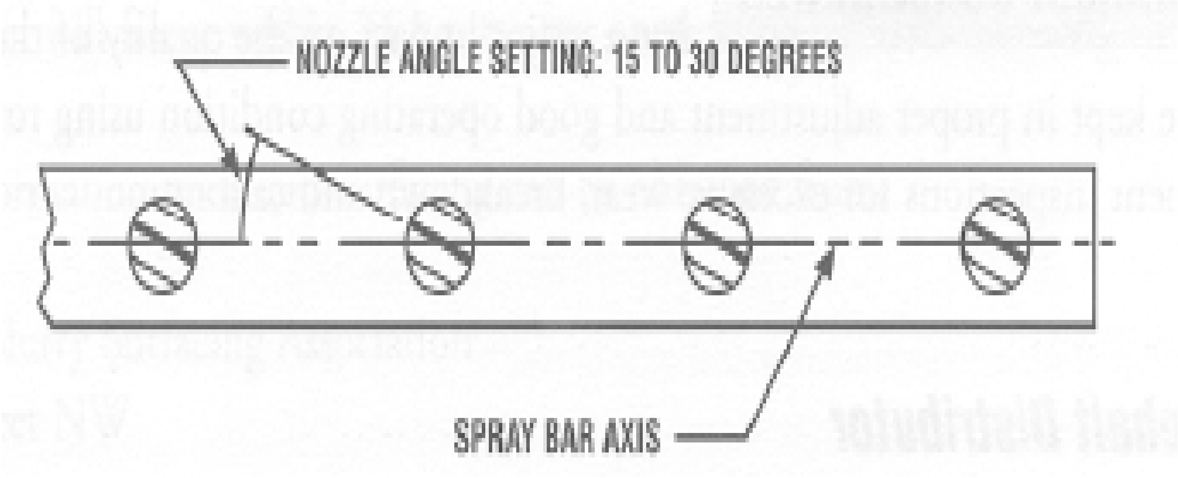


FIGURE 4 Proper Nozzle Angle Setting (*9*)

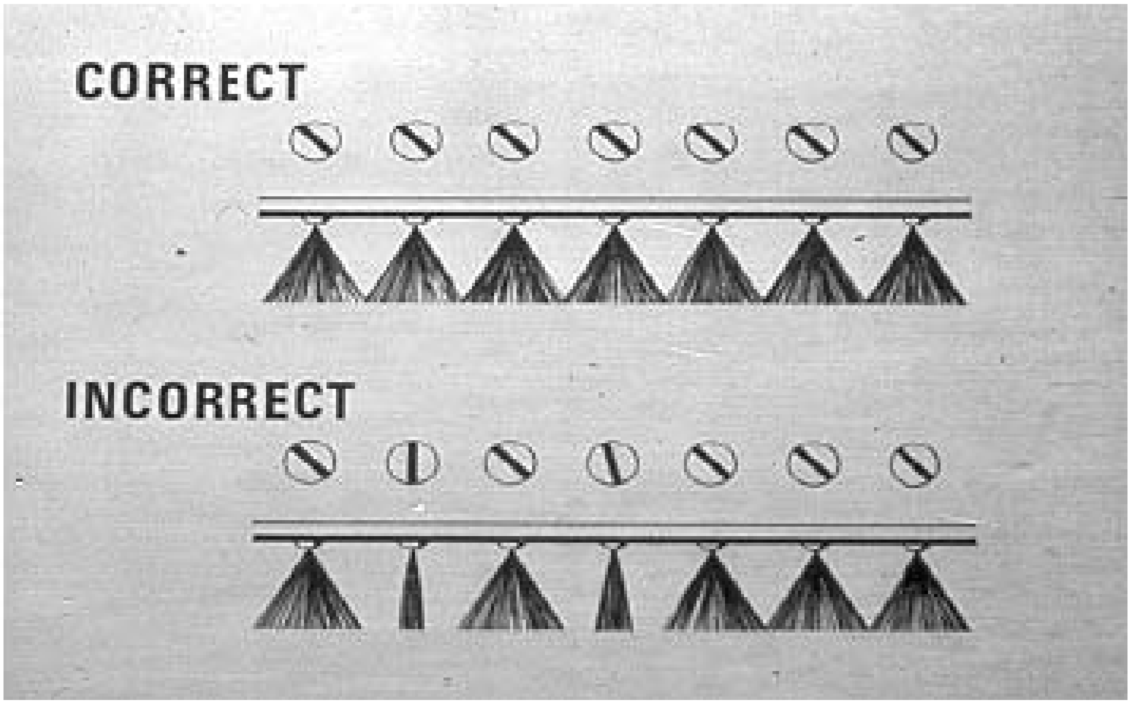


FIGURE 5 Spray Bar Nozzle Adjustment (*15*)

Quality control procedures should be in place to ensure a proper application of tack coat. Improper application could cause excessive tack coat on the pavement.

2.5 PROCEDURE FOR APPLICATION OF TACK COAT

One of the reasons the tack coat fails, is due to, presence dust and oil on the pavement during application. The pavement surface receiving tack coat should be free of any substances that will inhibit the bond. A dirty or dusty surface will inhibit the ability of the tack coat to bond. Slippage cracking, tearing and delaminating are typical distress seen when there is lack of cleanliness. The tack coat is not a substitute for cleaning the pavement prior to overlay (*14*).

The application rate should vary depending on the condition of the pavement being overlayed. The objective is to apply a sufficient quantity of tack coat, resulting in a thin, uniform coating of asphalt covering approximately 90% of the pavement surface. Excessive tack coat is detrimental. In the case of excessive application, the excessive tack coat acts as a lubricant and creates a slipping plane (*14*).

Improper handling causes the tack coat to loose its bonding properties Only slow setting emulsion should be diluted in the field. Adding emulsion to water may cause the tack coat to break. The dilution rate should be 1:1. When using diluted emulsified asphalt tack coat material, an adjustment to the application rates will be necessary to ensure the desired residual asphalt is achieved. Failure to do so will result in inadequate bonding between layers because of thin coating of bituminous material. Table 2 shows the typical application rates for various pavement conditions (*14*).

TABLE 2 Application Rates for Various Pavement Types (*14*)

Existing pavement condition	**Application rates (gallons/sy)**		
	Residual	**Undiluted**	**Diluted (1:1)**
New asphalt	0.03-0.04	0.05-0.07	0.10-0.13
Oxidized asphalt	0.04-0.06	0.07-0.1	0.13-0.2
Milled surface (asphalt)	0.06-0.08	0.1-0.13	0.2-0.27
Milled surface (PCC)	0.06-0.08	0.1-0.13	0.2-0.27
Portland cement concrete	0.04-0.06	0.07-0.1	0.13-0.2

Allowing the emulsifying tack coat material to set prior to placing the asphalt overlay will facilitate a better bonding. When possible, paving equipment and traffic should stay off the tack coat until the set has occurred.

During the break, dispersed droplets of asphalt cement in the emulsified asphalt will begin to coalesce. This starts when the emulsified asphalt is exposed to the pavement surface, and is complete after all the moisture have evaporated. A change in color of the emulsified asphalt material from brown to black is a visible indicator of a broken emulsion.

2.6 TESTS TO DETERMINE BONDING - FIELD TESTS

Since field conditions differ from laboratory conditions, there is usually a difference between the expected outcome and actual outcome. Research has been done to identify an appropriate test that can provide quick results and be used for field-testing so that any repairs can be done before the road is opened to the traffic. After a considerable literature review, it has been found that researchers and various organizations have developed testing procedures; the primary procedures are presented below.

2.6.1 **InstroTEK ATACKer™**

The Mississippi Transport Research Center performed tests to evaluate the effects of application rates, set time, and type of tack coat on tensile and torque shear strength of tack coat. To evaluate the bonding strength, a tack coat evaluation device (TCED) (a prototype) was developed by InstroTEK Inc. The prototype device is named ATACKer™ (*16*).

ATACKer™ (*16*) consists of a rod at its center with a dial gauge attached to an aluminum contact plate as shown in Figure 6. Screws at the bottom of the rod attach the aluminum contact plate (5-inch in diameter) to the rod. The load is applied from the top by means of a lever, and to prevent the device from lifting up due to the applied load, balancing loads are used.

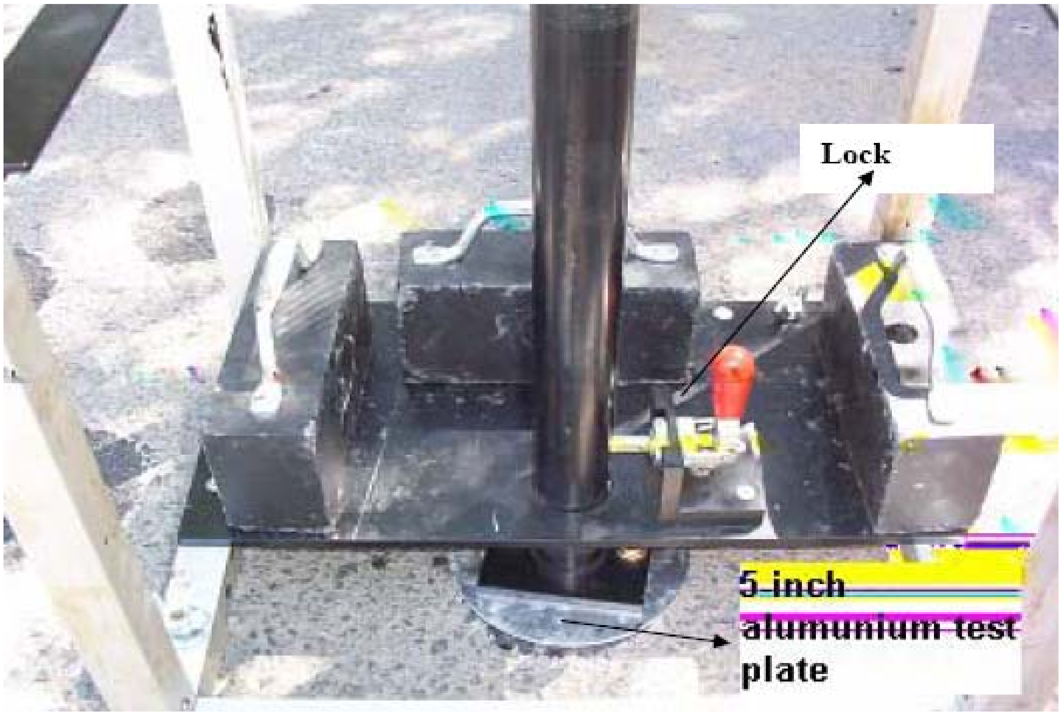


FIGURE 6 ATACKer^{TM} Test Setup (*17*)

ATACKer™ (*16*) determines the adhesive strength of tack coat application by applying normal pressure to a test plate with tack coat. The device records the tensile force or torque required to break the tack coat between two test plates. The equipment is placed on the tack-coated area, a load of 18 kg is applied by moving the leaver in a clockwise direction, and the applied load is monitored with the load dial. The load applied is maintained for a specified duration of time. After the set time, the applied load is removed and the shear force required to break the bond is measured with a torque wrench as shown in figure 7. This method can be used for determining the tension, where in the loads required to detach the plate from the pavement is recorded.

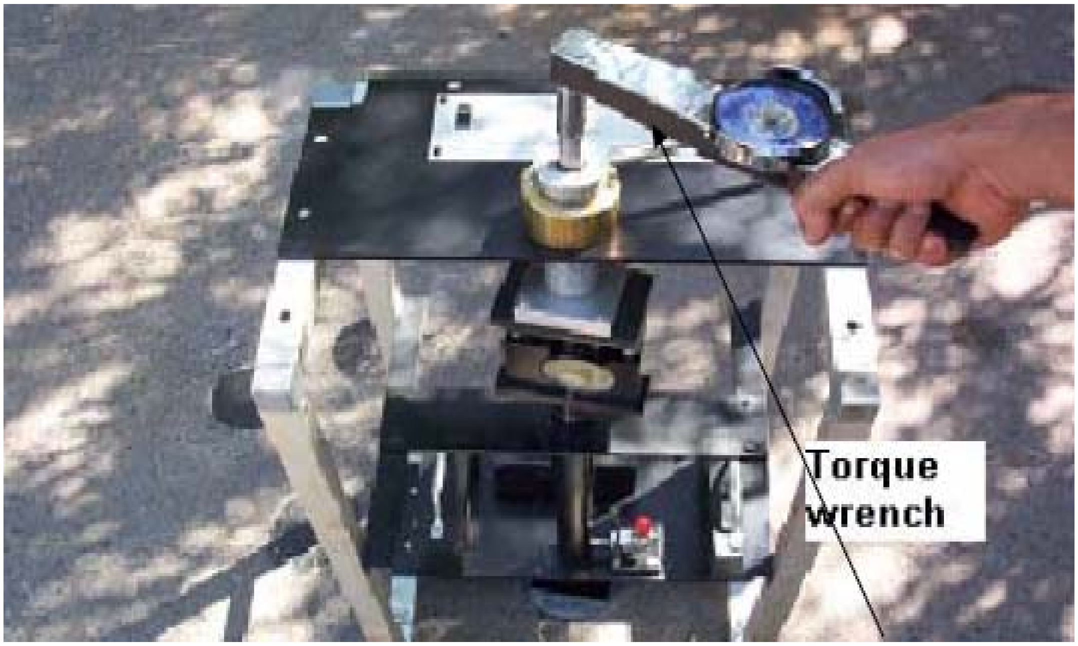


FIGURE 7 ATACKer™ Shear Strength Measurement With Torque Wrench(*17*)

TCED (*16*) was used for testing four separate sets, namely non-diluted tensile strength, non-diluted torque-shear strength, diluted tensile strength, and diluted torque-shear strength. Three emulsions evaluated with TCED (*16*) showed slightly varying tensile and torque-shear strengths, while CRS-2 exhibited the highest strength of all emulsions. From the statistical analysis, it was found that application rate is directly proportional to the tensile and torque shear strengths and inversely to set time. Temperature did not affect strength.

TCED (*16*) produced an interesting result when tested on performance grade (PG) binder, tensile strength decreased with increase of application rate, but torque-shear strength increased with the increase of application rate.

In addition to TCED(*16*), a laboratory bond interface strength device (LBISD) (*16*) was developed to assess interface bond strength between pavement layers by direct shear loading.

A cylindrical HMA specimen is cut into halves. Using a cotton tip applicator, 200ml of tack coat is applied and cured for 24 hours at 24^{o}C. The prepared specimen is placed in the SGC mold and HMA is compacted over it to simulate an HMA overlay. This is allowed to cure for 24 hrs and, after curing, the specimens are placed in the shear device. The whole setup is placed in the Marshall device, which is operated at a rate of 5.08 cm/min. The data logger records the measurements and displacements every 0.1 seconds until the shearing is complete.

Results from LBISD (*16*) concluded that tack coat type significantly affects maximum strength and reaction index. PG 67-22 performed better than emulsions in both shear strength as well as in reaction index.

2.6.2 **UTEP Direct Shear Device**

University of Texas at El Paso (UTEP) modified a test device originally developed by Soil Tests Inc that is commonly used by geotechnical engineers to measure the shear strength of soil (*17*). The modifications included the replacement of load and deformation measuring dial gauges with load cell and LVDT, specimen holding mold, and the data acquisition system shown in Figure 8. Figure 9 shows the modified UTEP test setup. The shear box developed is made of aluminum, has a bottom plate thickness of 2 inches, and an upper plate thickness of 3 inches. It is capable of testing 4-inch and 6-inch diameter asphalt specimen, and four leveling screws are placed at the corners on the upper plate to accommodate a gap between the shearing plates. Figure 10 shows the shear box and figure 11 shows the aluminum test cylinder

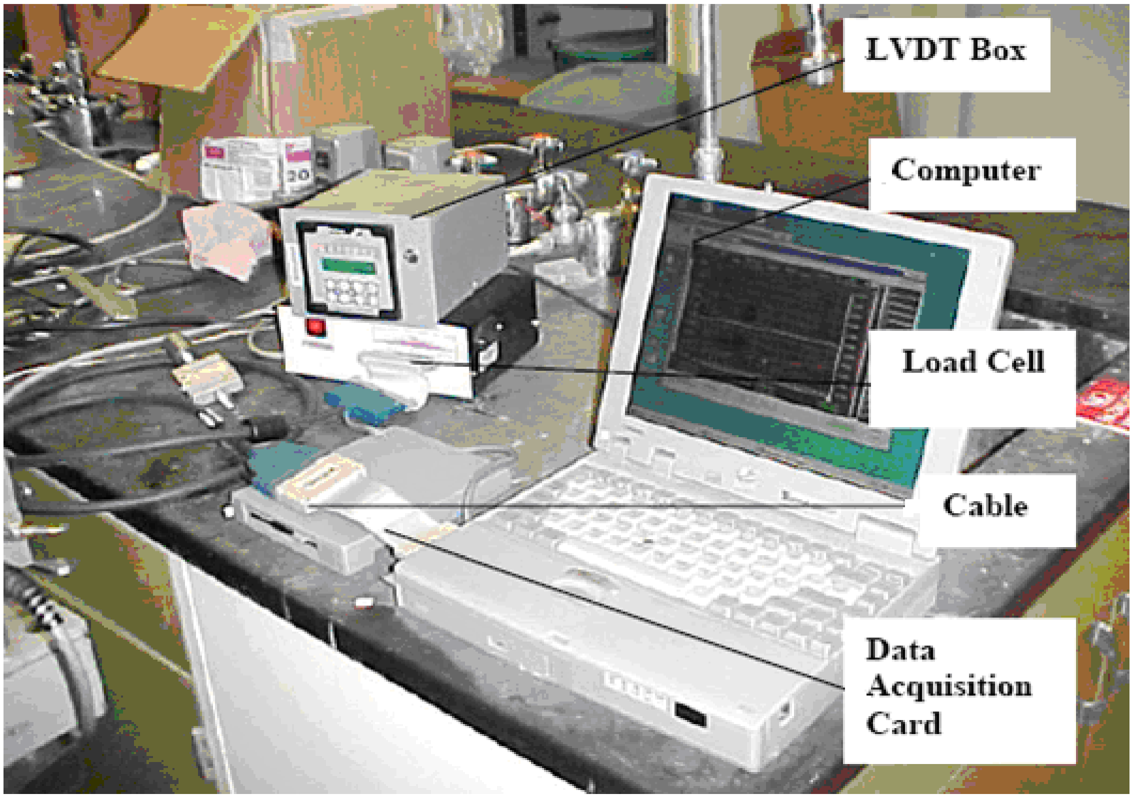


FIGURE 8 Data Acquisition System (*17*)

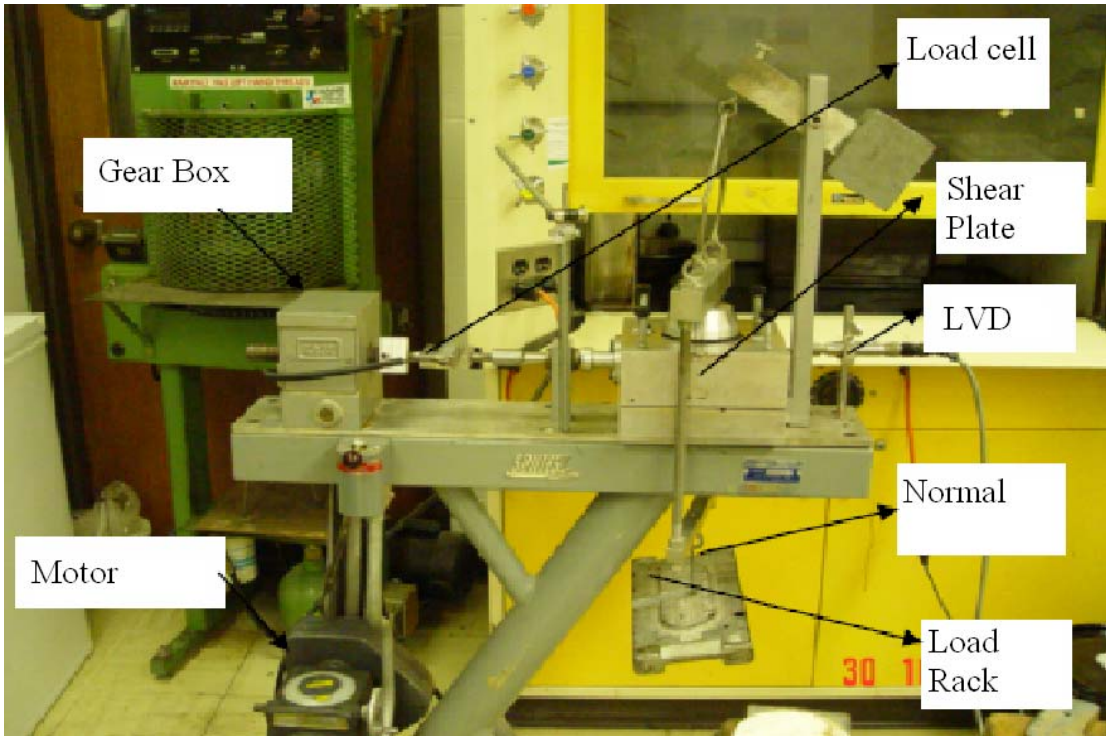


FIGURE 9 Modified UTEP Test Setup (*17*)

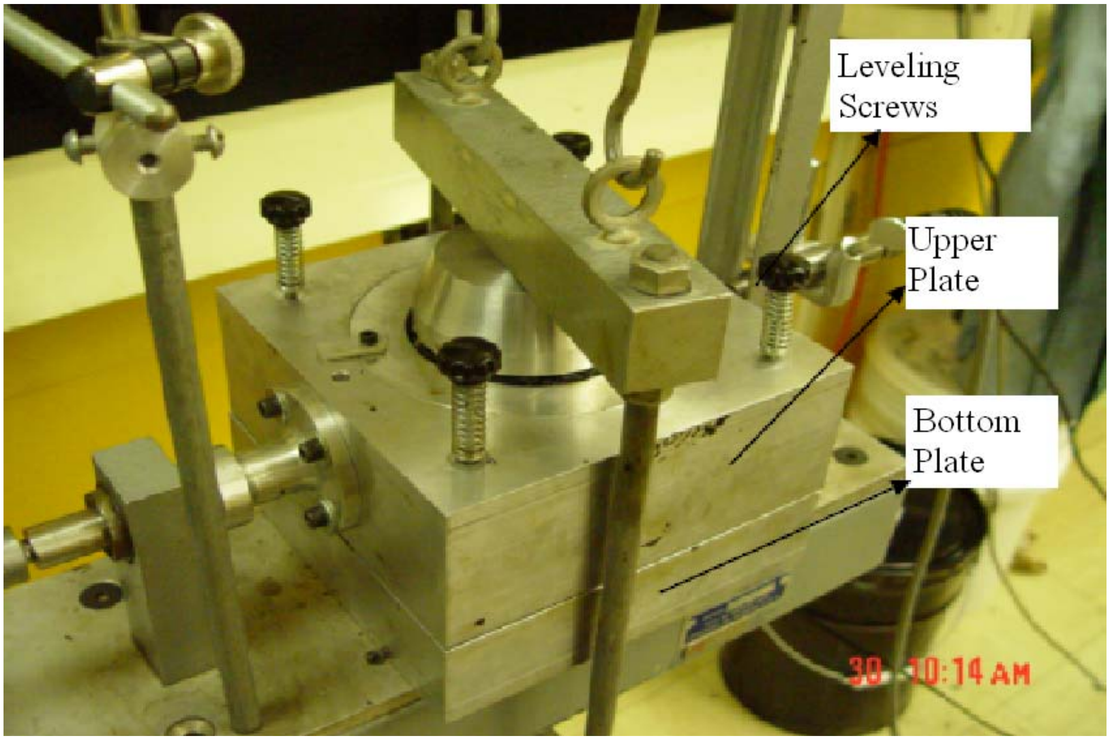


FIGURE 10 Shear Box (*17*)

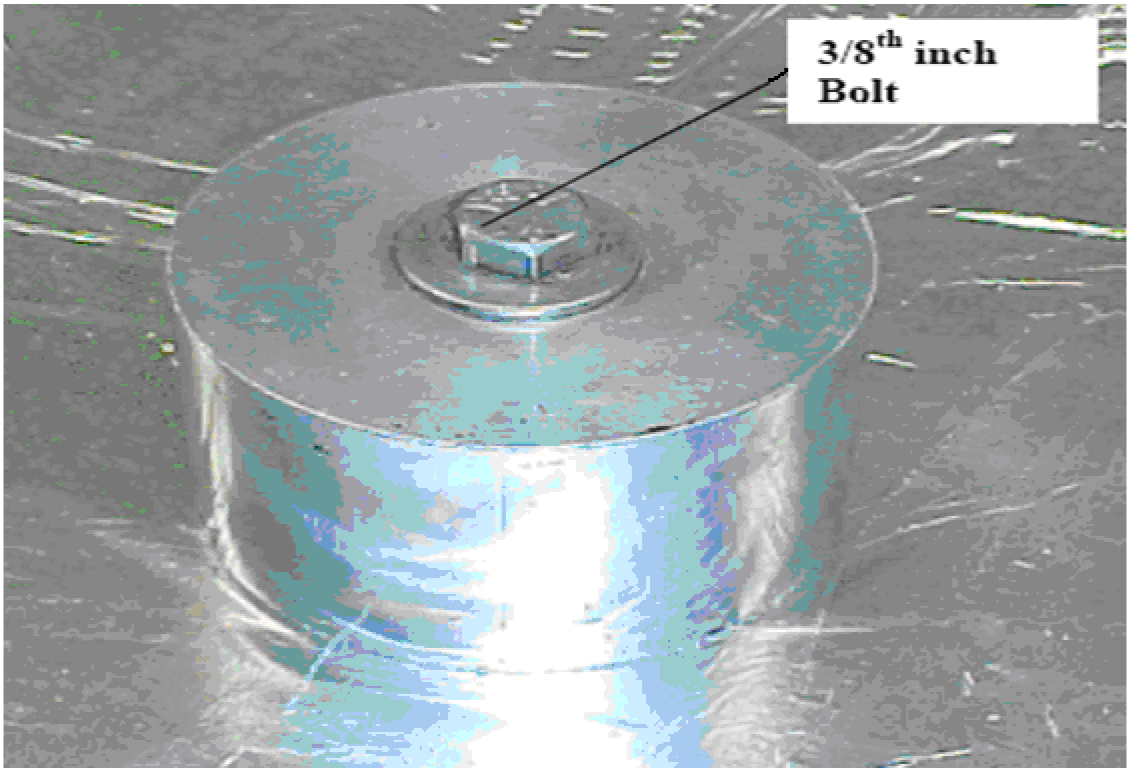


FIGURE 11 Aluminum Test Cylinder (*17*)

The prepared specimen is placed in the mold, the screws are removed, and a desired vertical load is placed on the loading rack. A horizontal load at a rate of 0.05 in/min is applied, the load and the movement is recorded. The load cell and LVDT readings are converted and analyzed to get shear strength.

2.6.3 **UTEP Torque Test Setup**

UTEP (*17*) also reported on a test developed by Deysarkar (*17*), used to measure the shear strength in the field as well as in the laboratory. The equipment consists of an aluminum cylinder with spiral grooves at the bottom to provide frictional resistance. Figure 11 shows the aluminum cylinder used in the torque test set up.

Tack coat is applied at a specified rate on to the surface and the aluminum cylinder is placed on top of tack coat. Care should be taken to place the cylinder after a specified set time. A load of 18 kg is applied to improve contact. After 10 minutes, a torsional force is applied with a torque wrench. The maximum torque at failure is measured from the torque wrench, which is converted to shear to identify bond shear strength.

The test method is portable and simple, and can be easily transported to the field and the laboratory. The torque test device can be fabricated with minimum cost. This test can be used to determine the quality of tack coat. Figure 12 shows the field set-up for the torque test.

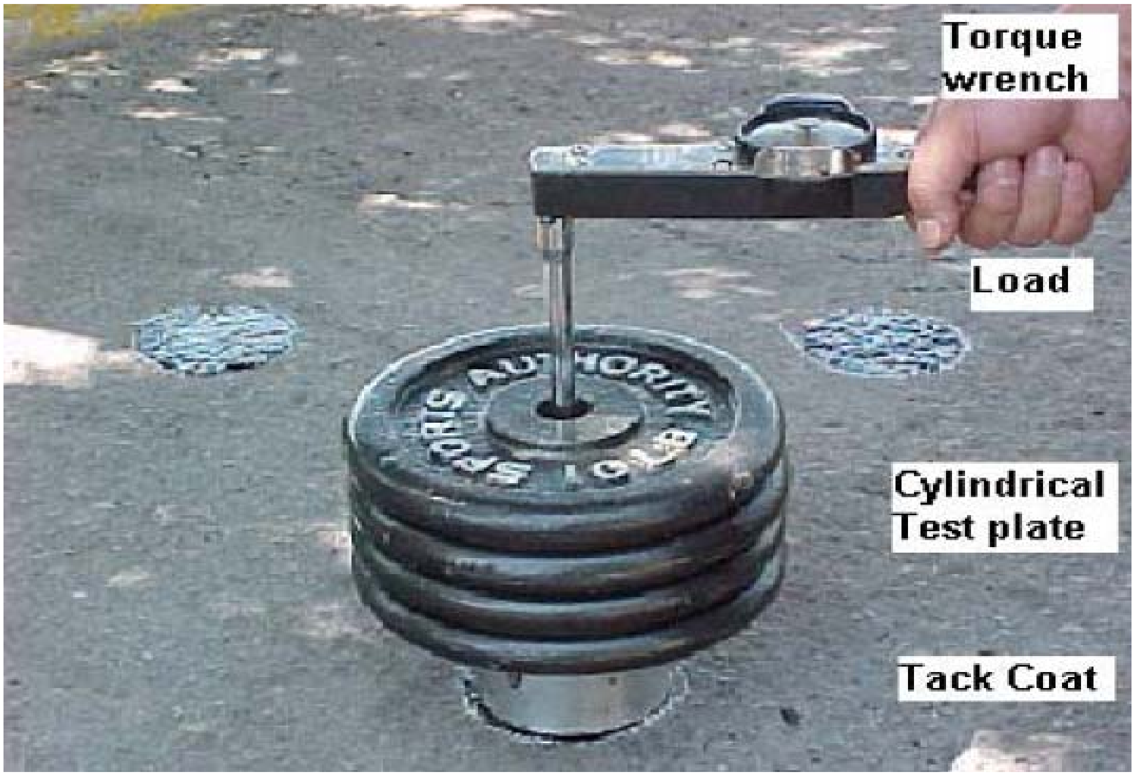


FIGURE 12 Field Set Up Torque Test (*17*)

2.6.4 **UTEP Pull-off Device (UPOD)**

UPOD (*17*) was developed to determine the adhesive property of tack coat using a torque wrench. Figure 13 shows the UTEP pull-off test setup. The device weighs 23lb and has a 3/8 inch nut which fits 3/8 inch drive torque wrench used to pull the plate up from a tack coated surface as shown in Figure 14. Contact plates are developed which conform to the rough pavement surface, shown in Figure 15. In addition, two aluminum plates are fabricated measuring 16.5 x 14.5 x 0.25 inches and 15.5 x 12 x 0.031 inches. The thinner plate has a hole in the center (diameter = 5 inches). The plate with the hole is placed on top of the solid plate to allow the tack coat to be placed at the center (*17*) as shown in Figure 13.

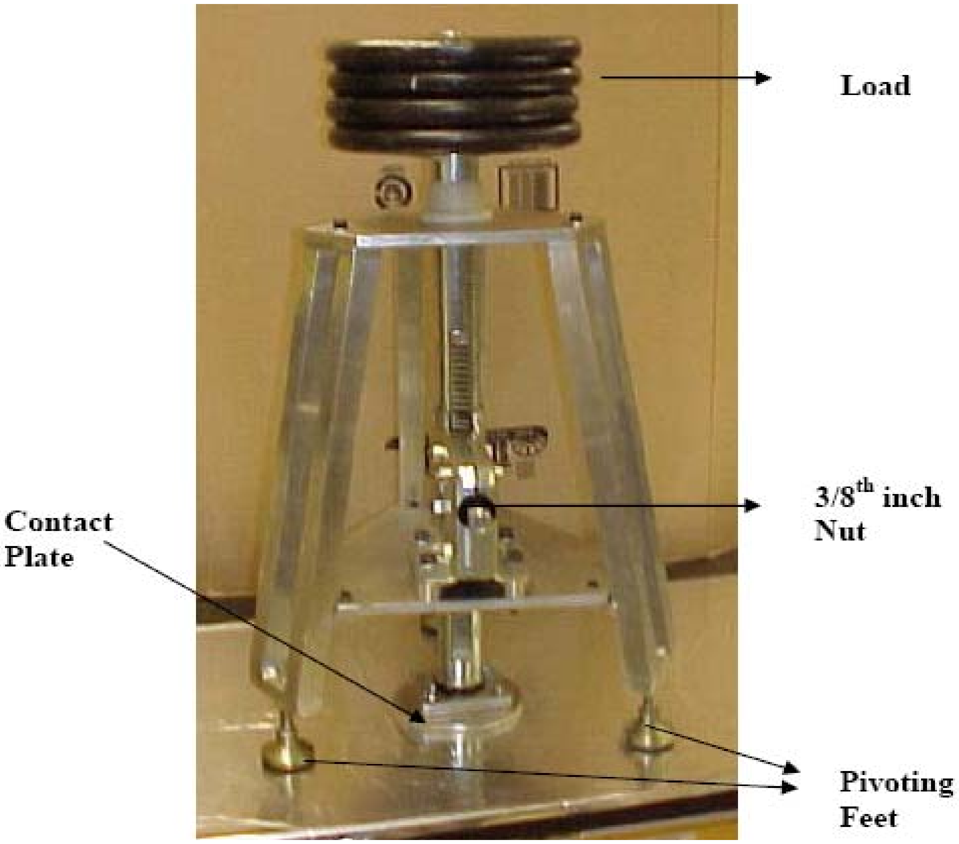


FIGURE 13 UTEP Pull-off Test Setup (*17*)

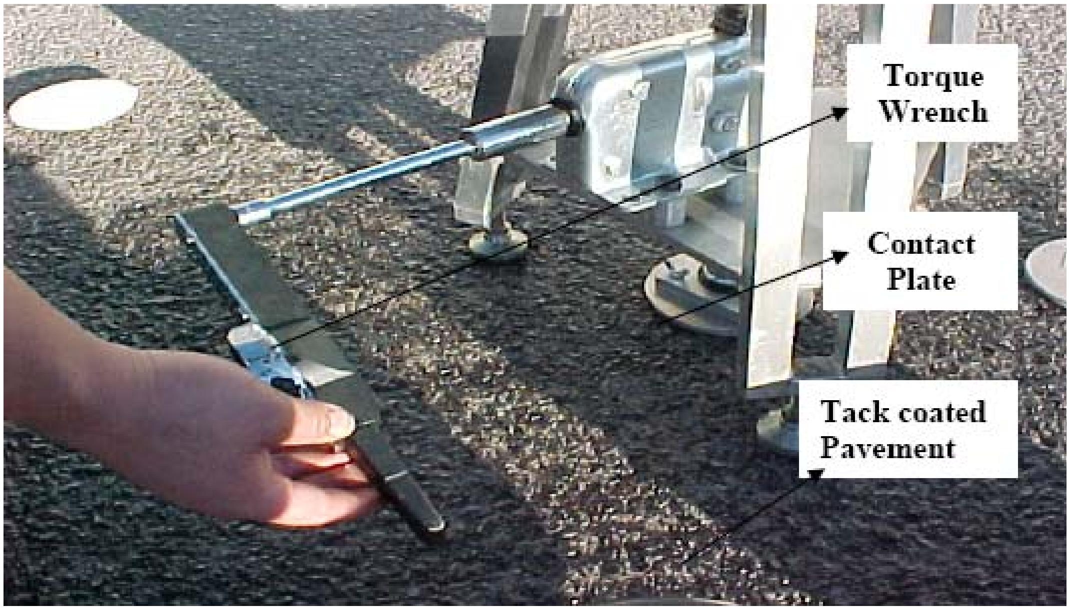


FIGURE 14 Torque Wrench Used During Testing (*17*)

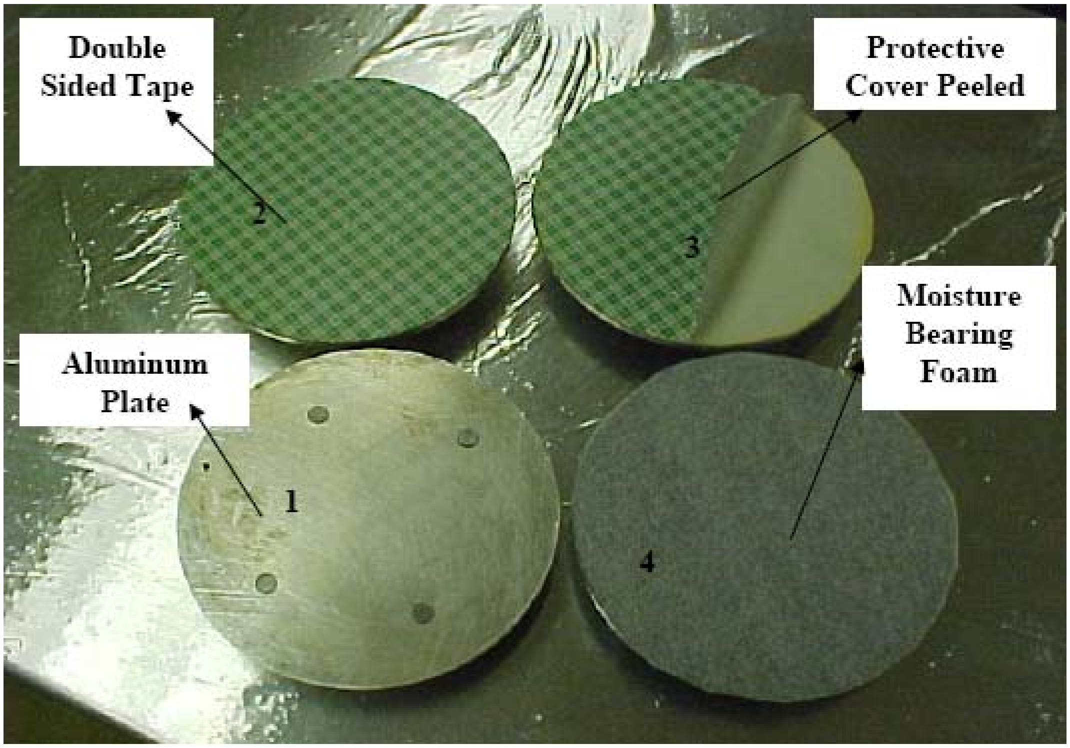


FIGURE 15 Contact Test Plates (*17*)

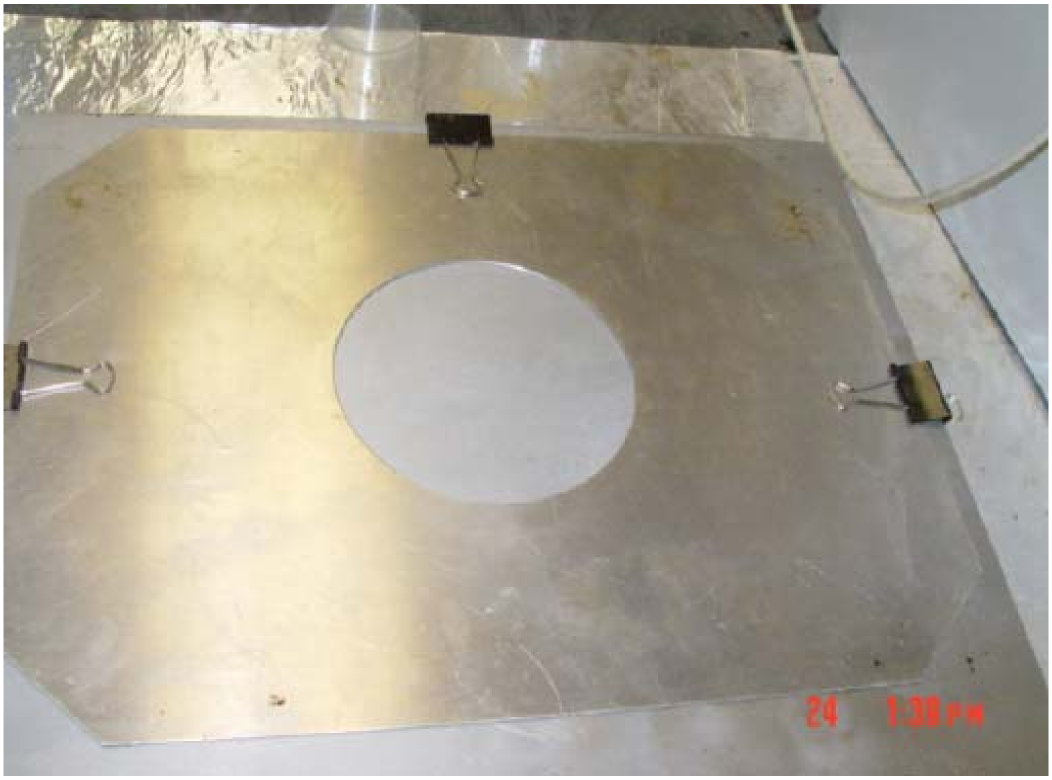


FIGURE 16 Base Plates (*17*)

2.6.5 **Koch Materials Equipment**

Deysarkar (*17*) experimented with test set up developed by *Koch Materials Company* (KMC). The test setup is portable (i.e. it can be transported from the laboratory to the field). The KMC test setup is shown in Figure 17. Field tests by Tandon (*18*) on KMC test setup included testing at different times of the day with varying residual application rates, dilution, and set time for three tack coats and a paving grade asphalt.

The test developed by KMC for field-testing consisted of molds to hold the specimen and a loading mechanism to apply horizontal shearing load. Horizontal shearing load is applied with a 24-volt drilling machine at a rate of 1.7 in/min. The digital load cell records the maximum load before de-bonding. This is converted into interface shear strength (*17*).

The main advantage of this setup is that it is portable. For the field test, a 4-inch diameter, 0.5-inch tall, and 1-inch wide ring with a fine wire attached to it is placed on the tack-coated pavement. Once the paving operation is completed, the fine wire attached to the ring is pulled out. A semi-circular ring is placed in the groove formed, and the force is applied using a 24-volt cordless drilling machine at a strain rate of 43 mm/min to measure shear (*17*).

FIGURE 17 Koch Materials Company Test Setup (*17*)

2.6.6 **FDOT Test Setup**

Sholar (*19*) developed a test method that conducts tests with direct shear and has the capability to vary testing parameters such as loading rate, temperature and gap width between shearing plates. The main objective of the research was to develop a test apparatus practical enough to be used in district laboratories. The test apparatus is used to determine the effect of tack coat application rate with bond strength and the effect of water on tack coat performance.

The apparatus consists of a simple direct shear device to hold 150-mm nominal diameter roadway cores. The device is designed so that the gap between the platens can be adjusted. The testing is done in a Material Testing System (MTS). MTS can apply either strain or stress loading. The data acquisition and reporting is done with software modified for this application. Figure 18 shows the shear measurement set-up.

FIGURE 18 Shear Measurement Setup Developed by FDOT (*17*)

The parameters examined in the construction of the test apparatus are specimen diameter, mode of loading, rate of loading, testing temperature, and gap width between plates. The primary concern in examining the parameters is to select the final version of the testing parameters and to maintain practicality and simplicity in the test procedure.

Repeated field-testing at US-90, I-95, SR-19, and SR-2 was conducted with a combination of different tack coat applications, applications of water and varying the setting times. It was concluded that the apparatus should be designed to hold a specimen of diameter of 152.4mm, the mode of loading should be strain controlled with a rate of loading of 50.8mm, testing temperature of 25°C and gap width between shearing platens of 4.8 mm.

Table 3 summarizes the various tests discussed previously.

TABLE 3 Summary of Field Tests

#	TEST	USES
1	InstroTEK ATACKer™	Can be used to determine the adhesive strength of Tack coat by the application of Normal Pressure.
2	UTEP Direct Shear Device	Modified equipment primarily used to determine the shear strength of soil. This equipment can be used to determine the shear strength of 4’’ and 6’’ diameter samples.
3	UTEP Torque Test Setup	Shear strength is determined by the application of Torsional force.
4	UTEP Pull-Off Device (UPOD)	Adhesive force of the tack coat is determined by the application of Torsional force.
5	Koch Materials Equipment	The interface shear strength is determined by the application of horizontal shearing load.
6	FDOT	The test apparatus is used to determine the effect of tack coat application rate with bond strength and the effect of water on bonding.

The site engineer should check the calibration of the distributors. During the use of the distributor, if any traces of sludge and residue are found, then a recalibration is necessary.

CHAPTER 3 EXPERIMENTAL PLAN

3.1 MATERIALS

Based on the literature review, factors altering the interlayer bond strength in HMA pavements are tack coat type, application rate, temperature, normal stress, and surface frictional resistance. In this research, interlayer bond strength in HMA pavements was determined using these parameters. Table 5 summarizes the testing matrix used in this research.

3.1.1 Type of Tack Coat

The tack coats selected are commonly used in Arkansas. The two tack coats used in this research were SS 1 and NTSS 1.

SS 1 is anionic slow setting emulsion and was diluted to 1:1 ratio to help increase the volume for application. The application temperature for SS 1 tack coat is 122 $^{\circ}$F.

NTSS 1 is trackless tack coat emulsion produced by BLACKLIDGE EMULSIONS, INC. NTSS 1 is not diluted on site and was used as obtained from the manufacturer. As per the manufacturers instructions application temperature had to be increased to 130 $^{\circ}$F.

3.1.2 **Application Rate**

The application rate alters the interlayer bonding because too much tack coat causes a shear plane, and too little increases the opportunity for debonding. Optimum application rate is the key to proper bonding. The application rate is measured in

gal/yd^2. The application rates used were 0.02 gal/yd^2, 0.06 gal/yd^2, and 0.10 gal/yd^2. The application rate range allowed in Arkansas is 0.03 gal/yd^2 - 0.10 gal/yd^2.

3.1.3 Testing Temperature

Two testing temperatures were used to study the effect of temperature on interlayer bond strength. The temperatures were 70°F to analyze the debonding due normal temperatures and 130 °F is considered as the nominal temperature range for slippage (*13*).

3.1.4 Normal Stress

The normal stresses applied to the specimen during testing were 0 and 10 psi. The normal stresses chosen were used to simulate the variation in frictional resistance due to differences in the surface texture of underlying layer.

3.1.5 HMA Mix

Two hot mix asphalts with 12.5-mm nominal maximum aggregate size and 25-mm nominal maximum aggregate size were selected. These two mixes were selected since they have different surface textures and, therefore, should provide different frictional surface. There were 36 samples prepared for each tack coat type. The combinations were Surface-Surface (12.5-12.5 mm) , Surface-binder (12.5-25 mm), Binder-Binder (25-25 mm).

3.1.6 Arkansas State Highway and Transport (AHTD) specifications

AHTD states that all rapid curing cutback asphalt should conform to the requirements of AASHTO M 81. If anionic emulsified asphalt is used, then it shall conform to the requirements of AASHTO M 140. Cationic emulsified asphalt shall conform to the requirements of AASHTO M 208 (*9*).

In addition, CRS-2 should have a minimum saybolt furol viscosity of 122^{o}F at the point of manufacture, an origin of 200 seconds, and a maximum saybolt furol viscosity of 500 seconds. The saybolt furol viscosity at 122^{o}F on destination field samples shall be within the limits of 100-500 seconds. If the asphalt being tested begins to drip at 122^{o}F, the test should be repeated at 160^{o}F and must be within the limits of 90-200 seconds. Moreover, the minimum residue from distillation by weight should be 68% (*9*).

AHTD requires the asphalt to be applied a temperature which provides proper and uniform distribution and within practical limits. Material should not be heated above the temperature range shown in Table 4 (*9*).

TABLE 4 Maximum Heating Temperatures of Asphalt (*9*)

Type and grade	**Recommended range ^{o}F**	**Maximum allowable ^{o}F**
SS 1, SS 1H	70-160	160
CRS 1, CRS 2, CRS 2P	125-185	185
CSS 1, CSS 1H	70-160	160

3.1.7 Quality Control

The samples having air voids of 6±1 % were used, appendix B shows the air voids of the samples. SS 1 was diluted to 50% and applied at room temperature, where as, NTSS 1 was not diluted (specified by the manufacturer) and was applied at 130 °F. The samples prepared for SS 1 were cured in the open and NTSS 1 samples were cured in an oven at 100 °F.

TABLE 5 Testing Matrix

Application rate (gal/yd^2)	Temperature °F	Normal Stress (psi)	Mix Type
0.02	70	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25
	130	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25
0.06	70	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25
	130	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25
0.1	70	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25
	130	0	12.5 / 25
			12.5 / 12.5
			25 / 25
		10	12.5 / 25
			12.5 / 12.5
			25 / 25

3.2 LABORATORY SPECIMEN PREPARATION

Mix designs for the 12.5 mm and 25 mm HMA were provided by AHTD. The specimens were prepared in a slab compactor shown in Figure 19 .

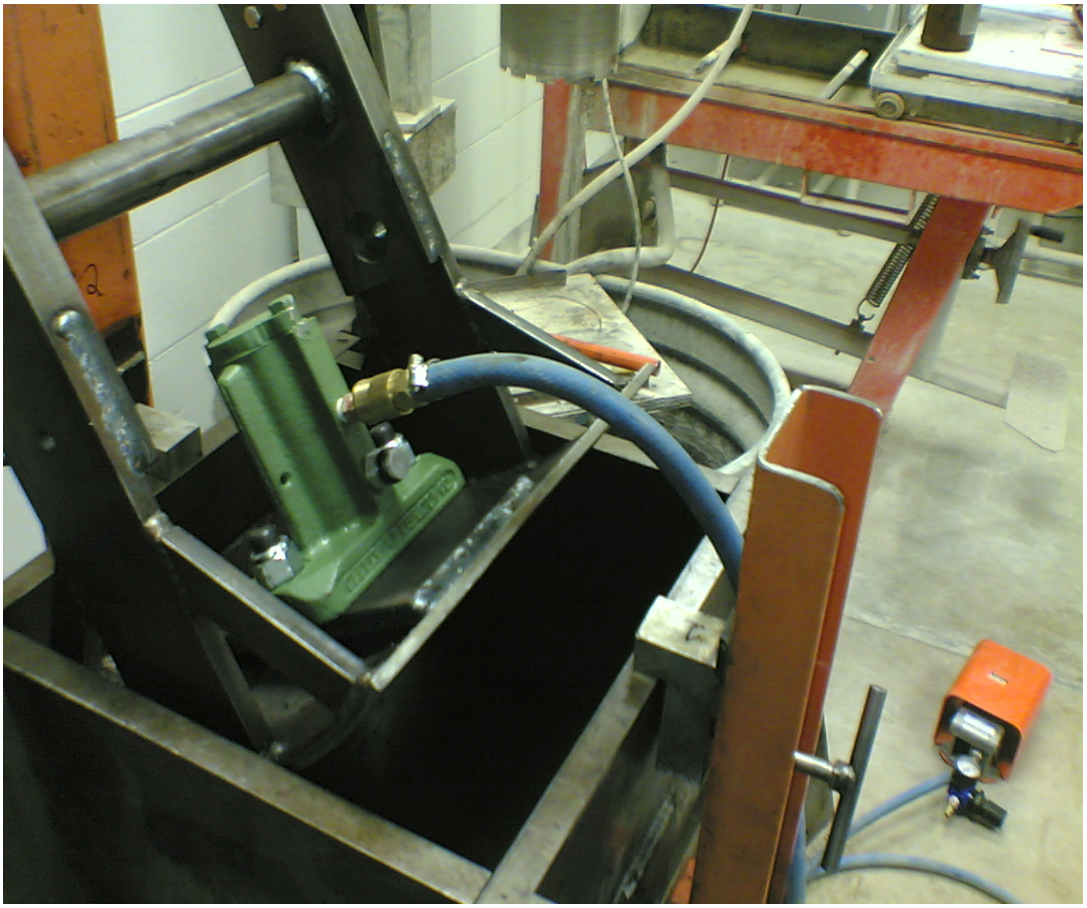


FIGURE 19 SLAB COMPACTOR

The slab compactor consists of a steel chamber measuring approximately one foot square. The compactor head is semi-circular steel plate with a vibrator, designed to simulate a roller in the field. Three mix combinations used are binder-binder, surface-surface, and surface-binder. The samples were prepared in a manner similar to that used in the field. Thirty-six blocks were prepared for each tack coat type. Figure 20 show the spreading of aggregates in the steel chamber before compaction.

FIGURE 20 Spreading Mix

After spreading the mix, the sample was compacted by rocking the compactor head back and forth, with the application of the vibrations to simulate field compaction as shown in the figure 21. The compaction was done in two stages, first, the bottom slab was compacted, tack coat was applied and the next layer was compacted on top of it. Figure 22 shows the compacted bottom slabs.

FIGURE 21 Compaction

FIGURE 22 Compacted Bottom Slabs

A block consists of two layers with a tack coat at the interface of these layers. The bottom layer (can be 12.5 mm or 25 mm mix depending on the combination) is compacted and after cooling, a predetermined amount of tack coat is applied with a brush; once the tack coat is cured/broken, the next layer is compacted. The final block is shown in the Figure 23 below.

FIGURE 23 Slab

The block is cored to get two representative samples with a diameter of 150 mm shown in figure 24.

FIGURE 24 Core

The core is tested for shear strength in a shearing device show in Figure 25. The shearing device has one movable head, with the other fixed. The device has a calibrated normal stress loading frame. The loading frame has a screw which is used to apply the normal stress, figure 26 shows the loading frame. The shearing device is mounted in a Marshall press. The Marshall press is connected to a plotter, which can plot the load required to shear the sample, a sample graph is shown in figure 27.

FIGURE 25 Shearing Device

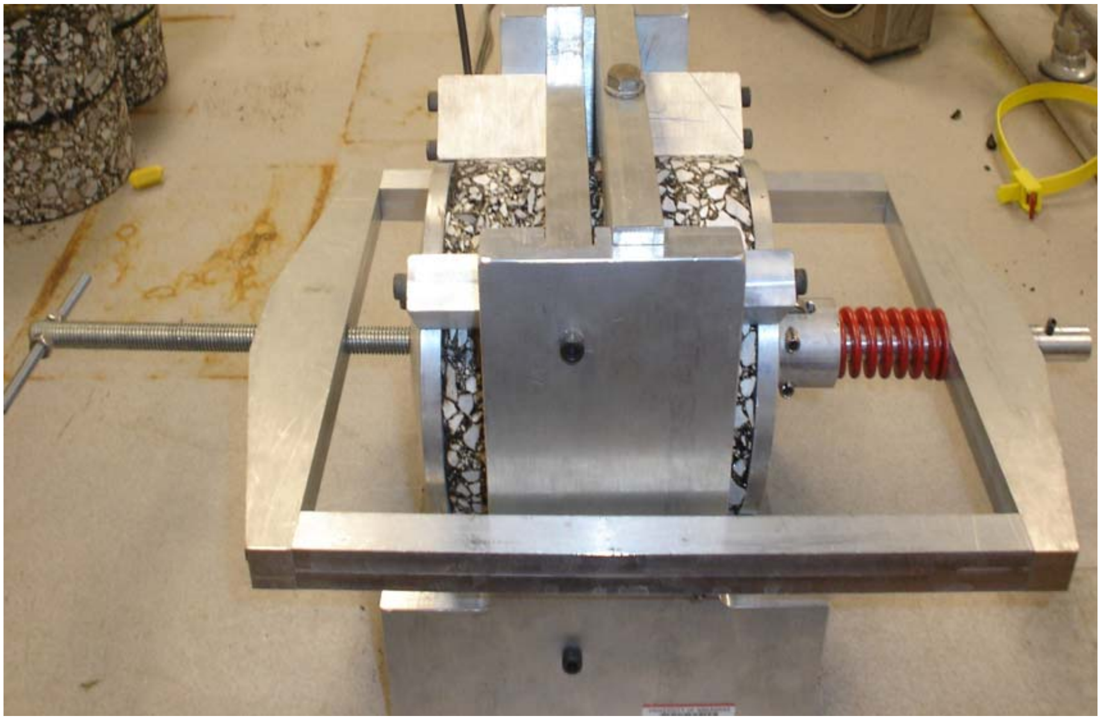
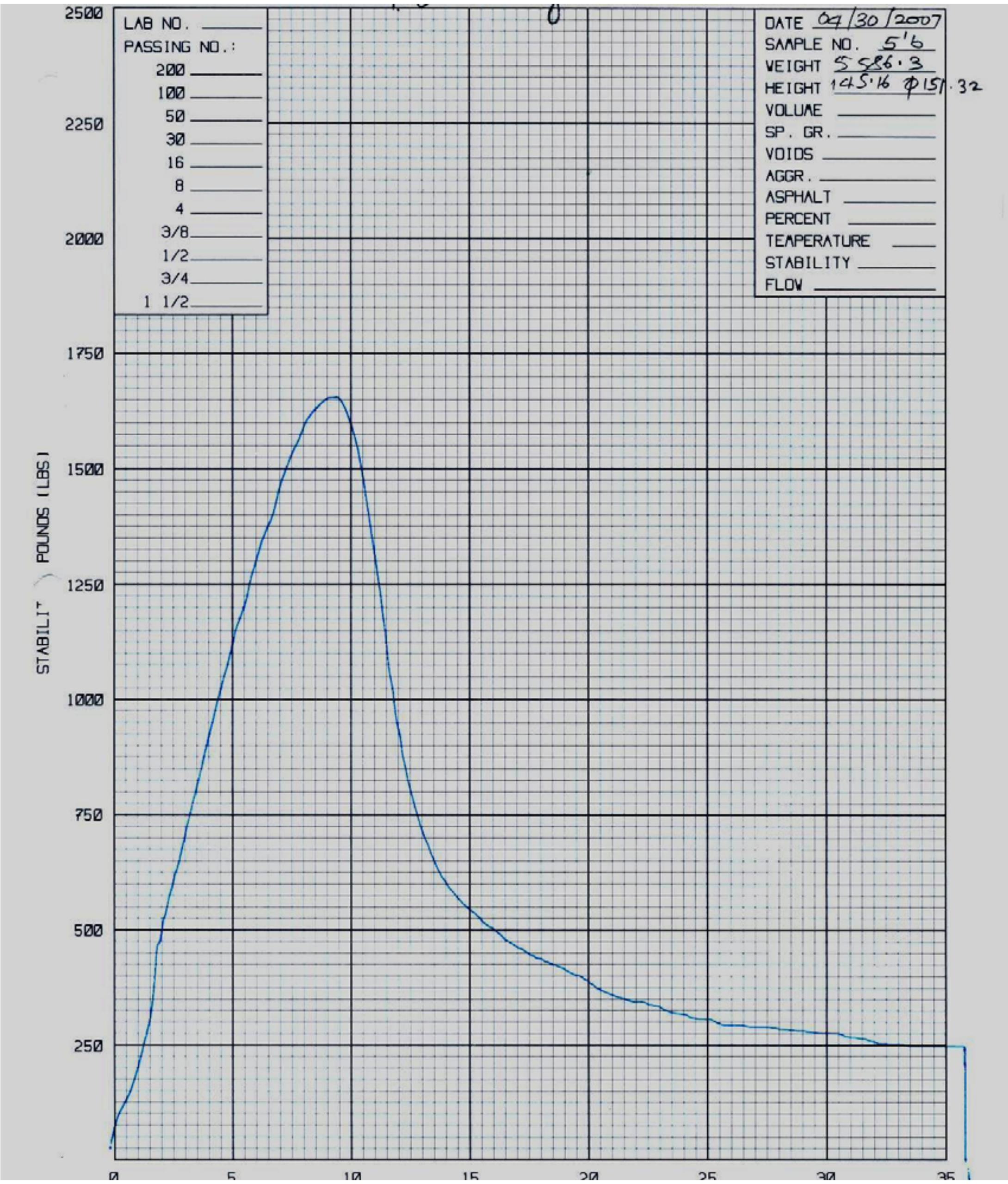


FIGURE 26 Normal Stress Frame



DATE 04/30/2007
SAMPLE NO. 5'6
WEIGHT 5586.3
HEIGHT 145.16 ϕ151.32

FIGURE 27 Sample Load Plot

CHAPTER 4 RESULTS & ANALYSIS

The test experimental design provided two samples for each combination of application rate, temperature, normal stress, and mix types. The load at failure was obtained from the graphs, the load is converted to shear strength, the sample calculations are shown in Appendix C.

4.1 SS 1

Table 6 presents the average shear strength for the SS 1 tack material.

TABLE 6 Average Shear Strength for SS 1

Application rate (gal/yd^2)	Temperature ºF	Normal Stress (psi)	Mix Type	Shear strength (lb/In^2)	Shear strength (lb/In^2)	Average Shear strength (lb/In^2)
0.02	70	0	12.5 / 25	149.67	156.78	153.22
			12.5 / 12.5	139.14	142.90	141.02
			25 / 25	175.99	190.59	183.29
		10	12.5 / 25	92.15	92.20	92.18
			12.5 / 12.5	115.07	113.99	114.53
			25 / 25	189.38	229.60	209.49
	130	0	12.5 / 25	24.22	17.32	20.77
			12.5 / 12.5	13.88	13.89	13.88
			25 / 25	38.02	34.75	36.39
		10	12.5 / 25	31.21	33.95	32.58
			12.5 / 12.5	48.72	38.16	43.44
			25 / 25	86.08	97.58	91.83
0.06	70	0	12.5 / 25	109.44	129.73	119.58
			12.5 / 12.5	104.42	101.00	102.71
			25 / 25	135.29	144.54	139.92
		10	12.5 / 25	159.95	157.12	158.53
			12.5 / 12.5	180.53	191.57	186.05
			25 / 25	167.00	154.75	160.88
	130	0	12.5 / 25	34.78	34.57	34.67
			12.5 / 12.5	15.68	17.39	16.54
			25 / 25	53.73	64.29	59.01
		10	12.5 / 25	38.23	38.93	38.58
			12.5 / 12.5	37.39	37.61	37.5
			25 / 25	49.24	48.38	48.81
0.1	70	0	12.5 / 25	110.82	170.33	140.58
			12.5 / 12.5	136.60	124.19	130.39
			25 / 25	95.52	86.51	91.01
		10	12.5 / 25	200.21	145.70	172.96
			12.5 / 12.5	87.43	129.08	108.25
			25 / 25	105.38	118.16	111.77
	130	0	12.5 / 25	10.35	13.14	11.74
			12.5 / 12.5	15.66	17.33	16.49
			25 / 25	12.14	13.21	12.67
		10	12.5 / 25	37.48	38.17	37.82
			12.5 / 12.5	36.35	38.82	37.59
			25 / 25	26.07	36.57	31.32

An analysis of variance (ANOVA) was performed on the data obtained, and from the analysis (summarized in Table 7), all the four factors (application rate, temperature, normal stress, mix type combination) are significant. There are two, two-way interactions and three, three-way interactions that showed significance. From the F-statistics, temperature is the most significant factor followed by normal stress, application rate, and finally mix type combination.

Table 7 ANOVA Results for SS 1

Source (SS 1)	DF	Seq SS	Adj SS	Adj MS	F	P	Significance
Application rate	2	5224.7	5224.7	2612.4	15.82	<0.0001	Yes
Temperature	1	199516.1	199516	199516	1208.58	<0.0001	Yes
Normal Stress	1	4690	4690	4690	28.41	<0.0001	Yes
Mix Type Combination	2	4596.2	4596.2	2298.1	13.92	<0.0001	Yes
Application rate * Temperature	2	191.2	191.2	95.6	0.58	0.566	No
Application rate * Normal Stress	2	1242.4	1242.4	621.2	3.76	0.033	Yes
Application rate * Mix Type Combination	4	15573.1	15573.1	3893.3	23.58	<0.0001	Yes
Temperature * Normal Stress	1	227.8	227.8	227.8	1.38	0.248	No
Temperature * Mix Type Combination	2	218.2	218.2	109.1	0.66	0.523	No
Normal Stress * Mix Type Combination	2	547.5	547.5	273.8	1.66	0.205	No
Application rate * Temperature * Normal stress	2	6879.8	6879.8	3439.9	20.84	<0.0001	Yes
Application rate * Temperature * Mix Type Combination	4	4856.4	4856.4	1214.1	7.35	<0.0001	Yes
Application rate * Normal Stress * Mix Type Combination	4	6954.4	6954.4	1738.6	10.53	<0.0001	Yes
Temperature * Normal Stress * Mix Type Combination	2	163.7	163.7	81.8	0.5	0.613	No
Application rate * Temperature * Normal stress * Mix Type Combination	4	1357	1357	339.3	2.06	0.107	No
Error	36	5943	5943	165.1			
Total	71	258181.5					

Figure 28 shows the shear strength for temperature, normal stress, and mix type combinations.

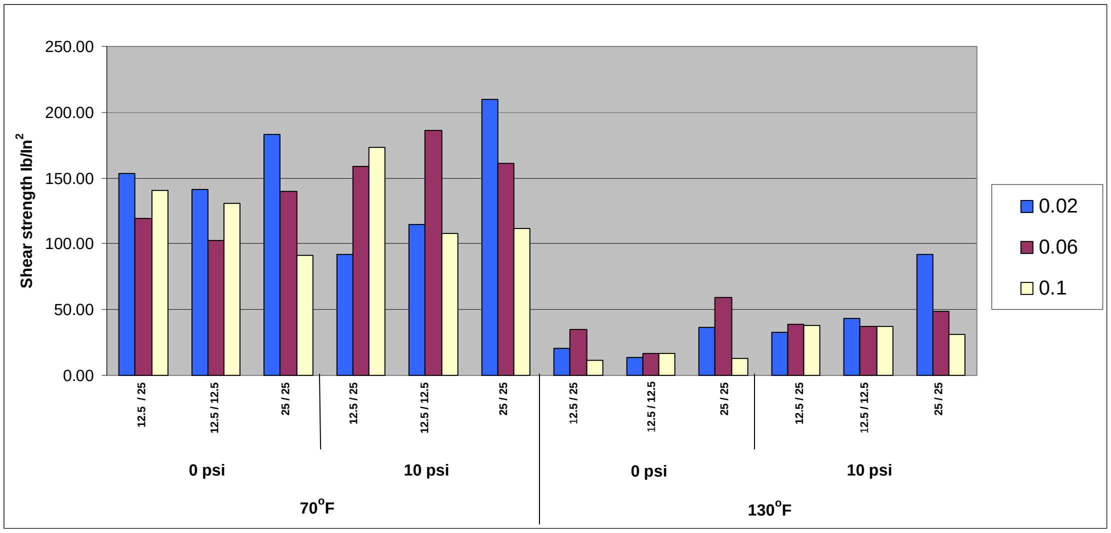


FIGURE 28 Effects of Temperature, Normal Stress, & Mix Type Combination on Shear Strength

From Figure 28, it is evident with an increase in temperature, the shear strength decreases; this is true for all mix type combinations, application rates and normal stress levels. The tack coat at 70 ^{o}F is stiff and well bonded with the adjacent layer; at 130 ^{o}F the tack coat becomes weak, and perhaps acts as a lubricant, hence the low shear strength.

The shear strength increases with increase in normal stress. Although the temperature affects the shear strength, if we compare the results within a specific temperature range, increase in normal stress increases the shear strength. In addition, the shear strength is higher for Binder – Binder (25 mm / 25 mm mix) mix type combination for lower (0.02 gal/yd^2) application rate. This could be because of the increased frictional resistance at the interface and the presence of just enough residual tack coat to increase the shear strength.

In the field, the pavement temperature easily reaches 130 ^{o}F, and since the shear strength is low at this temperature, it is necessary to analyze the bond strength results at 130 ^{o}F to determine if any other factors influence the bonding. ANOVA was performed on the data obtained at 130 ^{o}F and the results are summarized in Table 8

TABLE 8 ANOVA Results for Shear Strength at 130 ^{o}F

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance
Application rate	2	1776.67	1776.67	888.34	57.74	<0.0001	Yes
Normal Stress	1	3492.61	3492.61	3492.61	227.01	<0.0001	Yes
Mix Type Combination	2	2670.22	2670.22	1335.11	86.78	<0.0001	Yes
Application rate * Normal stress	2	1147.05	1147.05	573.53	37.28	<0.0001	Yes
Application rate * Mix Type Combination	4	2415.14	2415.14	603.78	39.24	<0.0001	Yes
Normal stress * Mix Type Combination	2	159.64	159.64	79.82	5.19	0.017	Yes
Application rate * Normal stress * Mix Type Combination	4	1319.23	1319.23	329.81	21.44	<0.0001	Yes
Error	18	276.94	276.94	15.39			
Total	35	13257.5					

From the analysis results it is evident that all the three factors (application rate, normal stress, and mix type combination) all two way and all three way interactions show significance. From the F – Statistic, Normal stress influences the shear strength followed by mix type combination, and application rate.

From the analysis, we can be sure that temperature, normal stress, mix type combination and application rate influences the bond strength, therefore is it is logical to analyze the shear strength results at 130 ^{o}F and 10 psi which is the worst case conditions.

Figure 29 shows the shear strength versus application rate and mix type combination at 130 °F and 10 psi. The shear strength varies with the mix type combination. The shear strength is almost equal at 0.06 gal/yd^2 for Surface-Binder (12.5 mm by 25 mm) mix combination. For a Surface-Surface (12.5 mm by 12.5 mm) mix combination the lower application rate of 0.02 gal/yd^2 produces higher shear strength. Interestingly, the shear strength is almost double for Binder-Binder (25 mm by 25 mm) mix combination.

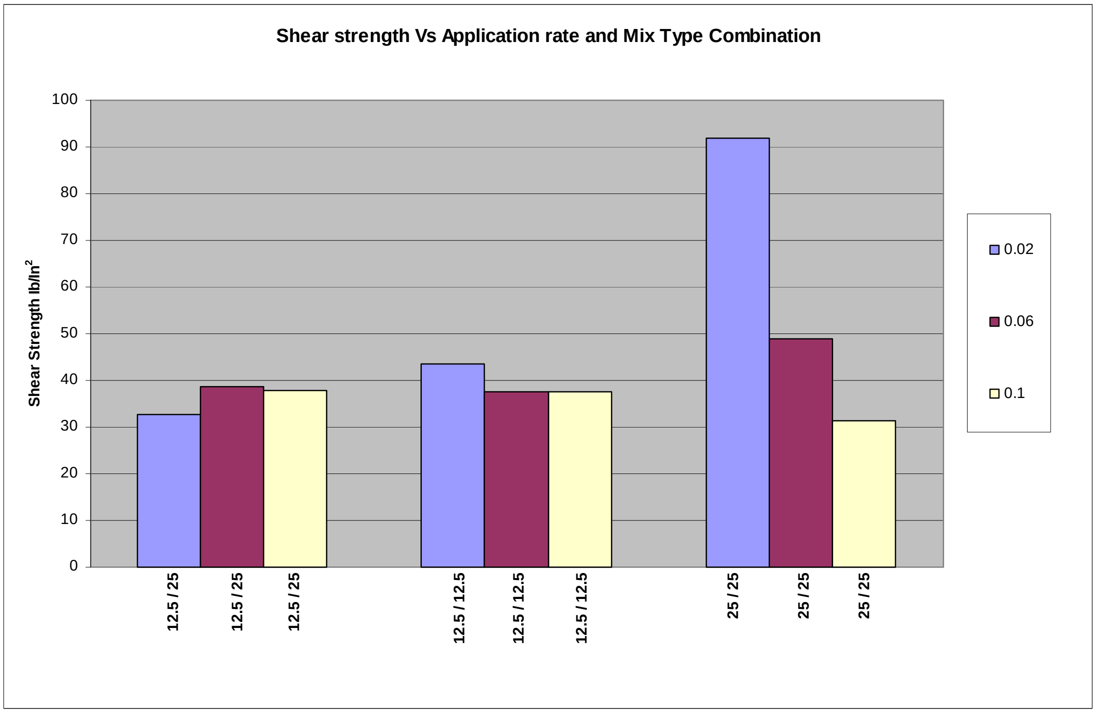


FIGURE 29 Application Rate Vs Mix Type Combination at 130^{0}F and 10 PSI

A logical explanation for this is the lack of residual tack coat present on the surface. The tack coat is soaked into the lower layer or it runs off the surface because of the sudden large volume. The basic principle of tack coat is to melt when hot asphalt comes into contact and lock the upper and lower layer as it cools.

4.2 NTSS 1

Table 9 presents the average shear strength for NTSS 1.

TABLE 9 Average Shear Strength for NTSS 1

Application rate (gal/yd^2)	Temperature (^{o}F)	Normal Stress (psi)	Mix Type	Shear strength (lb/In^2)	Shear strength (lb/In^2)	Average Shear strength (lb/In^2)
0.02	70	0	12.5 / 25	106.13	112.21	109.17
			12.5 / 12.5	105.65	112.91	109.28
			25 / 25	118.78	99.15	108.96
		10	12.5 / 25	120.28	151.00	135.64
			12.5 / 12.5	120.26	129.80	125.03
			25 / 25	130.92	104.71	117.81
	130	0	12.5 / 25	20.60	27.54	24.07
			12.5 / 12.5	27.53	17.23	22.38
			25 / 25	23.76	20.70	22.23
		10	12.5 / 25	48.45	48.08	48.26
			12.5 / 12.5	47.97	44.99	46.48
			25 / 25	24.11	41.11	32.61
0.06	70	0	12.5 / 25	127.66	133.05	130.35
			12.5 / 12.5	131.17	130.71	130.94
			25 / 25	99.75	115.15	107.45
		10	12.5 / 25	147.90	162.19	155.04
			12.5 / 12.5	163.40	174.94	169.17
			25 / 25	193.39	162.00	177.69
	130	0	12.5 / 25	31.00	27.64	29.32
			12.5 / 12.5	20.74	31.05	25.89
			25 / 25	24.20	31.18	27.69
		10	12.5 / 25	55.10	55.20	55.15
			12.5 / 12.5	37.90	34.57	36.23
			25 / 25	38.00	24.18	31.09
0.1	70	0	12.5 / 25	167.09	184.40	175.75
			12.5 / 12.5	137.91	153.30	145.6
			25 / 25	153.93	167.93	160.93
		10	12.5 / 25	210.22	186.22	198.22
			12.5 / 12.5	176.81	166.11	171.46
			25 / 25	154.71	160.99	157.85
	130	0	12.5 / 25	24.87	24.71	24.79
			12.5 / 12.5	10.49	14.04	12.27
			25 / 25	27.46	24.11	25.79
		10	12.5 / 25	37.99	37.85	37.92
			12.5 / 12.5	41.20	44.57	42.89
			25 / 25	44.86	41.20	43.03

ANOVA was performed on the data obtained and from the analysis (summarized in Table 10), all the four factors (Application rate, Temperature, Normal Stress, Mix Type Combination) are significant. There are one, two-way interactions two, three-way interactions; and one four way interaction that showed significance. From the F-statistics, temperature is the most significant factor followed by Normal stress, Application rate, and finally Mix type combination, which is similar to SS 1.

TABLE 10 ANOVA Results for NTSS 1

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance
Application rate	2	7309.9	7309.9	3655	42.95	<0.0001	Yes
Temperature	1	221839.1	221839.1	221839.1	2606.93	<0.0001	Yes
Normal stress	1	8394.8	8394.8	8394.8	98.65	<0.0001	Yes
Mix Type Combination	2	1123.8	1123.8	561.9	6.6	0.004	Yes
Application rate * Temperature	2	8178.3	8178.3	4089.2	48.05	<0.0001	Yes
Application rate * Normal stress	2	466.7	466.7	233.4	2.74	0.078	No
Application rate * Mix Type Combination	4	507.7	507.7	126.9	1.49	0.225	No
Temperature * Normal stress	1	274.1	274.1	274.1	3.22	0.081	No
Temperature * Mix Type Combination	2	110.5	110.5	55.2	0.65	0.528	No
Normal stress * Mix Type Combination	2	132.4	132.4	66.2	0.78	0.467	No
Application rate * Temperature * Normal stress	2	1236.8	1236.8	618.4	7.27	0.002	Yes
Application rate * Temperature * Mix Type Combination	4	1319.5	1319.5	329.9	3.88	0.01	Yes
Application rate * Normal stress * Mix Type Combination	4	764.7	764.7	191.2	2.25	0.083	No
Temperature * Normal stress * Mix Type Combination	2	117.9	117.9	59	0.69	0.507	No
Application rate * Temperature * Normal stress * Mix Type Combination	4	1295	1295	323.8	3.8	0.011	Yes
Error	36	3063.5	3063.5	85.1			
Total	71	256134.9					

Figure 30 shows the shear strength for temperature, normal stress, and mix type combinations

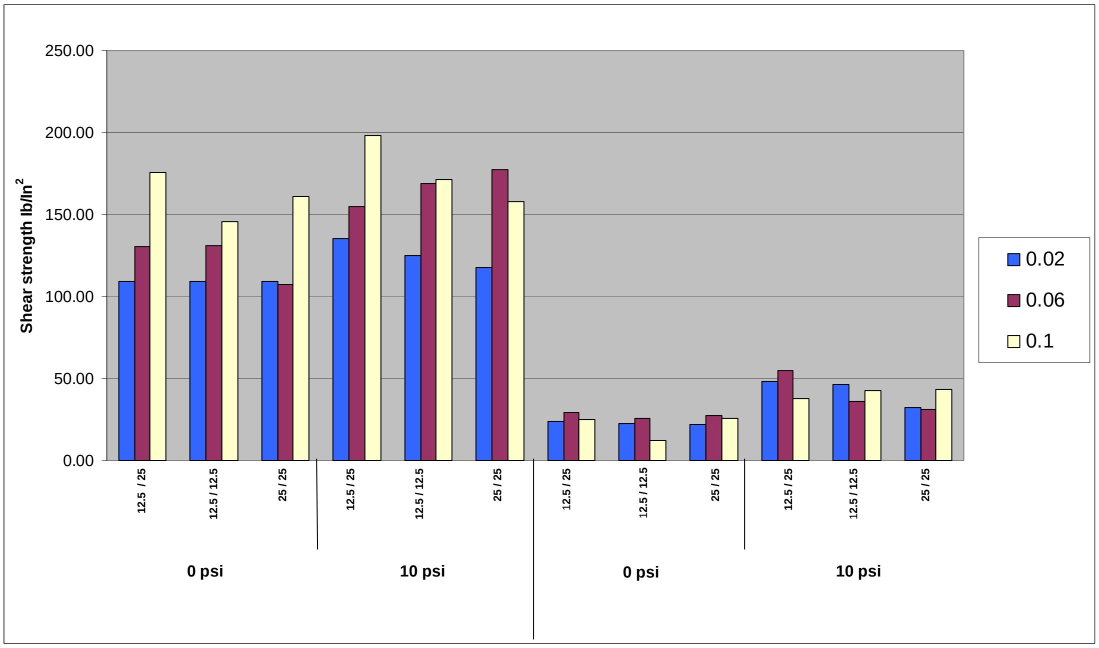


FIGURE 30 Effects of Temperature, Normal Stress, & Mix Type Combination on Shear Strength

From Figure 30, it is evident with the increase in temperature, the shear strength decreases; this is true for all mix type combinations, application rates and normal stress levels. Similar to the results from SS-1 the tack coat at 70 ^{o}F appears stiff and well bonded with the adjacent layer; at 130 ^{o}F the tack coat becomes weak, and perhaps acts as a lubricant, hence the low shear strength.

The shear strength increases with increase in normal stress. Although the temperature affects the shear strength, if we compare the results within a specific temperature range, increase in normal stress increases the shear strength. At 70 ^{0}F, the shear strength is higher for Surface – Binder (12.5 mm / 25 mm mix) mix type combination for both the normal stress values but with a higher application rate of 0.1 gal/yd^2 .

In the field, the pavement temperature easily reaches 130 ^{o}F, and since the shear strength a this temperature is lower compared to shear strength at 70 ^{o}F , it is necessary to analyze the bond strength results at 130 ^{o}F to determine if any other factors influence the bonding. ANOVA was performed on the data obtained at 130 ^{o}F and the results are summarized in Table 11.

TABLE 11 ANOVA Results for Shear Strength at 130 ^{o}F

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Significance
Application rate	2	58.31	58.31	29.16	1.19	0.326	No
Normal stress	1	2817.49	2817.49	2817.49	115.44	<0.0001	Yes
Mix Type Combination	2	278.06	278.06	139.03	5.7	0.012	Yes
Application rate * Normal stress	2	92.16	92.16	46.08	1.89	0.18	No
Application rate * Mix Type Combination	4	377.32	377.32	94.33	3.86	0.019	Yes
Normal stress * Mix Type Combination	2	243.82	243.82	121.91	4.99	0.019	Yes
Application rate * Normal stress * Mix Type Combination	4	313.53	313.53	78.38	3.21	0.037	Yes
Error	18	439.33	439.33	24.41			
Total	35	4620.01					

Based on the ANOVA results, two factors (normal stress, and mix type combination) two, two way and all three-way interaction show significance. From the F – Statistic, normal stress has the maximum influence on the shear strength followed by mix type combination and application rate.

Since temperature, normal stress, and mix type combination influences the bond strength at 130 °F, it is practical to analyze the shear strength results at 130 °F and 10 psi, which is the worst-case scenario.

Figure 31 shows the shear strength versus application rate and mix type combination at 130 °F and 10 psi. The shear strength varies with the mix type combination. The shear strength is maximum for surface-binder (12.5 mm by 25 mm) mix type combination at 0.06 gal/yd^2. A surface-surface (12.5 mm by 12.5 mm) mix combination with lower application rate of 0.02 gal/yd^2 produces higher shear strength, but for binder-binder (25 mm by 25 mm) mix type combination, a higher application rate of 0.1 gal/yd^2 produces higher shear strength. It does not appear that application rate practically affects strength, therefore can use lower application rate.

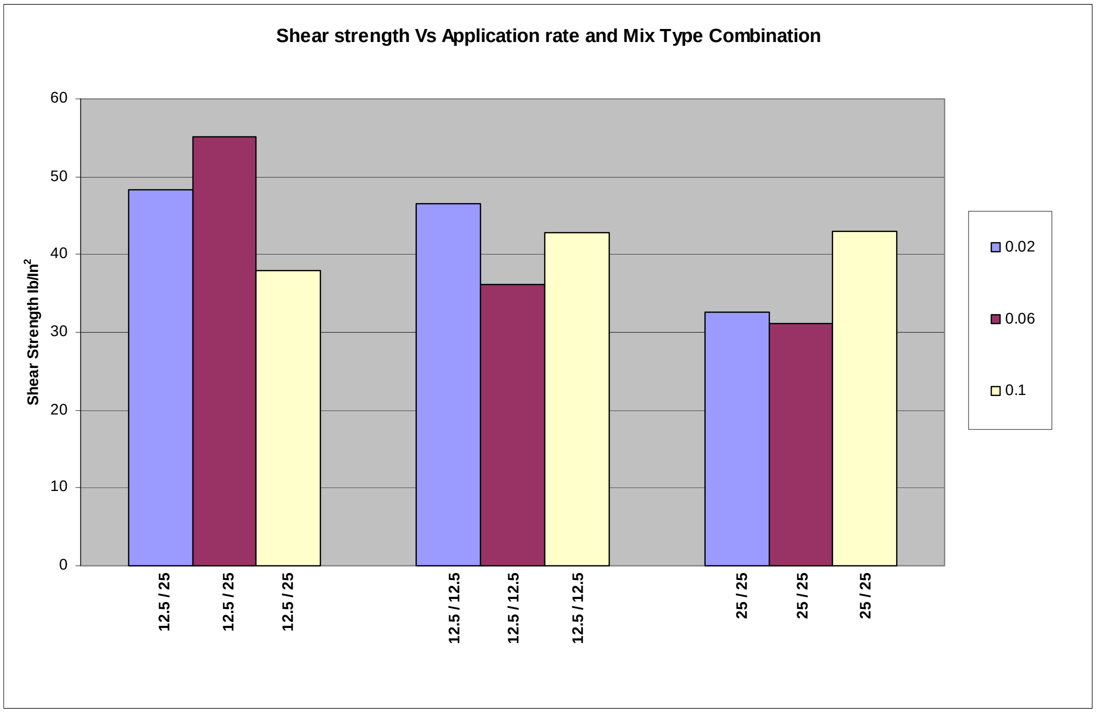


FIGURE 31 Application Rate Vs Mix Type Combination at 130^{0}F and 10 PSI

4.3 NTSS 1 Versus SS 1

Table 12 shows the t- test results for NTSS 1 and SS 1, since t $_{stat}$ is less than t $_{critical}$; NTSS 1 and SS 1 are not significantly different.

TABLE 12 t-test for NTSS 1 and SS 1

	SS 1	**NTSS 1**
Mean	44.38555556	41.51777778
Unequal variance	343.9908028	61.13501944
Observations	9	9
Hypothesized Mean Difference	0	
df	11	
t Stat	0.427436679	
P(T<=t) one-tail	0.338654269	
t Critical one-tail	1.795884814	
P(T<=t) two-tail	0.677308538	
t Critical two-tail	2.200985159	

The sample preparation for SS 1 and NTSS 1 were slightly different. SS 1 specimen was cured in open air and the tack coat was at 50 % dilution. Where as, NTSS 1 was not diluted and oven cured at 100 °F. Therefore, the two samples have unequal variances.

However, comparing results from the SS 1 and NTSS 1 tack coat materials shown in Figure 32, we can observe that, SS 1 produces highest shear strength with lower application rate of 0.02 gal/yd^2 for Binder-Binder mix type combination. NTSS 1 produces highest shear strength for Surface-Binder mix type with the application rate of 0.06 gal/yd^2. However, for higher application of 0.1 gal/yd^2. NTSS 1 produces a slightly higher shear strength than SS 1

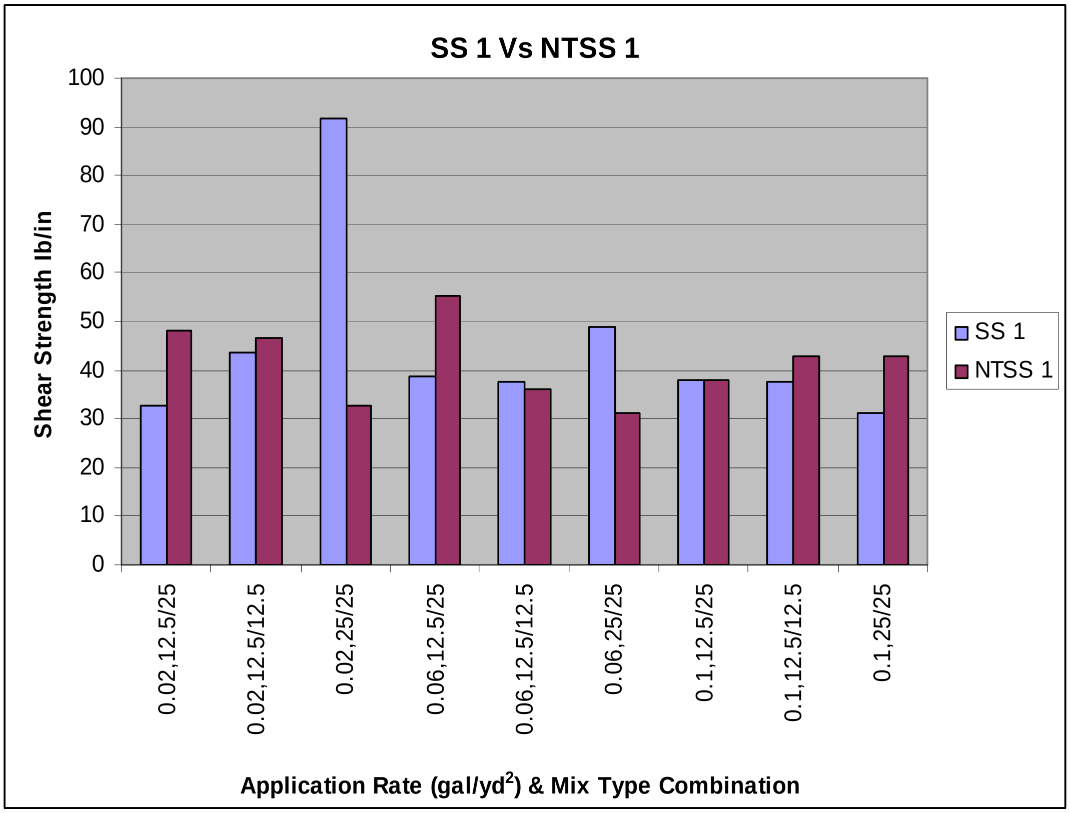


FIGURE 32 Application Rate Vs Shear Strength for NTSS 1 & SS 1

CHAPTER 5 CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

Laboratory tests were performed with two tack coat materials (SS 1, NTSS 1), three application rates (0.02, 0.06, 0.1 gal/yd^2), two normal stress levels (0, 10 psi), two temperatures (70, 130 ^{o}F), and three mix type combinations (surface-binder, surface-surface, binder-binder).

Application rate, temperature, normal stress, and mix type combination show significance for both SS 1 and NTSS 1. Temperature is the most significant factor followed by normal stress, application rate, and mix type combination, this is common for both SS 1 and NTSS 1.

Analysis of the results at 130^{0}F indicates normal stress is the most significant factor followed by mix type combination and application rate. From constructability and performance standpoint, we cannot control the temperature and normal stress effect in the field, but we can control the mix type combination, application rate and tack coat type to help increase bonding of layers.

SS 1 produces highest shear strength at 0.02 gal/yd^2 for a binder-binder (25 mm by 25 mm mix) mix type combination. NTSS 1 produces highest shear strength at 0.06 gal/yd^2 and the shear strength is almost the same at 0.02 gal/yd^2 for a surface-binder (12.5 mm by 25 mm) mix type combination, therefore using a lower application rate could cut construction cost.. For surface-surface (12.5 mm by 12.5 mm) mix type combination, both SS 1 and NTSS 1 produces almost same shear strength at 0.02 gal/yd^2 .

It can be concluded that, shear strength mainly depends upon mix type combination. Table 13 summarizes tack coat and application rates that produce the highest shear strength for a specific mix type combination.

TABLE 13 Best Tack Coat and Application Rate for Specific Mix Type Combination

Mix Type Combination	Tack Coat	Application Rate gal/yd^2
Surface – Surface (12.5 mm -12.5 mm)	SS- 1 or NTSS -1	0.02
Surface – Binder (12.5 mm – 25 mm)	NTSS - 1	0.02
Binder – Binder (25 mm -25 mm)	SS - 1	0.02

The lab tests should be done at higher temperature as far as possible the testing temperature should be similar to the highest temperature the pavement is likely to be exposed to. The presence of normal stress is vital to simulate the traffic loading during shear. Temperature and Normal stress is vital to imitate the field conditions.

5.2 Recommendations :

- The site engineer should identify the existing pavement mix and based on the existing pavement mix, suitable application rate with the appropriate tack coat should be used.

- Care should be taken, to check the application rate of tack coat, excessive tack coat does not help in bonding, but rather increase the construction costs.

5.3 Future Research :

- Validate the laboratory samples with the field cores.
- A field study should be conducted to check whether tack coat should be applied for the full length of the pavement or only at small radius curves, traffic signals, highly trafficked streets and steep gradient roads where the shear force is greater.
- The shear strength variation over time should be evaluated.
- Determine the maximum shear stress induced at the interface of the lifts, so that, we know the maximum bond strength required to resist debonding.

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APPENDIX A TACK COAT AND APPLICATION RATES IN USA

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Alabama	CSS-1 CSS-1h AC	NO	a) Normal range-0.45 b)Range on existing–evaluated c) Range on overlay-none	0.26	Minimum time-after emulsion is cured
Alaska	STE-1 CSS-1	CSS-1 is 50%	a) Normal range-0.35 b) Range on existing– 0.32 c) Range on overlay-none	0.09	Minimum- 15 min Maximum- 2 hrs
Arizona	SS-1 diluted with 1:1 water and AC	1:1 with water	a) Normal range-0.27-0.54 b) Range on existing–same c) Range on overlay-0.18-0.36	0.15	Minimum when emulsion breaks. Maximum no more tack coat than covered up in shift
Arkansas	SS-1	no	a) Normal range-0.23 b) Range on existing–0.14-0.23 c) Range on overlay-same	0.13	Minimum- after AC breaks Maximum-72hrs

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
California	RS-1 SS-1	0.14% asphalt to water	a) Normal range-0.09-0.45 b) Range on existing–0.09-0.45 c) Range on overlay-0.09-0.23	0.26	Minimum-depends on climate Maximum-nil
Connecticut	Asphalt emulsion	50%	a) Normal range-0.14-0.45 b) Range on existing–same c) Range on overlay-same	0.13	Not specified
Florida	RS-1 RS-2	no	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	nil	Not specified
Georgia	AC-20 AC-30	nil	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	Nil	Not specified

States	Materials	% dilution of SS	Tack coat application rate	Residual Application rate	Time between application of tack coat and placing of HMA layer
Hawaii	Emulsified asphalt	1:1 by volume with water	a) Normal range-0.23-0.05 b) Range on existing–same c) Range on overlay-same	0.13	Minimum- after surface is cured Maximum- 4hrs
Illinois	Emulsified asphalt	50%	a) Normal range-0.41 b) Range on existing–same c) Range on overlay-0.10 RC-70	0.12	Minimum- after emulsion breaks Maximum-if traffic allowed, its covered with aggregates
Iowa	CSS-1 CSS-1h	nil	a) Normal range-0.09-0.23 b) Range on existing–same c) Range on overlay-same	0.13	Minimum- subject to engineers approval Maximum- not specified
Kansas	SS-1h CSS-1h	80%	a) Normal range-0.14-0.23 b) Range on existing–same c) Range on overlay-same	0.14-0.23	Minimum- 1hr Maximum- 5-6hrs

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Louisiana	SS-1h CSS-1h	50%	a) Normal range-0.09-0.36 b) Range on existing–0.32 c) Range on overlay-0.14	0.18	Minimum- broken Maximum- none
Maine	HFMS-1	nil	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	nil	nil
Maryland	AE-4	As is from refinery	a) Normal range-0.05-0.14 b) Range on existing–0.05 c) Range on overlay-0.05	0.08	Minimum- 15min Maximum-nil
Michigan	SS-1h	Cannot exceed original volume	a) Normal range-specified by the engineer b) Range on existing–0.45 c) Range on overlay-0.23	0.13	Minimum- when bond coat has cured Maximum- nil

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Louisiana	SS-1h CSS-1h	50%	a) Normal range-0.09-0.36 b) Range on existing–0.32 c) Range on overlay-0.14	0.18	Minimum- broken Maximum- none
Maine	HFMS-1	nil	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	nil	nil
Maryland	AE-4	As is from refinery	a) Normal range-0.05-0.14 b) Range on existing–0.05 c) Range on overlay-0.05	0.08	Minimum- 15min Maximum-nil
Michigan	SS-1h	Cannot exceed original volume	a) Normal range-specified by the engineer b) Range on existing–0.45 c) Range on overlay-0.23	0.13	Minimum- when bond coat has cured Maximum- nil

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Mississippi	SS-1	Contractor is not to dilute	a) Normal range-0.23-0.45 b) Range on existing–same c) Range on overlay-same	0.26	Minimum- allow emulsion to break Maximum- nil
Missouri	Emulsified asphalt	Up to 50%	a) Normal range-0.09-0.45 b) Range on existing– up to the engineer c) Range on overlay-uniform coverage	0.13	Minimum- when tack coat has cured Maximum- nil
Montana	SS-1	50%	a) Normal range-0.14-0.23 b) Range on existing–same c) Range on overlay-0.23	0.06	Minimum-until emulsion breaks Maximum- must be maintained intact
Nevada	SS-1 SS-1h	60%-40%	a) Normal range-0.23-0.45 b) Range on existing–0.23-0.32 c) Range on overlay-0.23	0.15	Minimum- after emulsion breaks Maximum- nil

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
New Jersey	CSS-1h	50%	a) Normal range-0.18-0.68 b) Range on existing–same c) Range on overlay-0.18-0.45		Minimum- cure to condition which is tacky to touch Maximum-same day
New Mexico	SS-1	50%	a) Normal range-0.36-0.54 b) Range on existing– + or – 0.54 c) Range on overlay-+ or – 0.36	0.15	Minimum- 15 min to 1hr Maximum- nil
New York	HFMS-2h SS-1h CSS-1h	50%	a)Normal range-0.14-0.32 b) Range on existing–same c) Range on overlay-same	0.09	Minimum-when emulsion breaks Maximum-time placement of HMA
North Carolina	CRS-1 CRS-2	Nil	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	Nil	Minimum-immediately after tack coat application Maximum-same day as tack coat

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
North Dakota	Emulsified asphalt	50%	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	Nil	Not specified
Ohio	SS-1h	Nil	a) Normal range-0.32-0.45 b) Range on existing–same c) Range on overlay-none	0.26	Minimum-several minutes Maximum- limited by traffic zone
Oklahoma	SS-1	50%	a) Normal range-0.45 b) Range on existing–same c) Range on overlay-none	0.13	Minimum-emulsion must break Maximum-same day
Oregon	CSS-1	Nil	a) Normal range-0.23-0.91 b) Range on existing–same c) Range on overlay-same	0.52	Nil

States	**Material**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Pennsylvania	CSS-1h	50%	a) Normal range-0.09-0.32 b) Range on existing–engineers judgment c) Range on overlay-engineers judgment	0.32	Minimum- until cure Maximum-not specified
Rhode island	SS-1	40%	a) Normal range-0.23-0.09 b) Range on existing–same c) Range on overlay-none	0.08	Nil
South Carolina	CRS-2	Nil	a) Normal range-nil b) Range on existing–nil c) Range on overlay-nil	Nil	Minimum- allow emulsion to break Maximum-time on ambient air temperature, humidity and material temp.
South Dakota	SS-1h CSS-1h	1:1	a) Normal range-0.23 b) Range on existing– same c) Range on overlay- same	0.13	Minimum-emulsion must be broken Maximum- not specified

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Tennessee	Emulsified asphalt	30%	a) Normal range- 0.23 b) Range on existing– same c) Range on overlay- 0.09	0.23	Minimum- until properly cured Maximum- contractor protects tack coat until next course is applied
Texas	SS-1 MS-2	1 to 1	a) Normal range- 0.05-0.23 b) Range on existing– nil c) Range on overlay-nil	0.06	Minimum- 30 min Maximum- 45min
Vermont	RS-1	Nil	a) Normal range- nil b) Range on existing– nil c) Range on overlay- nil	Nil	Nil
Virginia	CSS-1h	50%	a) Normal range- 0.23-0.45 b) Range on existing–same c) Range on overlay-0.45	0.13	Minimum- asphalt have broke Maximum- nil

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Washington state	CSS-1	50%	a) Normal range- 0.45 b) Range on existing– same c) Range on overlay- same	0.13	Minimum- 30min Maximum- nil
Washington D.C	SS-1h	3 to 1	a) Normal range- 0.09-0.23 b) Range on existing– nil c) Range on overlay-nil	0.10	Minimum- after it becomes tacky Maximum- regulated by the engineer
West Virginia	SS-1h	50%	a) Normal range-0.9-1.4 b) Range on existing–same c) Range on overlay-not used	0.51	Minimum- cured Maximum- nil
Wisconsin	Asphalt emulsion CSS-1	50%	a) Normal range- 0.11 b) Range on existing– same c) Range on overlay-same	0.03	Minimum- after it breaks Maximum- nil

States	**Materials**	**% dilution of SS**	**Tack coat application rate**	**Residual Application rate**	**Time between application of tack coat and placing of HMA layer**
Wyoming	CSS-1	50%	a) Normal range- 0.14 b) Range on existing– same c) Range on overlay-same	0.05	Broken
Utah	SS-1 SS-1h CSS-1 CSS-1h	50%	a) Normal range- 0.36-0.45 residual b) Range on existing– same c) Range on overlay-same	0.36-0.45	Minimum- 20 min Maximum- nil

APPENDIX B AIR VOIDS IN SS 1 & NTSS 1

SS 1 AIR VOIDS

Sample ID	Mix Type	% Air voids
1 Top	12.5	5.89
1 Bottom	25	5.75
2 Top	12.5	5.95
2 Bottom	12.5	5.51
3 Top	25	6.46
3 Bottom	25	6.80
4 Top	12.5	5.39
4 Bottom	25	6.22
5 Top	12.5	5.55
5 Bottom	12.5	5.69
6 Top	25	6.89
6 Bottom	25	6.52
7 Top	12.5	5.11
7 Bottom	25	6.16
8 Top	12.5	5.12
8 Bottom	12.5	5.89
9 Top	25	5.75
9 Bottom	25	5.99
10 Top	12.5	6.41
10 Bottom	25	5.65
11 Top	12.5	6.32
11 Bottom	12.5	6.28
12 Top	25	5.52
12 Bottom	25	5.64
13 Top	12.5	5.50
13 Bottom	25	5.41
14 Top	12.5	6.91
14 Bottom	12.5	6.12
15 Top	25	6.40
15 Bottom	25	6.92
16 Top	12.5	6.58
16 Bottom	25	6.90
17 Top	12.5	6.10
17 Bottom	12.5	6.87
18 Top	25	6.35
18 Bottom	25	6.87

Sample ID	Mix Type	% Air voids
19 Top	12.5	6.00
19 Bottom	25	6.63
20 Top	12.5	6.49
20 Bottom	12.5	6.93
21 Top	25	6.98
21 Bottom	25	7.00
22 Top	12.5	5.51
22 Bottom	25	6.21
23 Top	12.5	5.93
23 Bottom	12.5	5.97
24 Top	25	6.79
24 Bottom	25	6.35
25 Top	12.5	6.16
25 Bottom	25	6.31
26 Top	12.5	5.27
26 Bottom	12.5	5.18
27 Top	25	5.56
27 Bottom	25	6.47
28 Top	12.5	5.44
28 Bottom	25	5.36
29 Top	12.5	5.81
29 Bottom	12.5	5.76
30 Top	25	5.63
30 Bottom	25	6.41
31 Top	12.5	5.41
31 Bottom	25	5.90
32 Top	12.5	5.16
32 Bottom	12.5	6.60
33 Top	25	5.98
33 Bottom	25	6.06
34 Top	12.5	6.36
34 Bottom	25	6.99
35 Top	12.5	6.44
35 Bottom	12.5	5.49
36 Top	25	6.41
36 Bottom	25	6.19

NTSS 1 AIR VOIDS

Sample ID	Mix Type	% Air voids
1 Top	12.5	5.62
1 Bottom	25	6.12
2 Top	12.5	6.57
2 Bottom	12.5	6.27
3 Top	25	6.88
3 Bottom	25	6.11
4 Top	12.5	6.06
4 Bottom	25	6.85
5 Top	12.5	6.22
5 Bottom	12.5	6.60
6 Top	25	6.37
6 Bottom	25	6.37
7 Top	12.5	5.09
7 Bottom	25	6.77
8 Top	12.5	5.69
8 Bottom	12.5	6.24
9 Top	25	6.43
9 Bottom	25	6.24
10 Top	12.5	6.93
10 Bottom	25	6.43
11 Top	12.5	5.61
11 Bottom	12.5	6.71
12 Top	25	6.84
12 Bottom	25	6.78
13 Top	12.5	6.12
13 Bottom	25	6.54
14 Top	12.5	6.36
14 Bottom	12.5	5.31
15 Top	25	6.65
15 Bottom	25	6.41
16 Top	12.5	5.41
16 Bottom	25	6.42
17 Top	12.5	6.82
17 Bottom	12.5	6.18
18 Top	25	6.42
18 Bottom	25	6.22
19 Top	12.5	6.36
19 Bottom	25	6.94
20 Top	12.5	6.68
20 Bottom	12.5	6.47
21 Top	25	6.61
21 Bottom	25	6.65
22 Top	12.5	6.26
22 Bottom	25	6.35
23 Top	12.5	6.33
23 Bottom	12.5	6.36
24 Top	25	6.73
24 Bottom	25	6.46
25 Top	12.5	6.54
25 Bottom	25	6.68
26 Top	12.5	6.62
26 Bottom	12.5	6.10
27 Top	25	6.59
27 Bottom	25	6.61
28 Top	12.5	6.24
28 Bottom	25	6.84
29 Top	12.5	6.46
29 Bottom	12.5	6.62
30 Top	25	6.79
30 Bottom	25	6.19
31 Top	12.5	6.74
31 Bottom	25	6.61
32 Top	12.5	6.27
32 Bottom	12.5	6.44
33 Top	25	6.82
33 Bottom	25	6.04
34 Top	12.5	6.71
34 Bottom	25	6.28
35 Top	12.5	6.37
35 Bottom	12.5	6.46
36 Top	25	6.30
36 Bottom	25	6.44

APPENDIX C SAMPLE CALCULATIONS FOR SHEAR STRENGTH

SS 1

SAMPLE ID 1

Load at failure (P) = 4350 lbs

Diameter of sample

D_1 = 15.27 cm

D_2 = 15.15 cm

D_{AVG} = 15.21 cm

Cross sectional area A = 181.65 cm^2

= 29.06 in^2

Shear strength (P/A) = 149.67 lb/In^2