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16. Abstract

Recently, TxDOT has experienced an increase in the number of pavement failures that may be attributed to the poor quality of tack coat applied. To identify quality of tack coat before overlay is placed on top of it, a device "UTEP Pull-off Device (UPOD)" that measures quality of tack coat has been developed. The device can be placed on top of the tack coat layer after specified interval and quality of tack coat is evaluated based on the magnitude of cohesive strength. The developed device is simple, reliable, economical, and could determine the quality of the tack coat in less than 45 minutes after application of tack coat.

Although UPOD can measure the quality of tack coat, a field acceptance criterion has not been established and is the objective of this research. To develop the criterion, the laboratory and field tests were performed with the help of TxDOT. Based on the laboratory and field test results, an acceptance criterion has been proposed.

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Tack Coat Field Acceptance Criterion

By

Srinivasa R. Eedula, BS
Vivek Tandon, PhD, PE

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Performed in cooperation with the

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The Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, Texas 79968-0516
May 2006

Disclaimer:

Srinivasa R. Eedula, BS
Vivek Tandon, PhD, PE (88219)

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ABSTRACT

Recently, TxDOT has experienced an increase in the number of pavement failures that may be attributed to the poor quality of tack coat applied. To identify quality of tack coat before overlay is placed on top of it, a device "UTEP Pull-off Device (UPOD)" that measures quality of tack coat has been developed. The device can be placed on top of the tack coat layer after specified interval and quality of tack coat is evaluated based on the magnitude of cohesive strength. The developed device is simple, reliable, economical, and could determine the quality of the tack coat in less than 45 minutes after application of tack coat.

Although UPOD can measure the quality of tack coat, a field acceptance criterion has not been established and is the objective of this research. To develop the criterion, the field tests were performed with the help of TxDOT. Based on the laboratory and field test results, an acceptance criterion has been proposed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

To improve performance of flexible pavements, it is quite common to place an overlay on top of the existing surface layer. A bonding agent commonly known as "tack coat" is placed on top of the old layer, before placement of overlay, to ensure proper bonding between the two layers. To ensure that tack coat is evenly spread at appropriate application rate, Ohio DOT (Ohio Technical Bulletin, 2001) has developed a procedure that ensures uniform application and has been adopted by the Texas Department of Transportation (TxDOT). However, no reliable field test is available that can quantify the quality of applied tack coat. Currently, TxDOT uses a boot heal test. The procedure suggests that an inspector stands on the applied tack coat area and if his/her boot sticks to the tack coat it is good, otherwise it is not. This field test is subjective and does not ensure that a good quality tack is applied. Hence, a test set up is needed to determine the bonding characteristics of the tack coat before paving.

TxDOT sponsored a project (0-4129) entitled "Development of an Objective Field Test to Determine Tack Coat Adequacy" to identify or develop a test setup the can quantify the quality of the tack coat in the field. The project was performed in two phases. In the first phase, the available devices that might be suitable in the field were evaluated. Since the initial field evaluation indicated that the available devices are not suitable, two new devices were developed in the second phase. The developed devices were evaluated and UTEP Pull-Off Device (UPOD) was selected for further field evaluation (Deysarkar and Tandon, 2005). The study suggested that the quality of tack coat can be identified in the field; however, the conclusions were based on only two field tests and a prototype UPOD device. To make sure that the developed equipment works under various conditions, it is essential that several UPOD devices be built and evaluated under several field conditions and is the focus of this study. Since prototype UPOD device was manufactured using off the shelf components, the device needed to be modified to make sure that the produced devices provide reproducible results and was focus of this study as well.

1.2 Research Objectives

The main objectives of this study were to modify prototype device, produce several modified UPOD devices, evaluate reproducibility of the devices, and perform field evaluation of these devices. To achieve these objectives, various components of the UPOD were identified to be replaced and reproducibility of the devices was evaluated using statistical analysis. In the end, a training material for the devices was developed such that TxDOT personnel can perform evaluation in the field and provide data to the UTEP research team for the development of an acceptance criterion.

1.3 Report Organization

Problem statement, research objective and organization of the report are presented in this chapter. In Chapter Two, the background information about the existing device and problems with the existing device are presented. The modifications to the device and reproducibility evaluation of the device are presented in Chapter Three. The field evaluation results and required shear strength (based on theoretical approaches) from tack coat are also included in Chapter Three. The summary and conclusion are included in Chapter Four.

CHAPTER 2 MODIFCATION, PRODUCTION AND REPRODUCIBILITY EVALUATION OF UPOD

2.1 UTEP PULL-OFF DEVICE (UPOD)

This device has been fabricated at UTEP based on Pull-off mechanism and can be used to determine the adhesive properties of tack coat. The developed system is presented in Figures 1through 4.

The instrument weighs about 23 lbs and can be easily leveled with the help of pivoting feet (Figure 1). It has a weight key on the top, which provides stability while placement of loads. A 3/8th inch nut fits a 3/8th inch drive torque wrench, which is used to pull the plate up from the tack-coated surface, as shown in Figure 2. A 6-150 in.-lb torque wrench is used for measuring pull-off torque that can be converted into pull-off strength. A contact plate that can conform to the rough pavement surface is developed, as shown in Figure 3.

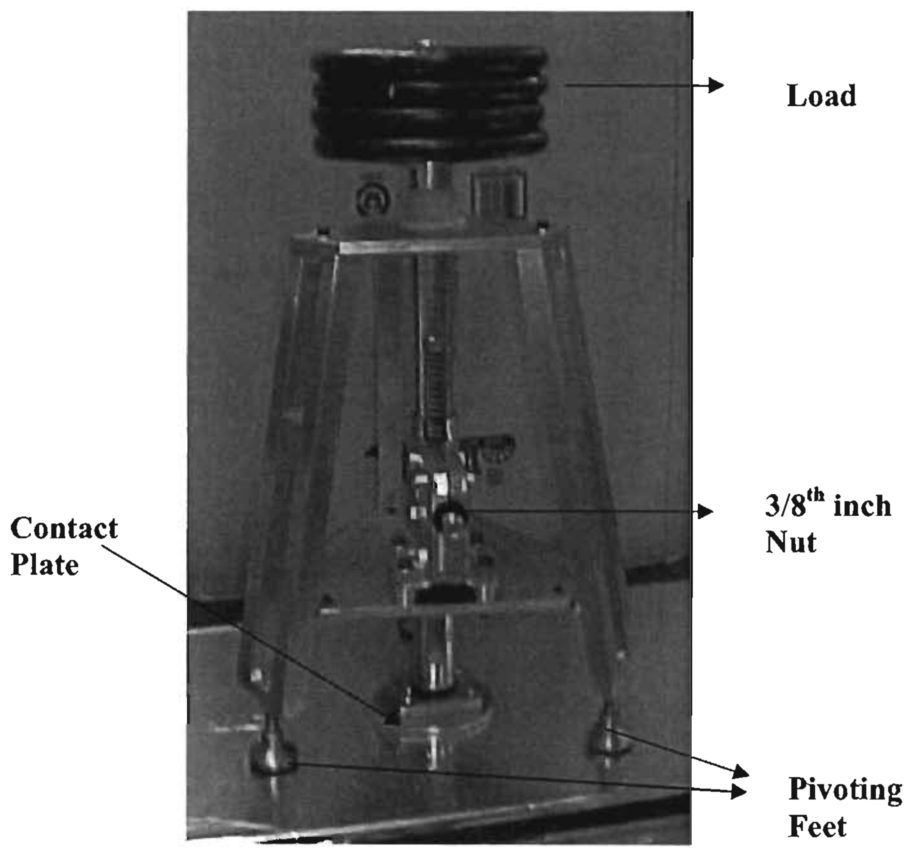


FIGURE 1 UTEP Pull-off Device Test Set-Up

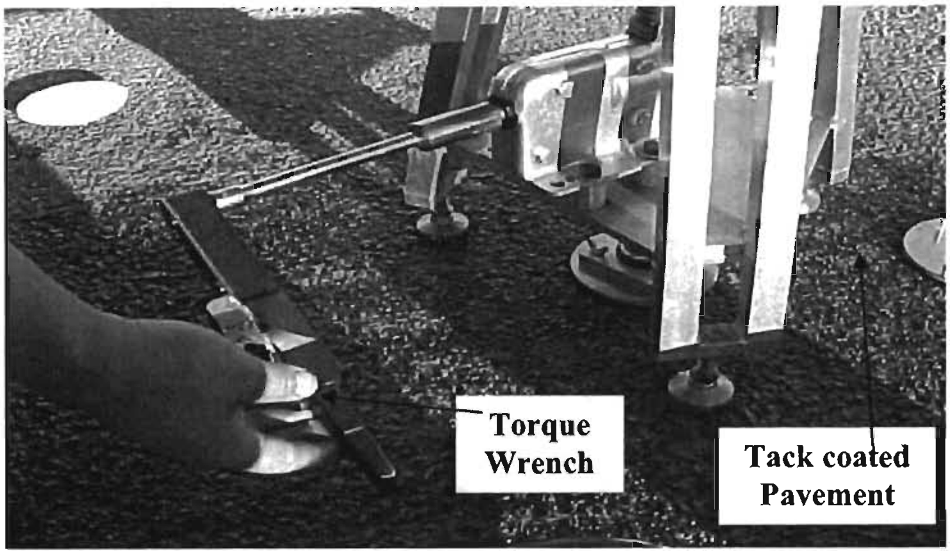


FIGURE 2 Torque Wrench used during UPOD Testing

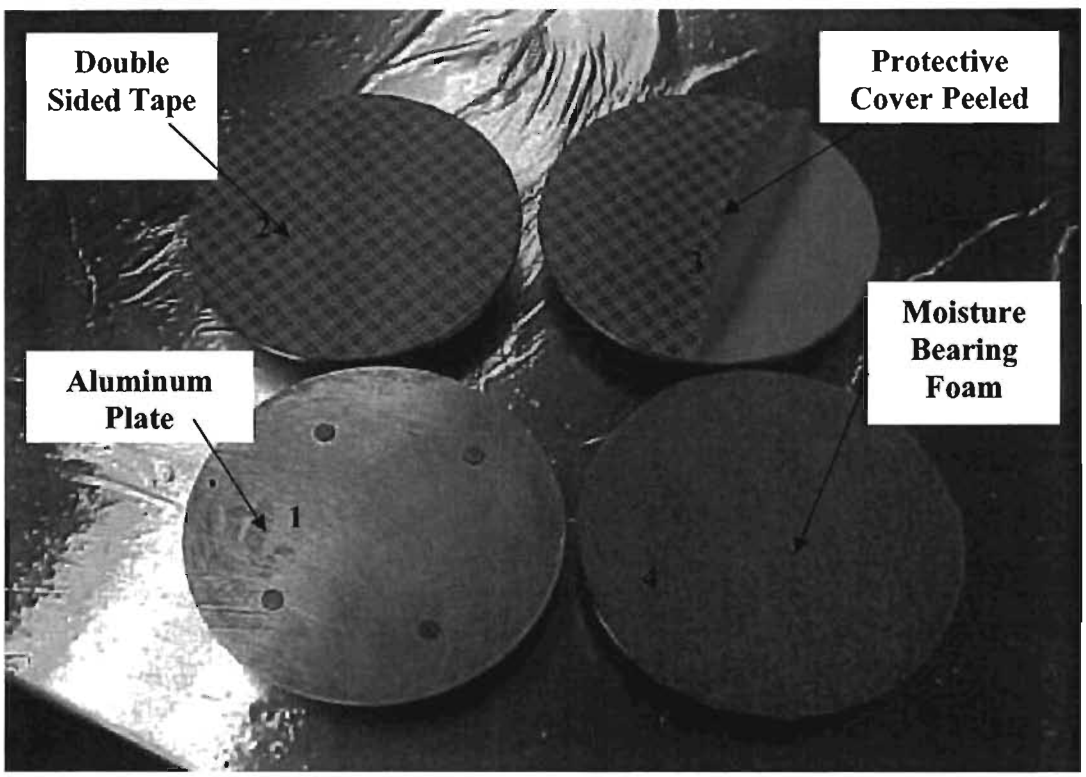


FIGURE 3 Contact Test Plates for UPOD

In addition, two aluminum plates were fabricated for laboratory testing. One of the plates is a thick solid plate with the dimensions of 16.5 by 14.5 by 0.25 in. The other plate is a thin plate with the dimensions of 15.5 by 12 by 0.03 in. and has a hole of 5 inches diameter in the center.

The plate with the hole in center is placed on top of the solid plate. This allows the placement of tack coat in the circular area, as shown in Figure 4.

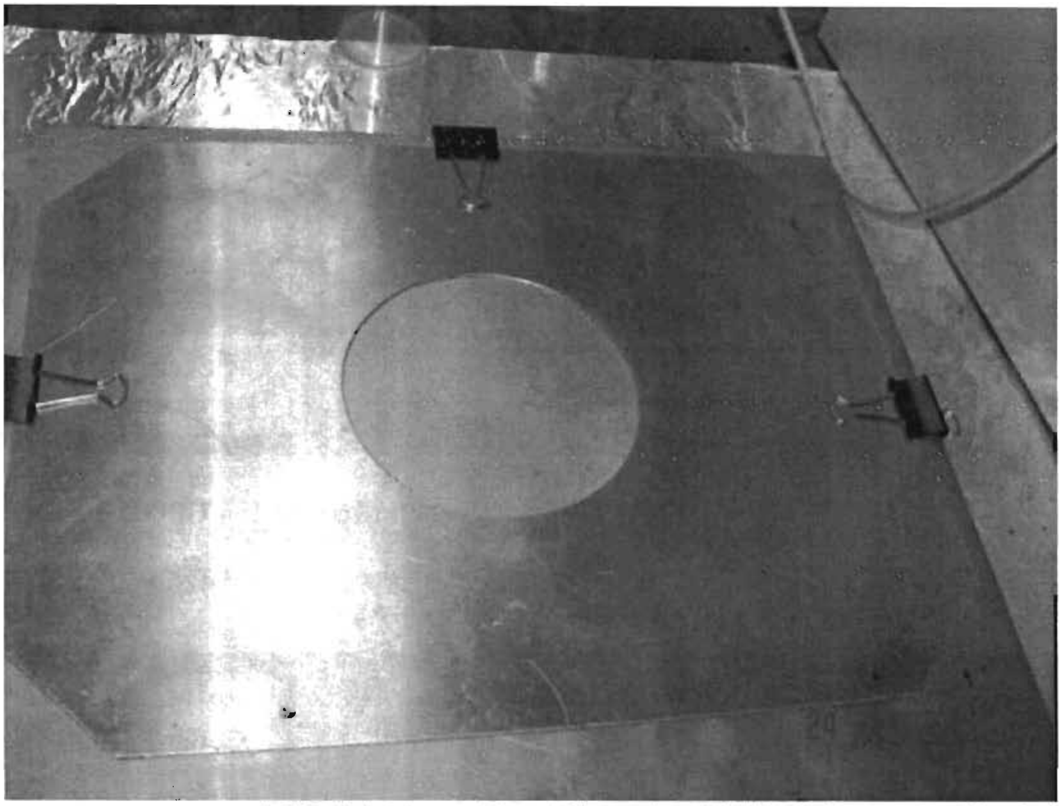


FIGURE 4 Base Plates for UPOD Laboratory Testing

The device consists of a 5-in. diameter aluminum contact test plate. A 5 in^2 3M double-sided tape is used and attached to the aluminum contact plate and 5 in^2 moisture bearing foam is placed over the tape (Figure 3). The advantage of the moisture bearing foam is that it can be easily peeled off the double sided tape and four to five tests can be performed before the adhesive layer (double sided tape) needs replacement. Figure 3 shows the 5 in. aluminum contact test plate and placement of adhesive layer as well as moisture bearing foam.

The device consists of three gears namely a worm, a worm gear, (also acts as a pinion) and a rack arrangement. The worm and the worm gear are used to transfer the force that is being applied in the form of a hand cranking (torque) in horizontal direction to the rotational force. The worm gear also acts as a pinion for the pinion and rack gear that is attached to the vertical shaft through which the load is being applied to the tack coat. The pinion then transfers the rotational force to the rack that moves vertically. The rack contains a horizontal base through which the force is being applied to the tack coat in order to form a good adhesion with the surface. The main purpose of the gear arrangement is to change the direction of the force that is being applied from one end to the other where it needs to be transmitted. Hence there is no change in the force (though, a small amount of force is lost due to the frictional forces between the mating gears, which is negligible) involved during this change of direction of the force.

The gear system allows the application of load to the surface, or pull-off load from the surface depending on the direction of torque wrench movement. If the torque is applied in the clockwise direction to the worm, the worm transmits the force to the worm gear during which the direction of force changes from horizontal to rotational. The pinion and the rack arrangement of gears change the force in the pinion from the rotational direction to the downward direction. Thus, a load is applied to the tack coat. If the torque is applied in the anticlockwise direction, the force pulls the contact plate in the upward direction until the tack coat is separated from the surface. The torque in the gauge is noted in in.-lb and the load required to pull the tack coat from the surface (adhesiveness of the tack coat) is estimated using calibration factor.

To perform testing in the field, the UPOD is placed on the tack-coated surface. After specified set time, a load of 40 lbs is applied and maintained for 10 minutes. After removal of loads, the torque wrench is attached to the nut and rotated in the counter clockwise direction to detach the contact plate from the tack-coated pavement. The torque (T) required to detach the contact plate from the tack coated pavement is recorded in in.-pound. The torque (T) is then converted to the load using a calibration factor. The relationship between the torque and load is developed by fitting a straight line through the data points. The estimated load is converted into tensile stresses for evaluation purposes.

To perform testing in the laboratory, the test is performed in similar fashion as that in the field except that the tack coat is placed on top of the base plate (Figure 4) and the temperature is maintained using lamps as shown in Figure 5. Different temperature levels can be maintained by changing the height of the lamps. Therefore, the laboratory tests can be performed to simulate field temperature changes.

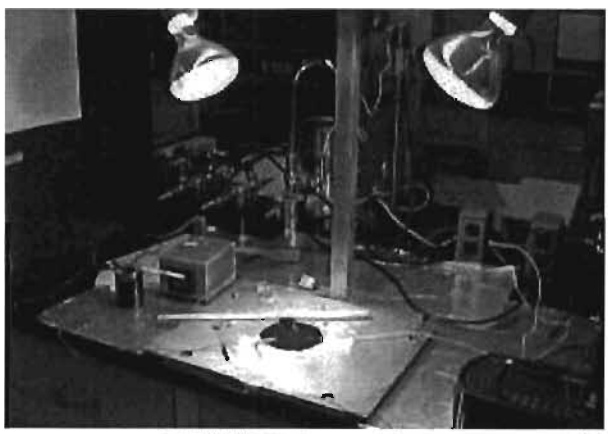


FIGURE 5 Temperature Test Setup

2.2 Typical Field and Laboratory Test Results

Under project 0-4129, various tests were performed in the parking lot as well as in the laboratory using various tack coat types. A typical laboratory test result for PG64-22 is shown in Figure 6. The tests were performed at three different set times and at three different temperatures. The results show that increase in temperature or set time increases the strength. In addition, time and temperature dependence on strength gain is nonlinear. The following relationship was developed between strength gain and set time and temperature:

$$Strength = Set\,Time * Time\,Factor * e^{(Test\ Temperature * Temperature\ Factor)} \tag{2.1}$$

where set time is in minutes and test temperature is in °F. The time and temperature factor for PG64-22 tack coat along with R^2 value is presented in Table 1. The R^2 value is higher than 0.95 indicating that a good correlation exists. Similar relationships were developed for different tack coat types. In general, the R^2 values were higher than 0.84 indicating that these relationships could be used for the evaluation of tack coat in the field.

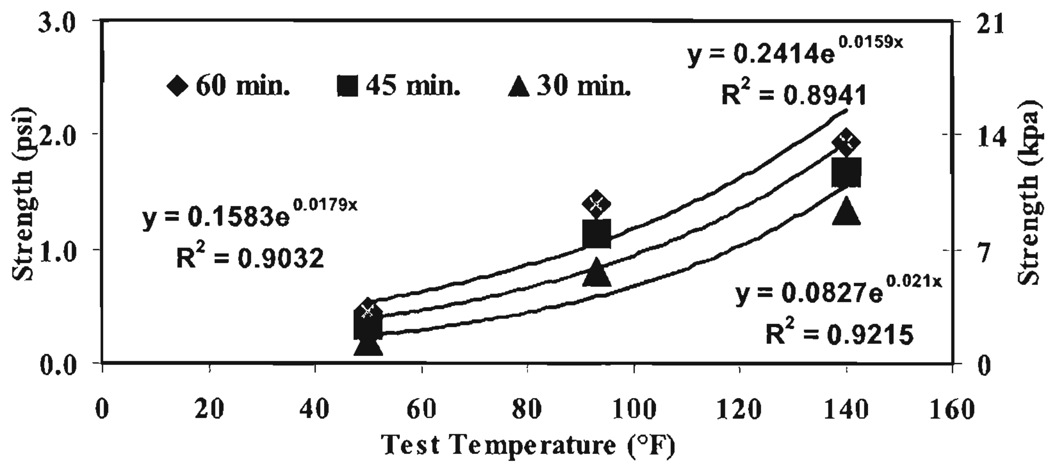


FIGURE 6 UPOD Laboratory Test Results for PG64-22

TABLE 1. Time Temperature Correlation Factors

Tack Coat	UPOD		
	Time Factor	Temp Factor	R^2
PG64-22	0.003392	0.018231	0.95

To validate the relationship proposed in Equation 2.1 and Table 1, a comparison between parking lot and laboratory data is presented in Table 2 for PG64-22 tack coat. The test results show that UPOD estimated strength is similar to measured values and a difference of only 0.3 psi was observed between the two measurements. The difference between estimated and measured strength could be due to environmental factors such as pavement temperature, wind velocity, relative humidity, etc. The results suggest that these factors should be monitored as well to see if that can reduce the differences between the measured and estimated strength. Similar trends were observed for other tack coat types and are reported in Deysarkar and Tandon (2005).

TABLE 2. **Field vs. Laboratory Test Results for PG64-22**

Residual App. Rate gal/yd2	Load, lbs	Test Temp., °F	Set Time, min	Measured, psi (kPa)	Estimated, psi (kPa)
0.04	40	52	20	0.12(0.84)	0.18(1.26)
			30	0.18(1.26)	0.26(1.82)
		61	20	0.18(1.26)	0.21(1.47)
			30	0.26(1.82)	0.31(2.17)

2.3 UPOD Test Procedure for Field Evaluation

Based on the test results and statistical analysis, the following test procedure was proposed at the end of Project 0-4129:

- To perform evaluation of tack coat, select an appropriate section of pavement after application of tack coat.
- Document tack coat properties and application rates
- Document the ambient temperature and time of tack coat application
- Wait for a period of 30 minutes after tack coat application
- Place UPOD (with contact plate attached) on top of the selected area
- Lower the contact plate with the help of torque wrench (clockwise direction) until it touches the pavement surface
- Place 40 lbs of load on top of the UPOD
- Wait for 10 minutes
- Remove load from UPOD and apply torque (counter clockwise direction) until the contact plate separates from the surface.
- Record peak torque and convert to strength using calibration factor.
- Compare measured strength with estimated strength
- Reject tack coat if measured strength is lower than the estimated strength.

2.4 Problems with the UPOD System and Proposed Research Approach

Although test results and analysis indicate that the quality of tack coat can be identified in the field, more research is needed to further enhance the measurement system. In 0-4129 study, only two field tests were performed and tests were performed at lower ends of allowable construction temperatures. To make sure that the system works, it is essential that the more field tests be performed at various temperatures as well as for various tack coat types. The tack coat from these sites can be brought back to the laboratory to perform UPOD laboratory tests as well.

The magnitude of strength gain in the field may be influenced by the presence of wind, pavement temperature as well as relative humidity. Therefore, these parameters need to be documented during field testing and level of influence on strength gain needs to be identified. Thus, the differences between measured and estimated strength could be minimized.

Another issue which has not been addressed in Project 0-4129 is the acceptance criteria. The current system proposes to perform test in the field and identify the strength of the tack coat. However, the usage of the device in terms of acceptance or rejection of tack coat is not provided. There needs to be a minimum acceptable limit on the basis of which tack coat can be accepted or rejected. Since this is a new test measurement system, a value has not been documented in the literature. Another issue is that the TxDOT specifies three tack types (CSS-1h, SS-1h, and PG64-22) which can be supplied by various manufacturers. In addition, the tack coats are placed at different temperatures. Therefore, it is essential that strength gain information be gathered about tack coat types before an acceptance criterion can be developed. One of the approaches could be to collect various types of tack coats supplied by various manufacturers and perform field as well as laboratory tests at various temperatures to identify a strength value. The advantage of this approach would be that a database of tack coat strength could be developed. However, it will not be feasible because the cost associated with performing enormous number of tests. An alternative approach would be to produce several of these devices and provide them to the TxDOT. The TxDOT personnel can perform tests and provide the UTEP Research Team with the field data which can then be utilized to develop an acceptance criterion. The advantage of this approach would be that the data from various environmental conditions and for tack coat type can easily be collected within shorter time frame. This approach was used in this study for the development of acceptance criterion.

Although field tests indicated that the device is repeatable, it is quite possible that further developed devices may not be reproducible. In other words, the device itself is repeatable but the results may be highly dependent on the device used. Therefore, it is necessary that the components of the UPOD device be evaluated and modified to improve reproducibility. The main component identified for changes is the lowering and raising mechanism of UPOD. This component was brought off the shelf and can impact the reproducibility of the device. Another issue that needs to be evaluated is the cost of manufacturing. It is quite a possible to develop equipment which is highly repeatable and very expensive. Therefore, it is essential that the reproducibility of the developed device be increased with minimal increase in cost of manufacturing.

To make sure that the developed devices are repeatable and reproducible, it is proposed that a repeatability and reproducibility analysis be performed. It is proposed that two tack coat types CSS-1h and PG64-22 be used for the evaluation purposes. In addition, the tests will be performed at 30 minutes of set time with 40 lbs of load. The tests will be performed at laboratory temperature (73 °F) and at high temperature (140 °F). The test with each device will be repeated five times. Since six devices will be developed, a total of 120 tests will be performed to identify the repeatability of individual device and reproducibility of all the devices. The statistical tools were utilized to evaluate reproducibility.

CHAPTER 3 MODIFICATION OF UPOD AND REPORDUCIBILITY EVALUATION OF UPOD

A preliminary investigation of the developed UPOD device identified that the device is repeatable but not reproducible due to utilization of off-the-shelf products. In addition, some of the components were added to the device based on field problems. In this chapter the modifications made to the prototype UPOD device and reproducibility evaluation of the modified device are discussed.

3.1 Modification of UPOD

The prototype UPOD device consists of a weight key at top on which the 40 lb load is placed. The load on the top is transferred to the bottom aluminum contact plate of 5 inch diameter through a jack system provided in the middle of the device. The jack system attached to a 3/8 inch nut transfers the rotational torque to vertical force. There were several modifications made to the device and are discussed in the following paragraphs.

One of the problems identified with the device was the stability. To improve the stability of the device, it was decided to reduce the height of the device and increase the spacing between legs. The height of the device was reduced from 25.6 in. to 20.6 in. and the spacing between legs was increased from 13.0 to 13.2 in., as shown in Figure 7. This was achieved by reducing the length of the legs and by increasing the middle support plate.

Another problem identified with the device was the off-the-shelf jack system (Figure 8). To improve the reproducibility of the device it was decided to replace the system with a better rack and gear system, as shown in Figure 8 (modified UPOD). The rack and gear system is commercially available and can significantly increase the reproducibility of the devices. In addition, it does not significantly increase the cost of manufacturing. The new system minimizes the friction between the gears and provides more precise results. The new gear system replaced has lower weight compared to the old system. Another factor influencing the repeatability of the device was the wobbling of the central rod (Figure 9). To minimize the wobbling, it was decided to add another nylon bushing between middle support plate and central rod. This minimized the wobbling and increased the repeatability of the device.

Few minor things were modified as well to overall improve the durability of the device like weight key and torque wrench. The weight key was added to the system after the development of the prototype device (Figure 10). For the new device, the weight key was integrated in the system to maximize the stability of the device (Figure 10). In addition, the old torque wrench was replaced with a new torque wrench made of durable material for ease of grip and better dials protection (Figure.11).

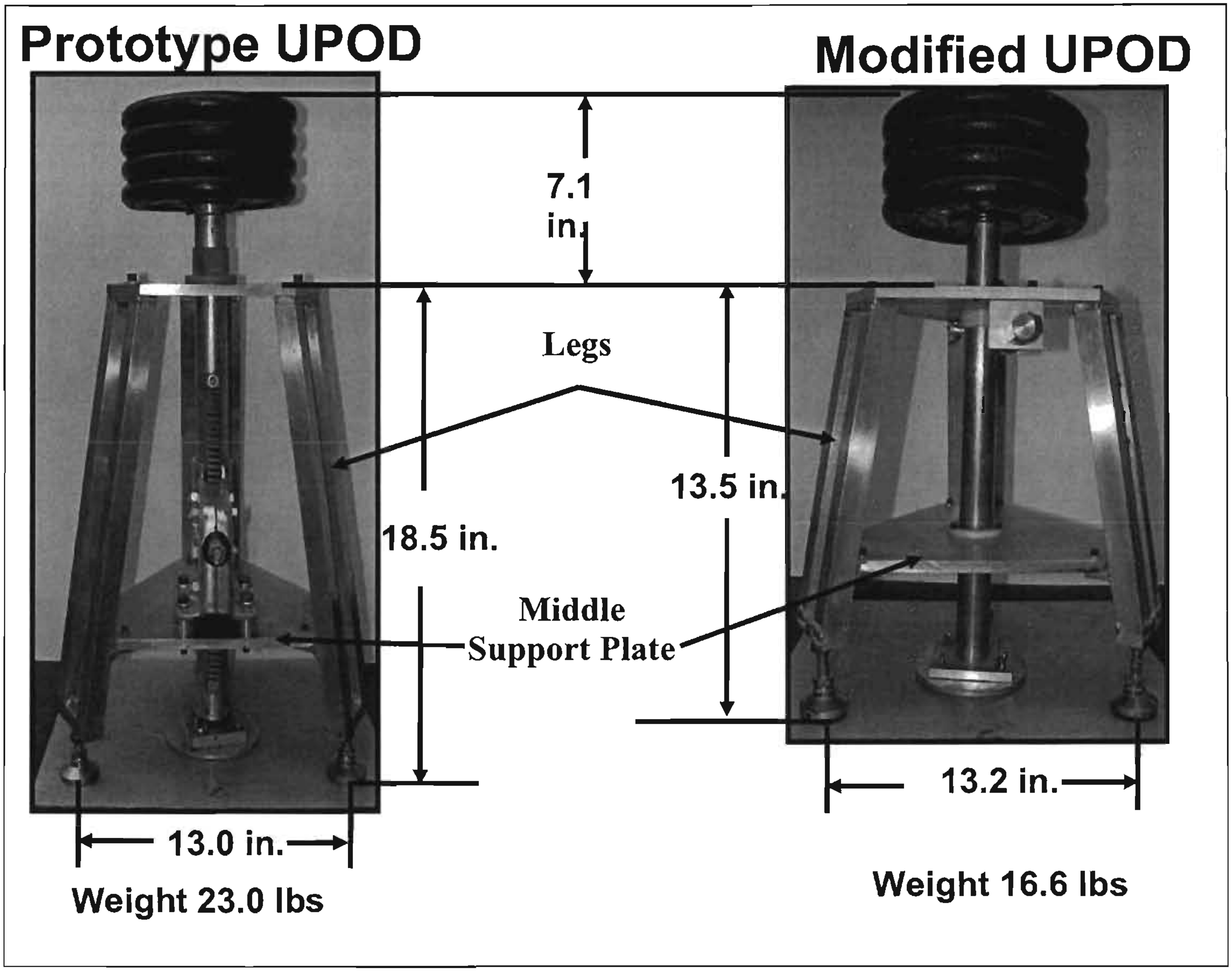


FIGURE 7 Dimensional Changes Made to Increase Stability

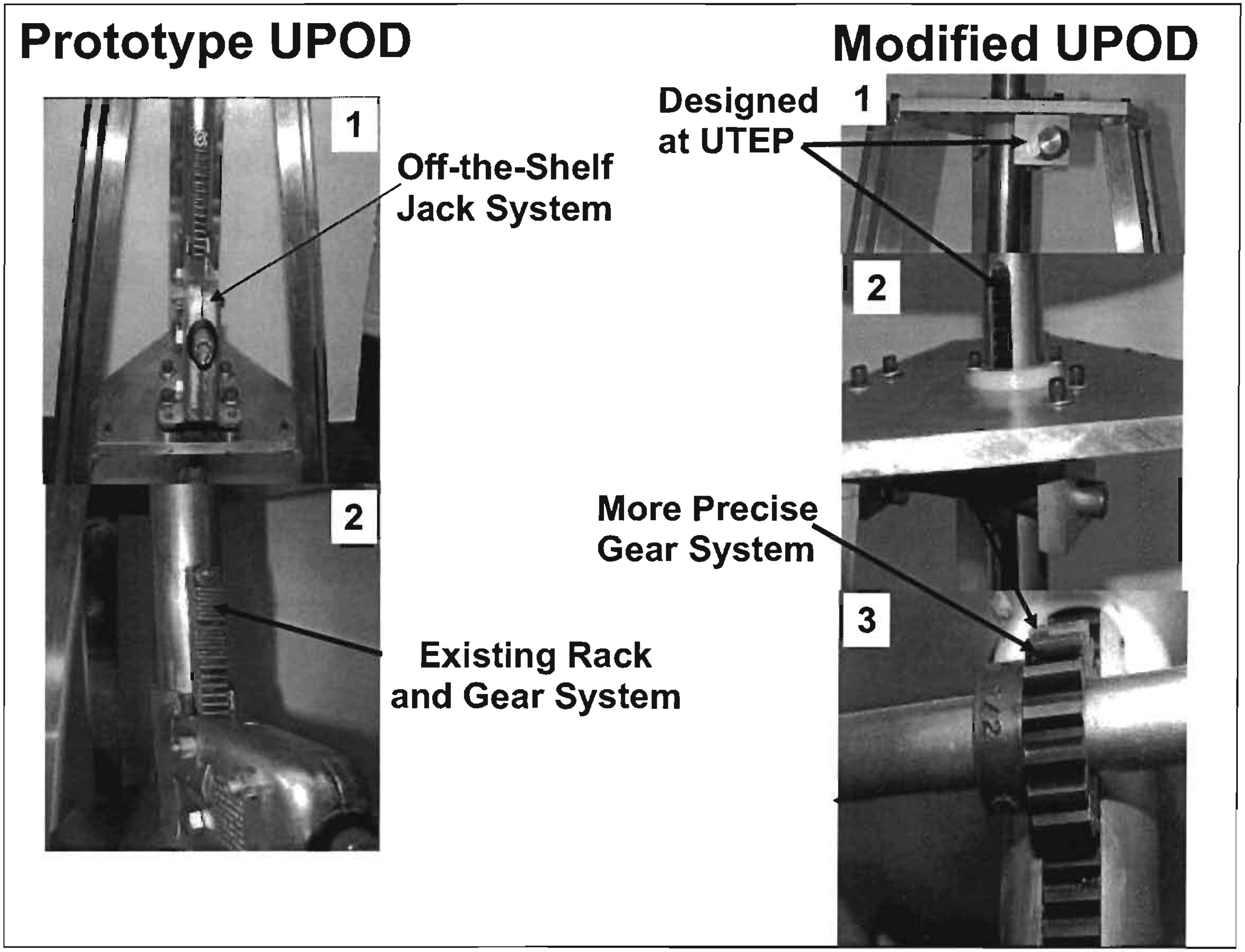


FIGURE 8 Gear Changes Made to Increase Precision

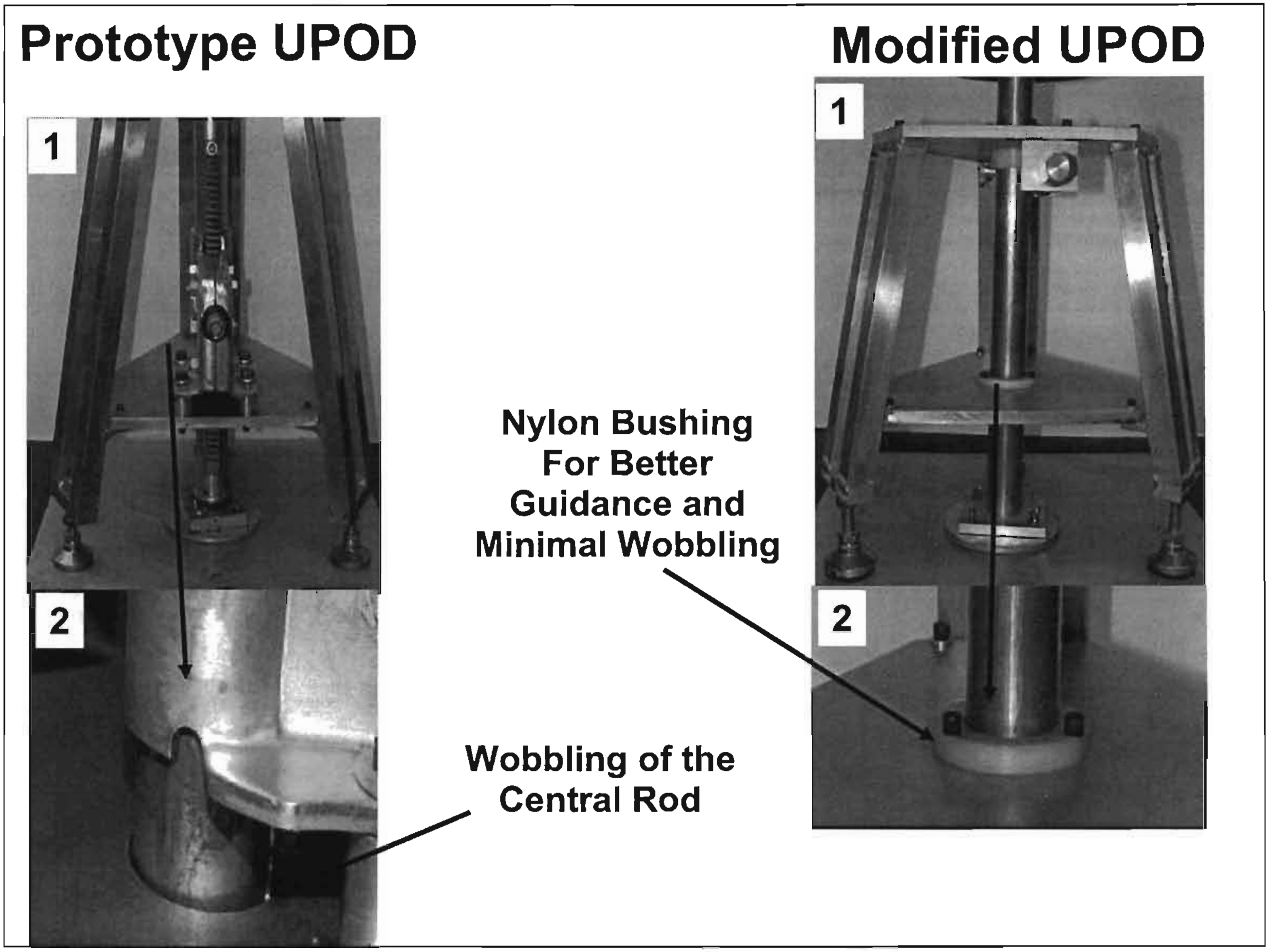


FIGURE 9 Changes Made to Minimize Wobbling

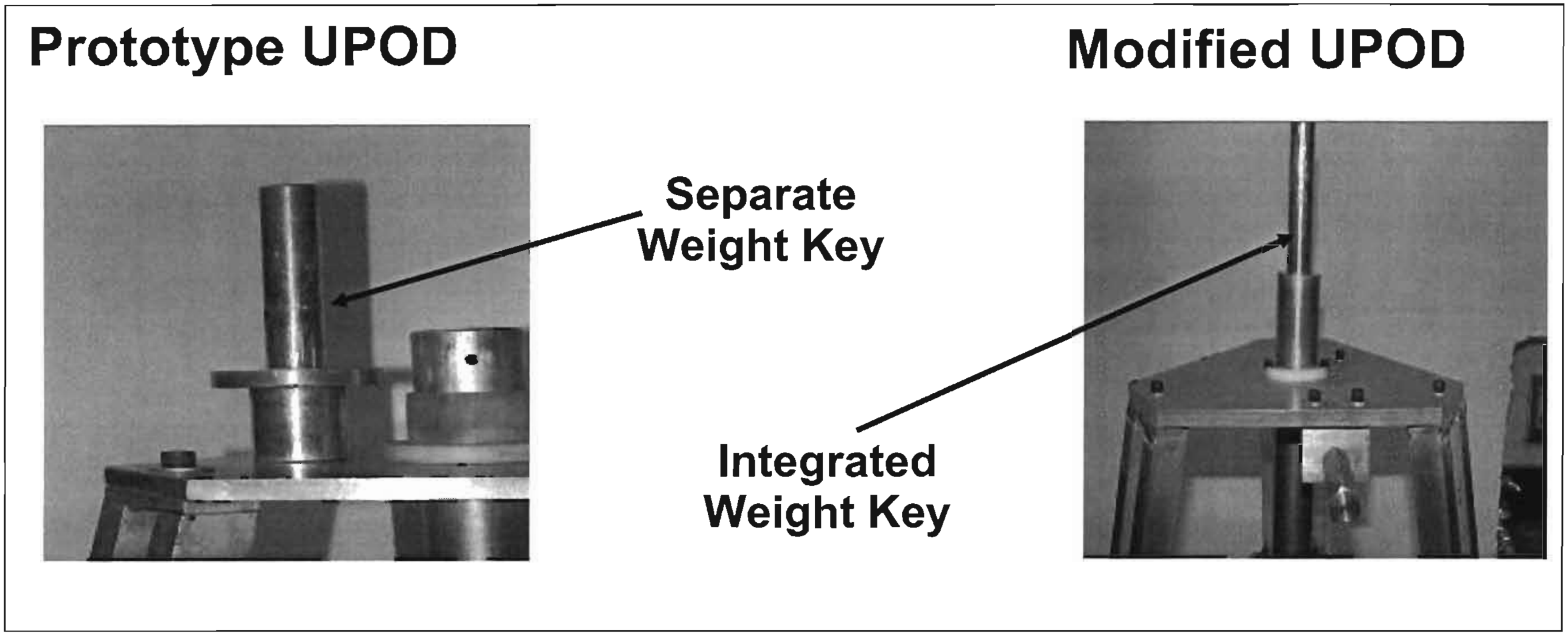


FIGURE 10 Changes Made to Stabilize Weight Application

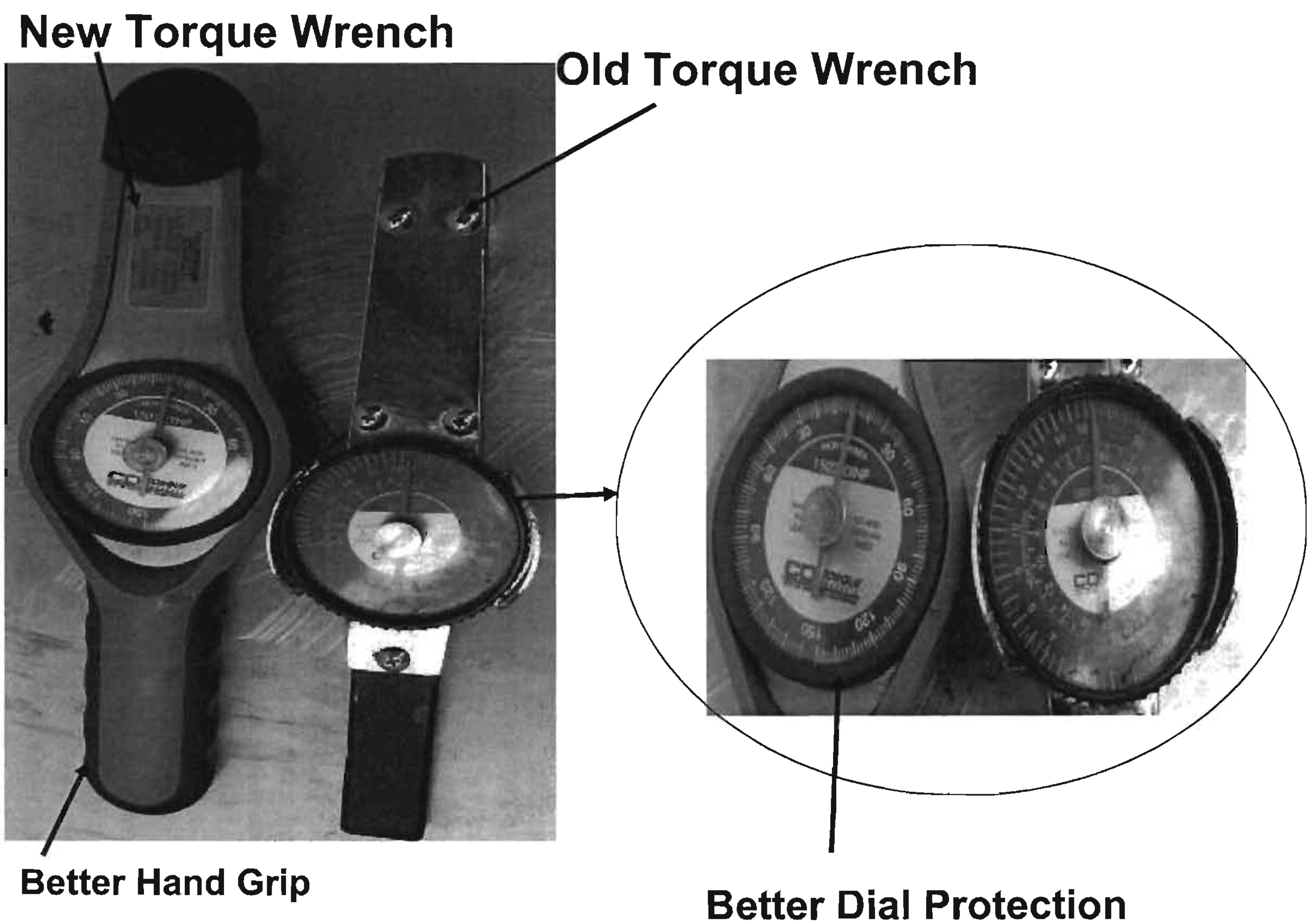


FIGURE 11 Comparison Between Old and New Torque Wrench

3.2 Reproducibility evaluation of modified UPOD

Based on proposed modifications, six new UPOD devices were fabricated and calibrated. The six devices were evaluated in the laboratory as well as in the field. The tests were performed at two different temperatures (73 and 136 °F in the laboratory and 60 and 95 °F in the field) using PG64-22 and SS-1h tack coat types. The tests were performed 30 minutes after tack coat application and a load of 40 lbs was maintained for 10 minutes before performing the tests. In addition, the tests were performed at one application rate of 0.04 gal/yd^2. Each test was repeated three times. In total, 144 tests were performed to evaluate the reproducibility of the device. The laboratory and field evaluation test results are discussed in the following sections.

3.2.1 Laboratory Evaluation Test Results

The test results for the PG64-22 tack coat evaluations at 73 and 136 °F test temperatures are presented in Tables 3 and 4, respectively. The test results suggest that the strength increased with increase in temperature. The average strength ranged from 2.11 to 2.50 psi at 73 °F and from 3.95 to 4.24 psi at 136 °F. The coefficient of variation (COV) was less than 7.5% at 73 °F and was less than 5.0% at 136 °F. The test results at 73°F test temperature suggest that the maximum average strength of 2.50 psi was measured with UPOD 5. However at 136°F test temperature, the minimum average strength of 3.95 psi was measured with UPOD 5 indicating that UPOD 5 is not necessarily measuring higher strength in comparison to other devices. The influence of repetition was also evaluated by comparing results at each repetition, as shown in rows 9 through 11. At both test temperatures, the second repetition provided maximum average values indicating that the repetition number may influence the measured strength.

The test results for the SS-1h tack coat evaluations at 73 and 136 °F test temperatures are presented in Tables 5 and 6, respectively. The test results suggest that the strength increased with increase in temperature. The average strength ranged from 1.23 to 1.55 psi at 73 °F and from 1.56 to 1.77 psi at 136 °F. The coefficient of variation (COV) was less than 6.0% at 73 °F and was less than 7.0% at 136 °F. The test results at 73°F test temperature suggest that the maximum average strength of 1.55 psi was measured with UPOD 3 while maximum average strength of 1.77 psi was measured with UPOD 5 indicating that UPOD 5 or UPOD 3 are not necessarily measuring higher strength in comparison to other devices. The influence of repetition was also evaluated by comparing results at each repetition, as shown in rows 9 through 11. At both test temperatures, the third repetition provided maximum average values which are different from PG64-22 test results indicating that the repetition number may not influence the measured strength. The test results suggest that the devices are repeatable in the laboratory and the COV is less than 7.5% at the tested temperatures and tack coat types.

3.2.2 Field Evaluation Test Results

For field evaluation, the tests were performed in the morning and in the afternoon to simulate two different temperatures. The ambient test temperature in the morning was around 65 °F and 96 °F in the afternoon. The test results are presented in Tables 7 through 10. The test results suggest that the strength measured in the laboratory is little bit higher than measured in the field and can be due to lower ambient temperatures in the field. In addition, the COV values increased from 7.5% to 13.5% indicating that higher variability can be expected in the field. Although COV increased from 7.5% to 13.5%, the device can be assumed to reproducible.

TABLE 3. Laboratory Test Results at 73° F for PG 64-22 Tack Coat

UPOD	Repetition			Avg., psi	SD, psi	COV, %
	1	2	3			
1	2.02	2.31	2.24	**2.19**	**0.15**	**6.9**
2	2.08	2.34	2.21	**2.21**	**0.13**	**5.9**
3	2.02	2.33	2.25	**2.20**	**0.16**	**7.3**
4	1.99	2.14	2.30	**2.14**	**0.16**	**7.2**
5	2.43	2.58	2.50	**2.50**	**0.08**	**3.0**
6	1.93	2.20	2.20	**2.11**	**0.16**	**7.4**
AVG., psi	**2.08**	**2.32**	**2.28**			
S.D., psi	**0.18**	**0.15**	**0.11**			
C.O.V, %	**8.6**	**6.5**	**4.9**			

TABLE 4. Laboratory Test Results at 136° F for PG 64-22 Tack Coat

UPOD.NO	No of Repetitions			Avg., psi	SD, psi	COV, %
	1	2	3			
1	4.04	4.04	4.40	**4.16**	**0.21**	**5.0**
2	4.15	4.15	3.96	**4.09**	**0.11**	**2.7**
3	4.19	4.11	4.42	**4.24**	**0.16**	**3.8**
4	4.13	4.13	3.90	**4.05**	**0.13**	**3.3**
5	3.95	4.10	3.80	**3.95**	**0.15**	**3.8**
6	4.06	4.06	3.92	**4.01**	**0.08**	**2.0**
AVG., psi	**4.09**	**4.10**	**4.07**			
S.D., psi	**0.09**	**0.04**	**0.27**			
C.O.V, %	**2.1**	**1.0**	**6.7**			

TABLE 5. Laboratory Test Results at 73° F for SS-1h Tack Coat

UPOD	No of Repetitions			Avg., psi	SD, psi	COV, %
	1	2	3			
1	1.30	1.30	1.44	**1.35**	**0.08**	**6.0**
2	1.30	1.17	1.23	**1.23**	**0.07**	**5.3**
3	1.55	1.47	1.63	**1.55**	**0.08**	**5.2**
4	1.30	1.30	1.38	**1.33**	**0.05**	**3.5**
5	1.37	1.52	1.44	**1.44**	**0.08**	**5.2**
6	1.31	1.31	1.38	**1.33**	**0.04**	**3.0**

AVG., psi	**1.36**	**1.35**	**1.42**
S.D., psi	**0.1**	**0.13**	**0.13**
C.O.V, %	**7.3**	**9.5**	**9.2**

TABLE 6. Laboratory Test Results at 136° F for SS-1h Tack Coat

UPOD	No of Repetitions			Avg., psi	SD, psi	COV, %
	1	2	3			
1	1.59	1.59	1.59	**1.59**	**0.00**	**0.0**
2	1.62	1.56	1.69	**1.62**	**0.07**	**4.0**
3	1.71	1.78	1.78	**1.76**	**0.04**	**2.3**
4	1.68	1.84	1.61	**1.71**	**0.12**	**6.9**
5	1.82	1.75	1.75	**1.77**	**0.04**	**2.3**
6	1.51	1.51	1.65	**1.56**	**0.08**	**5.2**

AVG., psi	**1.66**	**1.67**	**1.68**
S.D., psi	**0.11**	**0.14**	**0.08**
C.O.V, %	**6.5**	**8.1**	**4.5**

TABLE 7. **Field Test Results at 65° F for PG 64-22 Tack Coat**

UPOD	Repetition			Avg., psi	SD, psi	COV, %
	1	2	3			
1	1.08	1.23	1.08	**1.13**	**0.08**	**7.4**
2	0.97	1.17	1.1	**1.08**	**0.1**	**9.2**
3	1.01	1.32	1.16	**1.16**	**0.16**	**13.3**
4	1.01	1.15	1.07	**1.07**	**0.08**	**7.1**
5	1.14	1.21	1.14	**1.16**	**0.04**	**3.8**
6	1.03	1.24	0.96	**1.08**	**0.14**	**13.3**
AVG., psi	**1.04**	**1.22**	**1.09**			
S.D., psi	**0.06**	**0.06**	**0.07**			
C.O.V, %	**5.9**	**4.9**	**6.4**			

TABLE 8. **Field Test Results at 96° F for PG 64-22 Tack Coat**

UPOD	Repetition			Avg., psi	SD, psi	COV, %
	1	2	3			
1	2.09	2.24	1.95	**2.09**	**0.14**	**6.9**
2	2.01	2.01	2.01	**2.01**	**0**	**0.0**
3	2.25	2.40	2.17	**2.28**	**0.12**	**5.2**
4	2.30	2.22	2.14	**2.22**	**0.08**	**3.5**
5	2.50	2.20	2.28	**2.33**	**0.16**	**6.8**
6	2.13	1.86	2.00	**2.00**	**0.14**	**6.9**
AVG., psi	**2.21**	**2.16**	**2.09**			
S.D., psi	**0.18**	**0.19**	**0.13**			
C.O.V, %	**7.9**	**8.9**	**6.0**			

TABLE 9. Field Test Results at 60° F for SS-1h Tack Coat

UPOD	Repetition			Avg., psi	SD, psi	COV, %
	1	2	3			
1	0.79	0.79	0.87	**0.82**	**0.04**	**5.1**
2	0.71	0.84	0.71	**0.76**	**0.07**	**9.9**
3	1.16	1.16	1.01	**1.11**	**0.09**	**8.1**
4	0.84	0.84	0.92	**0.87**	**0.04**	**5.1**
5	0.83	0.99	0.83	**0.89**	**0.09**	**9.9**
6	0.89	0.76	0.96	**0.87**	**0.11**	**12.1**
AVG., psi	**0.87**	**0.9**	**0.88**			
S.D., psi	**0.15**	**0.15**	**0.1**			
C.O.V, %	**17.6**	**16.9**	**11.8**			

TABLE 10. Field Test Results at 95° F for SS-1h Tack Coat

UPOD	Repetition			Avg., psi	SD, psi	COV, %
	1	2	3			
1	1.37	1.23	1.30	**1.30**	**0.07**	**5.6**
2	1.23	1.23	1.36	**1.28**	**0.07**	**5.9**
3	1.63	1.63	1.47	**1.58**	**0.09**	**5.7**
4	1.76	1.76	1.53	**1.68**	**0.13**	**7.9**
5	1.44	1.75	1.44	**1.54**	**0.18**	**11.4**
6	1.58	1.31	1.44	**1.44**	**0.14**	**9.5**
AVG., psi	**1.50**	**1.48**	**1.43**			
S.D., psi	**0.19**	**0.26**	**0.08**			
C.O.V, %	**12.7**	**17.2**	**5.8**			

3.2.3 STATISTICAL ANALYSIS

To effectively evaluate the reproducibility of new UPOD devices, an analysis of variance (ANOVA) was performed using MINITAB® 14.11 software. The purpose of this ANOVA was to identify whether the measured strength is device dependent. In this study, the measured strength in the field was considered to be the dependent parameter while device type, test temperature and tack coat types. Therefore, a one-factor, two-factor, and three-factor ANOVA was performed in this study.

The null hypothesis selected for the ANOVA was that the means measured with the devices are the same. In other words, the measured strength does not depend on the device type. If the null hypothesis is rejected, it can be concluded that the strength is dependent on the device type. A confidence level of 95% was assumed for the analysis purpose. The probability factor of falsely rejecting the null hypothesis (p-value) should be less than 0.05 in order to conclude that a difference is significant, since a 95% confidence level was chosen. The null hypothesis was rejected when the p-value was less than 0.05 and was accepted when the p-value was greater than 0.05.

The ANOVA analysis results for the six devices evaluated in the laboratory and in the field are shown in Tables 11 and 12, respectively. A one-factor, two-factor, and three-factor ANOVA was performed. Rows Two through Four shows results of one-factor ANOVA while rows Five through Seven show results of two-factor ANOVA and the last row shows the results of three-factor ANOVA. The first column shows number of factors evaluated while the second column shows evaluated factors and their interactions. The third column shows degree of freedom and the fourth column shows Sum of Squares. The fifth column shows F-statistics and the sixth column shows p-value obtained. The seventh column shows the conclusion of the ANOVA analysis. The Yes in the seventh column indicates that the device is able to identify the effect of parameter changes while No in the seventh column indicates that the effect of the parameter is insignificant.

The one-factor ANOVA results for both and field laboratory data suggest that the influence of device type is insignificant indicating that the measured strength is not influenced by the device type. The laboratory and field results also suggest that the measured strength depends on test temperature (Factor B) and tack coat types (C) suggesting that the devices are sensitive enough to changes in temperatures and tack coat types.

The two-factor ANOVA results for both field and laboratory data suggests that the influences of device type and tack coat type is insignificant indicating that the stresses measured are not influenced by the type of UPOD used and tack coat type. However, the tests results suggest that the stress measured are significantly influenced by the test temperatures.

The three-factor ANOVA results for both field and laboratory data suggest that the measured stresses are significantly influenced by the device type, type of tack coat, and test temperature. However, one-factor and two-factor ANOVA suggested that the stresses are not device dependent. Since three-factor ANOVA includes influence of test temperature and one and two factor ANOVA has identified that the influence of test temperature is significant, this suggests that the device dependence of stresses is mainly influenced by test temperatures, tack coat types and should be discarded. The presence or absence of interaction effect could be due to the masking of one parameter's effect on the other parameter.

Overall, the ANOVA of laboratory and field data suggest that the measured strength is not dependent on the device type; thus, the newly fabricated devices are reproducible.

TABLE 11. ANOVA Results of the Laboratory Test Results

Factor	Source	Degrees of Freedom	Sum of Squares	F	P	Significance
One-Factor	UPOD (A)	5	0.322	0.05	0.998	NO
	Temp (B)	1	20.877	24.18	<0.001	YES
	Tack (C)	1	48.102	101.36	<0.001	YES
Two-Factor	A	5	0.3220	0.06	0.997	No
	B	1	20.876	20.88	<0.001	Yes
	AB	5	0.1405	0.028	1.00	NO
	B	1	20.877	1037.4	<0.001	Yes
	C	1	48.102	2390.29	<0.001	Yes
	BC	1	10.975	545.4	<0.001	YES
	A	5	0.322	0.12	0.988	No
	C	1	48.10	87.90	<0.001	Yes
	AC	5	0.0620	0.02	1.000	NO
Three-Factor	A	5	0.322	5.12	0.001	Yes
	B	1	20.87	1659.25	<0.001	Yes
	C	1	48.10	3823.07	<0.001	Yes
	AB	5	0.1405	2.23	0.066	No
	BC	1	10.975	872.25	<0.001	Yes
	AC	5	0.0620	0.99	0.436	No
	ABC	5	0.2399	3.81	0.005	Yes

TABLE 12. ANOVA Results of the Field Test Results

Factor	Source	Degrees of Freedom	Sum of Squares	F	P	Significance
One-Factor	UPOD (A)	5	0.584	0.44	0.818	NO
	Temp (B)	1	11.880	134.8	<0.001	YES
	Tack (C)	1	3.768	18.46	<0.001	YES
Two-Factor	A	5	0.5842	1.30	0.278	No
	B	1	11.882	131.79	<0.001	Yes
	AB	5	0.175	0.39	0.855	NO
	B	1	11.882	544.62	<0.001	Yes
	C	1	3.7675	172.68	<0.001	Yes
	BC	1	0.918	42.08	<0.001	YES
	A	5	0.5842	0.52	0.763	No
	C	1	3.76712	16.65	<0.001	Yes
	AC	5	0.120	0.1	0.991	NO
Three-Factor	A	5	0.5842	10.25	<0.001	Yes
	B	1	11.88	1042.73	<0.001	Yes
	C	1	3.767	330.60	<0.001	Yes
	AB	5	0.1752	3.08	0.016	No
	BC	1	0.91801	80.56	<0.001	Yes
	AC	5	0.1202	2.11	0.078	No
	ABC	5	0.0515	0.9	0.493	NO

3.3 Comparison of the Prototype and Modified Device

Although a repeatable modified UPOD device has been developed, the modified device needed to be evaluated to identify whether the new device provides similar strength magnitudes and trends in comparison to the prototype device. Therefore, an experiment design was developed and is discussed in the following sections.

3.3.1 Experiment Design

A series of experiments were performed to compare the two devices and propose an acceptance criterion. The parameters selected to achieve these objectives are presented in Table 13. The reasons for selecting parameters are discussed in the following paragraphs.

TABLE 13. Matrix of Parameters for the Experiment

Tack Coat Types	**SS1-h,CSS1-h,PG64-22**
Temperature , °F	50,77, 95, and 140
Application Rate , gal/ yd²	0.04 and 0.1
Time Since Application, min	10,20,30,40,50,60

The most commonly used tack coat types, within the State of Texas, have been CSS-1h and SS-1h. SS-1h is a slow setting anionic emulsion and CSS-1h is a slow setting cationic emulsion. Occasionally, PG64-22 (AC-20) has also been used by some of the TxDOT districts. Therefore, these three tack coat types were utilized for comparison purposes.

Typically, obtained emulsions are diluted before application in the field. The main reason is to increase the flow ability of tack coat in order to cover the desired area. Another advantage is that it increases the set time, which is needed especially during paving operations at higher air temperatures. However, TxDOT has recently changed the specifications and the new specifications do not allow dilution of tack coats. Since the residual application rates of 0.04 to 1.0 gal/yd^2 are specified by the TxDOT, it was decided to use these residual application rates for the comparison purposes.

Basically, asphalt binder is mixed with water to produce emulsions. The time required for the water to completely evaporate depends on factors like wind velocity, temperature, etc. In general, the paving operation begins quickly after emulsion starts breaking. Therefore, it was decided to perform tests after certain time regardless of break time. Thus, six different time since application were selected; namely: 10, 20, 30, 40, 50, and 60 minutes. The 10 minute time was selected to identify the feasibility of performing tests at very early stages. The advantage of this would be that preventive measures can be taken if the quality of tack coat is not satisfactory. The 60 minutes time was selected to identify the actual bonding strength anticipated after tack coat is completely set (i.e., all of the water has evaporated). The remaining times were selected to cover the range of test times.

3.3.2 Test Procedure

The test procedure for both the UPODs is same. The testing apparatus consists of a bottom aluminum plate of size 16.5 by 14.5 by 0.25 in. In addition, the apparatus consists of a thin plate top plate with the dimensions of 15.5 by 12 by 0.031 in. and has a hole of 5 in. diameter in the center. The purpose of top plate with hole is just to place emulsion at the center of the plate. The UPOD consists with a 5 in. aluminum plate, on which a double sided tape is adhered. A moisture bearing foam was placed on the double sided tape. The moisture bearing foam can be peeled off from the double sided tape after the experiment performed. This allows the use of double sided tape for more tests.

A 6-150 in.-lb torque wrench is used to measure the torque required to break the tack coat. This torque is converted into load by using calibration factor of UPOD. The tack coat to be tested is applied in the center aluminum plate at required application rate. The tack coat is then allowed to break, as per the specified time. After specifiedt time, the UPOD is placed over the applied tack coat. The 3/8 inch nut is adjusted to make sure that aluminum contact plate has adhered properly to the tack coat. After this a 40 lb load was placed on top of UPOD for a load time of 10 minutes. After the loading time of 10 minutes weights are removed. Using the torque wrench, torque required to break the tack coat is recorded. The torque recorded converted in to stress by using the calibration factor for specific UPOD.

3.3.3 Application Temperature of Tack Coat

Typically, tack coats are applied to the pavement at higher temperatures to increase the flowability of the tack coats. Since the temperature of tack coat at the time of application can significantly influence the strength gain, the tack coats were heated to applicatio temperature for specified period of time. The recommended tack coat temperature ranges are specified in ITEM 300 and are summarized in Table 14. To make sure that the tack coats have achieved the specified temperature, the oven were preheated to either 130 or 350 °F (depending on the tack coat type) and tack coat was kept inside till it reached the desired temperature. Typically, one hour was required for CSS-1h and SS1-h tack coat types and two hours for PG binder.

TABLE 14. Tack Coat Application Temperature Range

Type of Emulsion	Recommended Range °F	Maximum allowable °F
SS1-h,CSS1-h	50-130	140
PG Binders	275-350	350

3.3.4 Comparison Test Results

To evaluate UPOD, a total of 264 tests were performed in the laboratory. The test results for CSS-1h are presented in Table 15. The results of CSS-1h evaluation at the residual application rate of 0.04 gal/yd^2 suggested that the new (modified) UPOD estimated higher strength in comparison to old (prototype) UPOD at each of the evaluated parameter. In general, the estimated strength was typically two times or higher when the strength was measured using new UPOD indicating that the new system offers less friction in comparison to the old system. For example, the strength measured using New UPOD for 60 minutes of set time at a temperature of 50 °F was 1.84 psi while only 0.77 psi was measured using old UPOD. The test results presented in the table also suggest that the strength increased with the set time for both devices. However, the measured strength gain increased more with new device in comparison to old device. For instance, the strength gain from 1.15 to 1.84 psi at a temperature of 50 °F was observed for new device while a strength gain from 0.46 to 0.77 was observed with the old device indicating that the new device is more sensitive in comparison to the old device.

TABLE 15. UPOD Results for CSS1-h at 0.04 gal/yd² Application Rate

Residual Application Rate, gal/yd²	Temp. °F	Time Since Application min	Avg. Cohesive Strength, psi	
			New UPOD	Old (Prototype) UPOD
0.04	50	10	1.15	0.46
		20	1.38	0.62
		30	1.65	0.66
		40	1.68	0.69
		50	1.84	0.77
		60	1.84	0.77
	77	10	2.07	0.77
		20	2.68	1.08
		30	2.91	1.39
		40	3.52	1.78
		50	4.28	2.08
		60	4.9	2.32
	95	10	2.22	1.24
		20	2.99	1.78
		30	3.67	2.01
		40	4.29	2.24
		50	4.82	2.86
		60	5.67	3.09
	140	10	5.13	2.16
		20	5.67	2.39
		30	5.97	2.55
		40	6.12	2.63
		50	6.43	2.78
		60	6.58	3.01

The test results are also presented graphically in Figures 12 and 13 for CSS-1h tack coat types. The data shows similar trends that were observed by Deysarkar and Tandon (2005) that is the strength gain increases with the time since application. However, the new UPOD device shows a significant increase in strength with time in comparison to the old device. An exponential curve was fitted to the data and the coefficients of determination (R^2) of more than 0.85 were obtained that the increase in strength depends on set time and the relationship is nonlinear.

Similar trends were observed for other tack coat types and application rates. The observed data is included in Appendix A for reference purposes. The overall test results suggested that the devices provide similar trends; however, the new device is more sensitive to the evaluated parameters and provides higher strength in comparison to the old device.

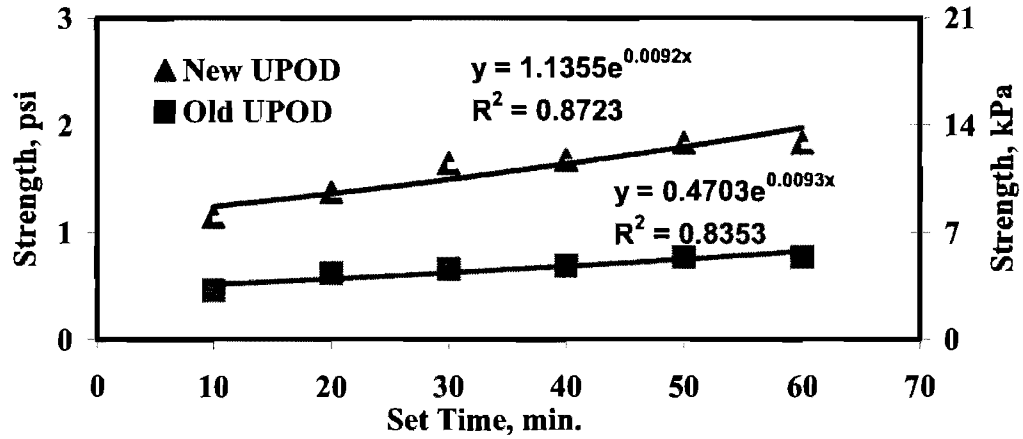


FIGURE 12 **UPOD Results for CSS1-h at 50°F at 0.04 gal/yd² Application Rate**

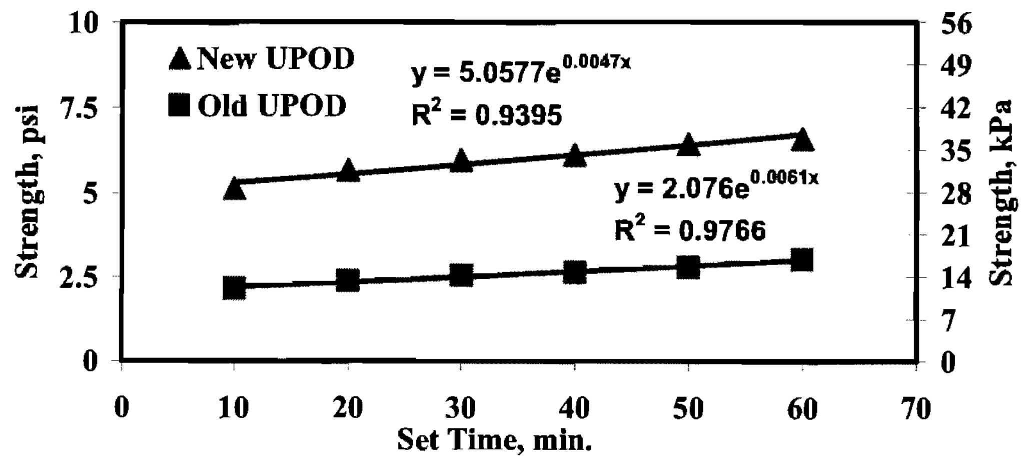


FIGURE 13 **UPOD Results for CSS1-h at 140°F at 0.04 gal/yd² Application Rate**

3.4 Training Material

Since the UPOD test results are typically dependent on the training of the operator, it is essential that proper training is given to the operators of the device. Thus, there are two purposes of the training. One of them is to train the people how to operate the device while the other purpose is how to document the collected information because it is needed for the development of field acceptance criterion. Since the strength gain depends on the environmental factors, the operators needed to be trained to properly collect and document wind velocity, ambient temperatures, as well. In addition, the results are highly dependent on the quality of applied tack coat, the operators needed to record, based on their visual observation, whether the tack coat is properly applied or not.

To train TxDOT personnel, a training manual was developed and has been delivered to the TxDOT along with the UPOD devices. To make sure that the training manual is adequate, El Paso District personnel were initially trained and problems with the training were rectified.

3.5 Development of an Acceptance Criterion

Although the objective of this study was to develop a field acceptance criterion, very limited field data was collected. Therefore, it was decided to develop a field acceptance criterion based on the laboratory test data and verify the developed criterion using limited field data. The main disadvantage of this approach is that the developed criterion may not be able to identify the influence of environmental factors, such as wind velocity, etc. But under the current circumstances it would be the only option.

The approach followed was that a series of tests were performed in the laboratory and nomographs were developed for the different tack coat types. The developed nomographs were then used to verify the test results from the field. The laboratory test data obtained in the Section 3.3 was used to develop nomograph and is explained in the following paragraphs.

The CSS-1h test results at different temperature, time since applicatio and two 0.04 gal/yd^2 and 0.1 gal/yd^2 application rates are shown in Figure14. The data shows that at 50 °F the gain in strength is less at longer set times while the strength gain is significant at 77 and 95 °F test temperatures. The strength gain at 140 °F test temperature is significantly higher at lower test times but the gain is not significant at longer set times. Similar trends were observed at different set times for SS-1h and PG 64-22 tack coat types and test results are included in Figures 15 and 16, respectively. The tests were not performed on PG64-22 at 140 °F because the moisture bearing foam separated from the contact plate; therefore, no data could be recorded.

The data presented in Figures 14 though 16 suggests that time temperature superposition principle proposed for linear viscoelastic materials can be used. The time temperature superposition principle suggests that the data obtained by performing tests at different temperatures can be converted to different set times and vice versa. A typical result for CSS-1h at 0.04 gal/yd^2 application rate is shown in Figure 17a. The data was shifted horizontally (time since application) such that the shape of the curve is sigmoidal (similar to that of hot mix asphalt concrete). The data shows three distinct behaviors: a flat portion, a steady increase in the strength and slower strength gain with the time since application. To generate a master curve, a sigmoid function of the following form was fitted to the data:

$$y = a + \frac{b}{\left(1 + \exp^{-\frac{(x-c)}{d}}\right)} \tag{3.1}$$

where y is the predicted stress and x is the reduced set times while a, b, c, and d are regression coefficients. Similar trends were observed for SS-1h and PG 64-22 tack coat types. The coefficient of determination (R^2) and regression coefficients obtained for each tack coat types are shown in Table 16.

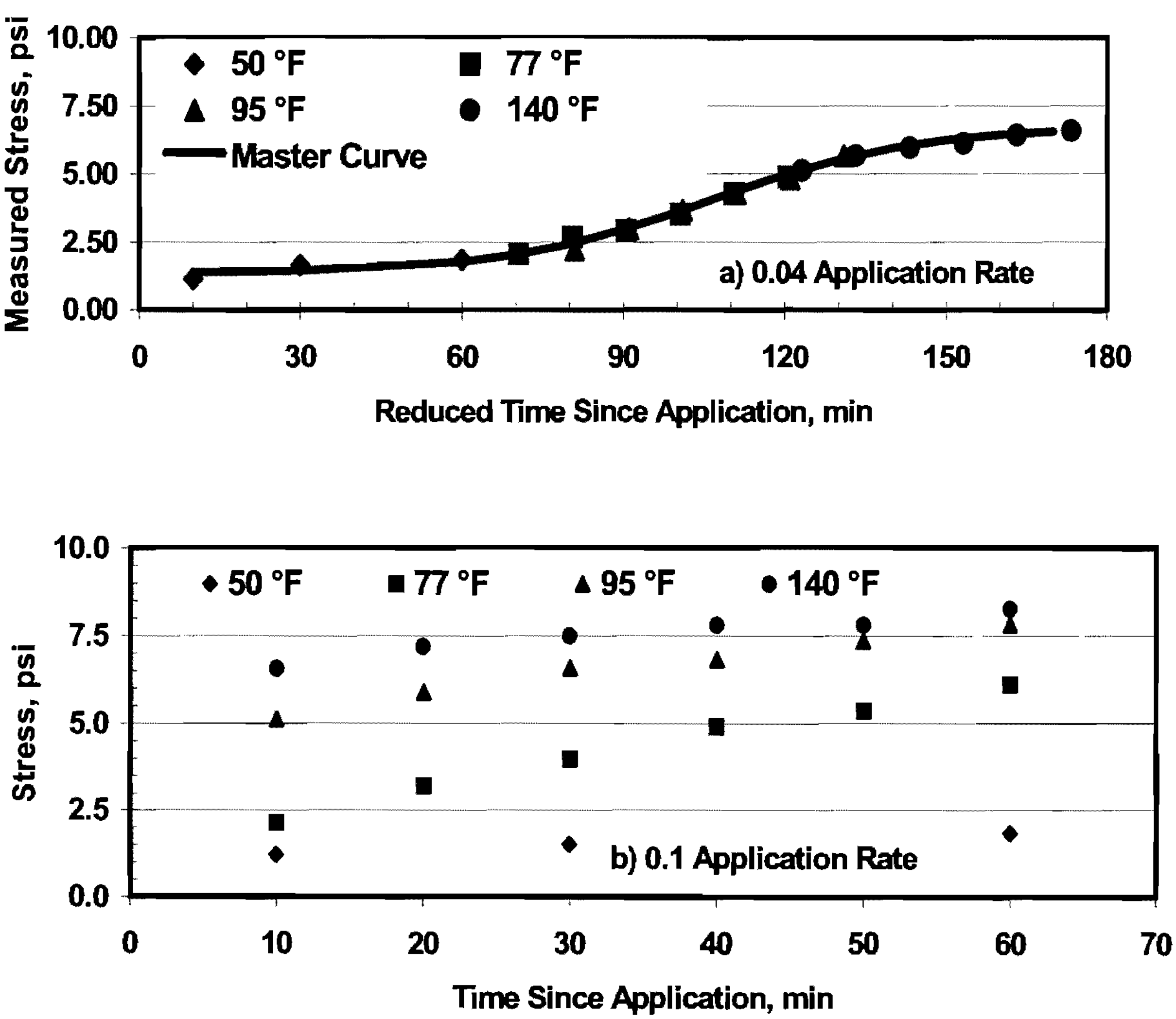


FIGURE 14 Measured Stresses at Different Time Since Application and Test Temperatures for CSS-1h Tack Coat Type

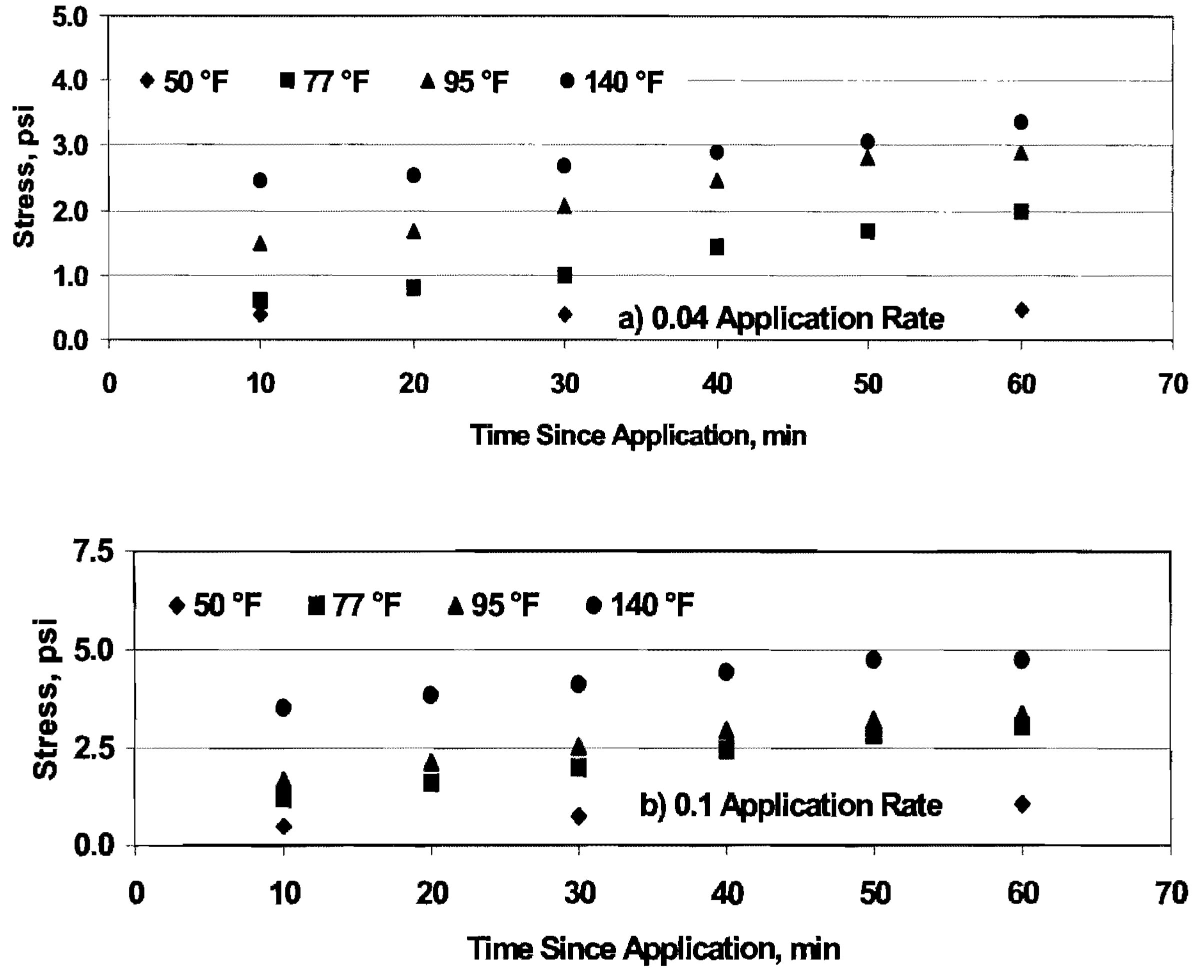


FIGURE 15 Measured Stresses at Different Time Since Application and Test Temperatures for SS-1h Tack Coat Type

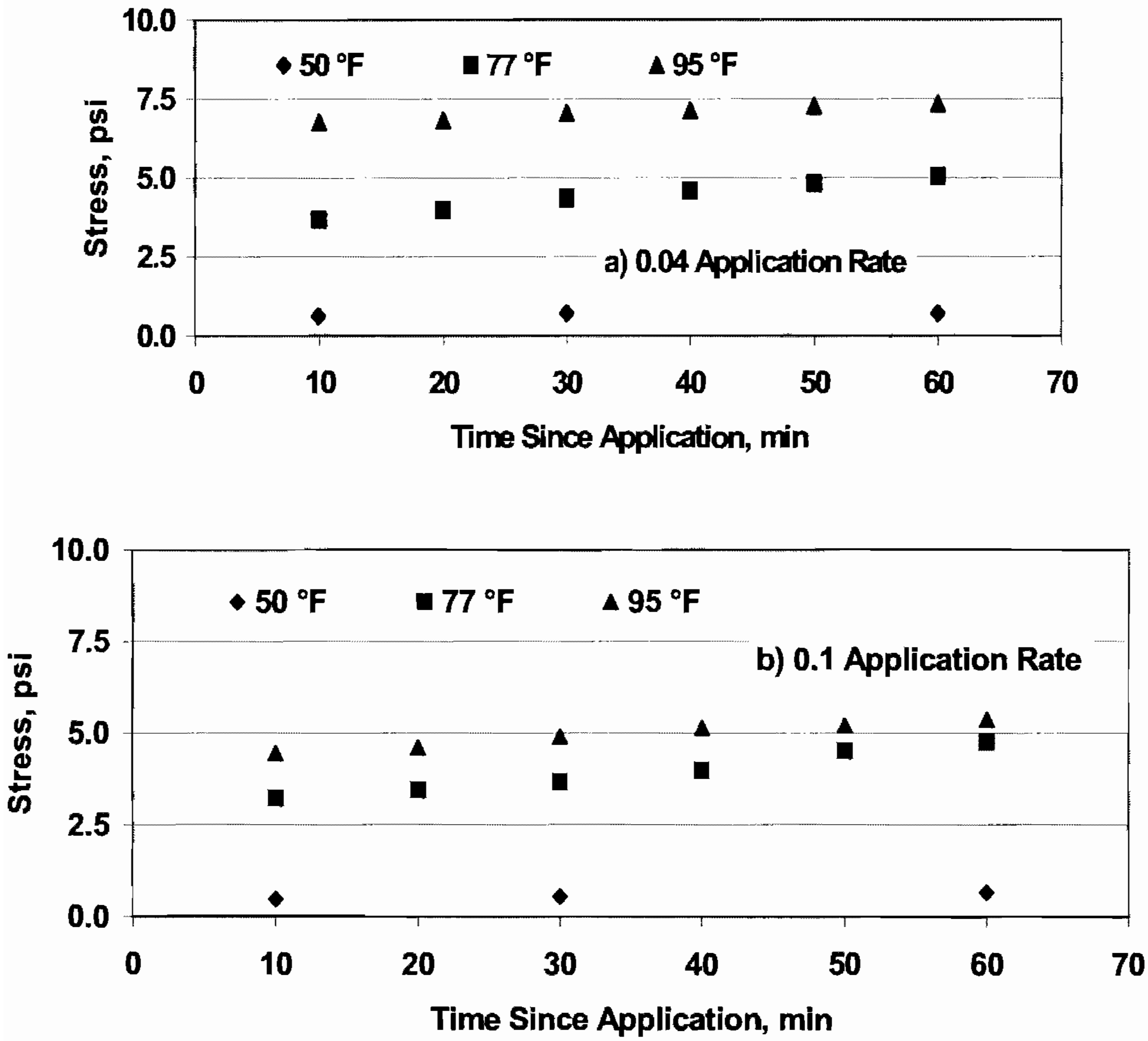


FIGURE 16 Measured Stresses at Different Time Since Application and Test Temperatures for PG 64-22 Tack Coat Type

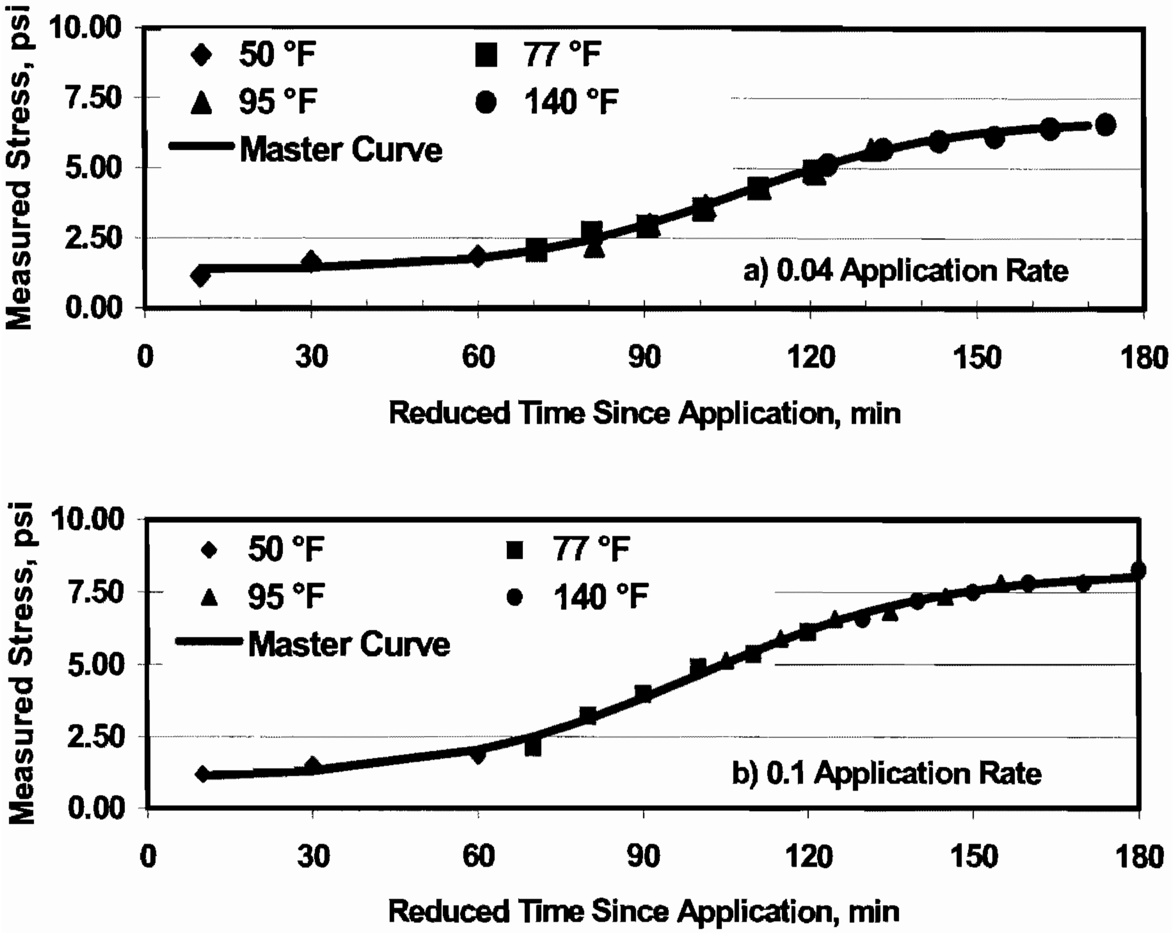


FIGURE 17 Reduced Time Since Application vs. Measured Strength for CSS-1h Tack Coat Type

TABLE 16. UPOD Results for CSS1-h at 0.04 gal/yd² application rate

Tack Coat Type	Application Rate, gal/yd²	Sigmoid Functions				
		R^2	a	b	c	d
CSS-1h	0.04	0.995	1.35	5.39	106.2	19.0
	0.10	0.996	1.05	7.16	99.9	21.9
SS-1h	0.04	0.0993	0.31	3.04	113.0	20.6
	0.10	0.992	0.23	4.90	109.0	33.5
PG64-22	0.04	0.995	0.29	5.50	149..0	37.2
	0.01	0.996	0.03	7.89	163.0	53.3

The sigmoid function for each tack coat type and time temperature superposition principles were then used to develop nomographs, as shown in Figures 18 through 20. The nomographs are developed for 0.04 gal/yd² application rates because this is the minimum acceptable rate of application. To accept or reject a tack coat, the field test results at a given time since application can be compared with the nomographs to see if the tack coat is acceptable or not. For instance, at a time since application of 45 minutes the tack coat will be acceptable if the measured stress is more than 6.5 psi when the pavement temperature is 140 °F and the applied tack coat is CSS-1h. The developed nomographs were then used for field verification, as discussed in the following section.

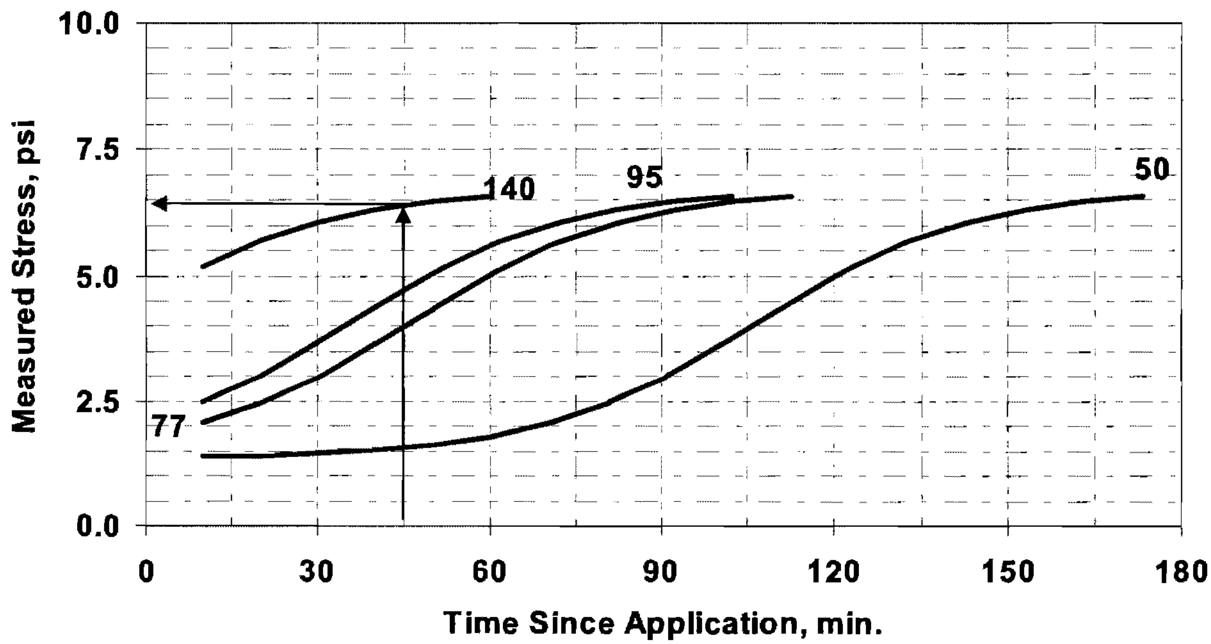


FIGURE 18 Nomograph for CSS-1h Tack Coat Type

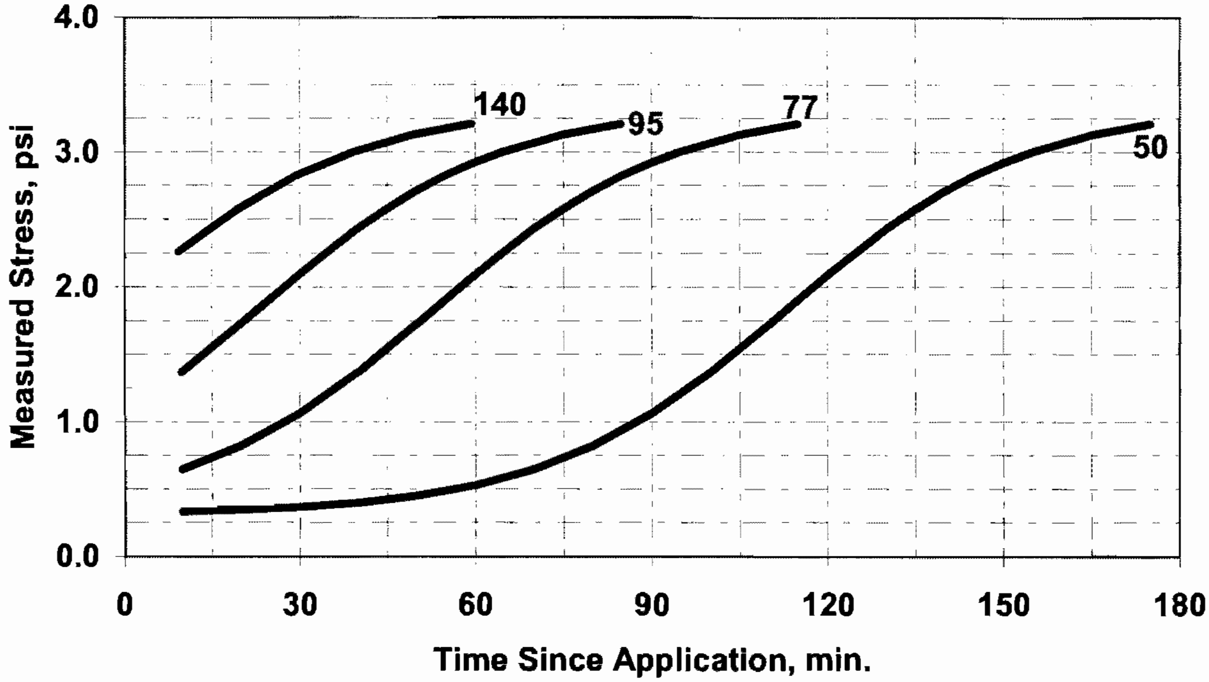


FIGURE 19 Nomograph for SS-1h Tack Coat Type

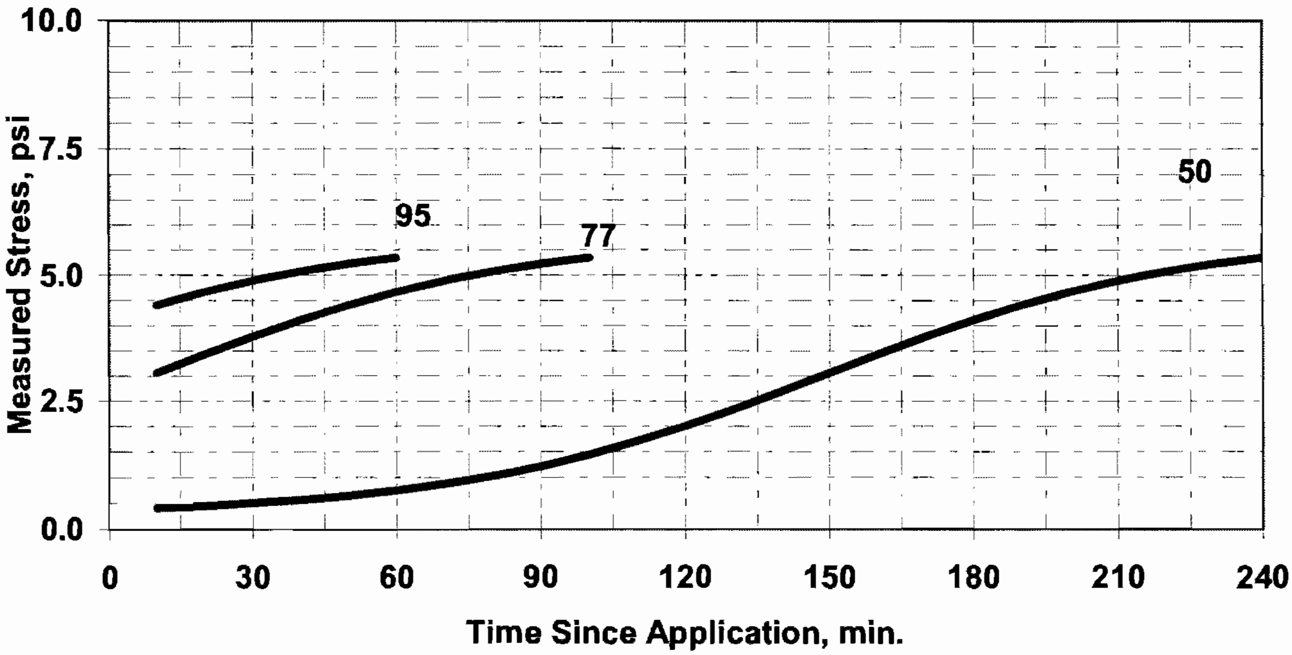


FIGURE 20 Nomograph for PG64-22 Tack Coat Type

3.6 Verification from the Field Data

Since only limited field data was collected, it was decided to use the criterion developed based on laboratory test data as a field acceptance criterion. Although the influence of wind velocity, ambient and pavement surface temperature plays a role on the initial gain in strength, there is not enough data to propose an acceptable criterion.

The limited field data collected from different counties within the State of Texas is summarized in Table 17. The tests were performed in four different counties and at different test temperatures and application rates. The collected data suggests that the rate of application varied from 0.08 to 0.20 gal/yd^2. The wind velocity varied from 2.4 to 12.0 mph and ambient temperature varied between 92 and 101 °F. The data suggests that the application quality was of very good quality for all of the tests performed.

To accept or reject a tack coat, it was decided to use pavement surface temperature to be the test temperature and ignore the influence of wind velocity and ambient temperature. Since TxDOT allows a minimum rate of tack coat application to be 0.04 gal/yd^2, it was decided to use the strength at this application rate to be cut-off point. In other words, if the measured strength is lower than the strength estimated at 0.04 gal/yd^2 than tack coat is not acceptable. The strength was estimated from the nomographs (Figures 18, 19 and 20) and is included as an estimated strength in Table 17. Since data is not available for all tack coat types, it was decided to use PG64-22 nomograph to represent AC-20 and SS-1h nomograph to represent SS-1 tack coat types.

The data presented in Table 17 suggests that the estimated strength is always lower than measured strength indicating that the tested tack coats are acceptable. Only, the tack coat tests performed in Parker County had lower measured than estimated strength. However, the nomograph is generated for PG64-22 material while the tack coat applied was AC-20. Since we do not have test results for AC-20, it may not be appropriate to reject the tack coat applied in Parker County.

One of the things to keep in mind is that the laboratory ambient temperature was 73 °F while the field temperature is more than 80 °F and the wind velocity was also present and both of these factors do influence the strength gain. Therefore, it is quite possible that the tests performed at lower ambient temperature may provide lower strength value. However, the field data at lower temperature is not available to verify the same.

Although limited field data is available, the nomographs developed from the laboratory data are reasonable. The field data suggests that the measured strength should be more than the strength obtained from the nomographs. In addition, the pavement surface temperature can be used as the test temperatures, as shown in the nomographs.

Based on the evaluation results, it can be proposed that if the measured tack coat strength is less than 1.0 psi then the tack coat should be rejected regardless of tack coat type, application rate, and pavement temperature. A value of less than 1.0 psi indicates that either tack coat is not properly applied or the tack coat is of poor quality.

TABLE 17. Field Data Obtained using UPOD

Test County	Test Location	Tack Coat Type	Residual Application Rate, gl/yd^2	Application Quality	Wind Velocity, mph	Ambient Temp., °F	Pavement Surface Temp., °F	Tested Time After Application, minutes	Applied Torque, In-lb.	Measured Strength, psi	Estimated Strength, psi	Difference, %
Comal	IH-35 (fronatge Road)	CSS-1h	0.20	A*	3.5	95.0	126.0	10	124	8.7	4.87	78.9
Comal	IH-35 (fronatge Road)	CSS-1h	0.20	A	3.5	95.0	126.0	10	124	8.7	4.87	78.9
Clay	SH-148	SS-1	0.11	A	2.1	91.0	109.2	10	42	2.8	1.72	63.3
Clay	SH-148	SS-1	0.11	A	3.9	91.0	112.1	10	60	4.1	1.83	124.3
Parker	US-180	AC-20	0.19	A	2.5	99.0	121.0	10	81	5.6	>5.5	N/A
Parker	US-181	AC-20	0.19	A	2.4	101.0	125.0	10	79	5.5	>5.5	N/A
Clay	SH-148	SS-1	0.11	A	12.0	82.0	89.4	10	55	3.7	1.8	108.0
Clay	SH-148	SS-1	0.11	A	10.1	82.0	89.2	10	51	3.5	1.8	92.0
Clay	SH-148	SS-1	0.08	A	6.2	87.1	100.2	10	58	4.0	2.1	88.6
Clay	SH-148	SS-1	0.11	A	4.1	89.1	106.9	10	56	3.8	2.1	81.7
El Paso	SH-20	SS-1h	0.10	A	4.8	83.1	91.8	12	21	1.5	1.37	11.7
El Paso	SH-20	SS-1h	0.10	A	7.6	87.7	90.6	36	42	3.3	2.2	50.7
El Paso	SH-20	SS-1h	0.10	A	9.8	90.5	96.9	48	55	4.4	2.69	64.3
El Paso	SH-20	SS1-h	0.10	A	10.6	91.4	105.0	60	62	5.0	2.92	71.7

A* Proper Coverage on Existing Surface

3.7 Estimation of Tack Coat Strength Using Direct Shear Device

Deysarkar and Tandon (2005) had proposed to use direct shear device test results to identify the tack coat quality. The main advantage of the test results is that the cores from the field can be obtained and tested especially in case of failures.

Although tests were performed on some of the hot mix provided by the TxDOT, the test results suggested that higher bond strength is obtained with no tack coat between the two surfaces which is totally in contradiction with the theory. For instance, the shear strength measured with SS-1h of 0.04 gal/yd2 application rate to be 123 psi while with no tack coat application the measured strength was 177 psi when the tests were performed at the room temperature (75 °F). The measured strength was significantly different from the ones observed by Deysarkar and Tandon (2005). The differences can be attributed to the difference in specimen preparation techniques. Deyasarkar and Tandon (2005) prepared two briquettes (4in. diameter by 2 in. height) and applied tack coat on one of the briquettes. After the specified set time, the other briquette was placed on top of the tack coat applied briquette and maintained a load of 40 lbs for 10 minutes before performing the direct shear tests.

In this study, the specimens were prepared using a different technique which simulates the construction practices of the field. The first briquette was prepared using Superpave Gyratory Compactor (SGC) and tack coat was applied on the prepared briquette. After specified time, the briquette was placed inside the SGC mold and new loose mix was placed on top of the briquette and composite briquette was prepared by placing the mold inside the SGC. Although this method simulated the construction practice of placing hot mix on top of the existing layer, it increased the strength significantly by heating the tack coat to a very high temperature. In addition, the gyratory action of SGC pushed aggregates of the loose mix inside the existing layer (briquette with tack coat). The examination of the broken specimens suggested that the briquettes prepared without tack coat allowed embedment of the loose mix inside the existing mix; thus, higher strength. The briquettes with tack coat created a layer which reduced the embeddment of the loose mix inside the existing layer; hence lower strength. Therefore, the idea of performing of direct shear tests on the hot mix asphalt concrete specimens was not further pursued.

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

To improve performance of flexible pavements, it is quite common to place an overlay on top of the existing surface layer. A bonding agent commonly known as "tack coat" is placed on top of the old layer, before placement of overlay, to ensure proper bonding between the two layers. However, no reliable field test is available that can quantify the quality of applied tack coat. Currently, TxDOT uses a boot heal test. The procedure suggests that an inspector stands on the applied tack coat area and if his/her boot sticks to the tack coat it is good, otherwise it is not. This field test is subjective and does not ensure that a good quality tack is applied. TxDOT sponsored a project (0-4129) entitled "Development of an Objective Field Test to Determine Tack Coat Adequacy" to identify or develop a test setup the can quantify the quality of the tack coat in the field. The study suggested that the quality of tack coat can be identified in the field using UPOD; however, a field acceptance criterion needed to be developed and was focus of this study. In addition, the UPOD needed to be modified to make sure the device is reproducible.

In this study, the existing device was modified and six devices were produced. The statistical evaluation of the six devices suggested that the devices are reproducible. A series of laboratory of tests were performed to develop a nomograph due to the limited availability of the field data and the developed nomographs were then used to verify the field data. Based on the limited data set, it was concluded that the nomographs can be used as an acceptance criterion. It is proposed that if the measured tack coat strength is less than 1.0 psi then the tack coat should be rejected regardless of tack coat type, application rate, and pavement temperature. A value of less than 1.0 psi indicates that either tack coat is not properly applied or the tack coat is of poor quality. However, more field tests are needed to verify the validity of the proposed acceptance criterion. A proposed test procedure and the acceptance criterion are included in Appendix B.

REFERENCES

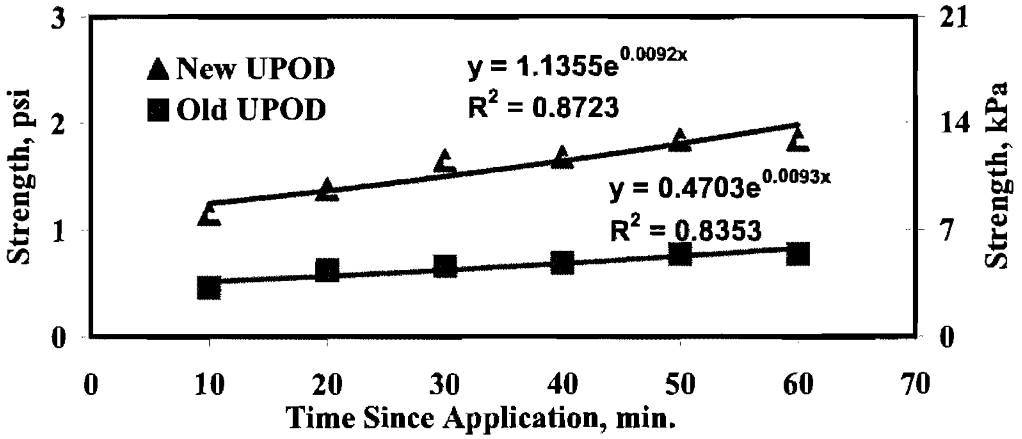
Ohio Technical Bulletin, <http:// http://www.flexiblepavements.org/images/Tack Coat Application 21May 01.pdf> Last Accessed on June 1, 2004, 2001.

Deysarkar, I. and Tandon, V. (2005), "Development of an Objective Field Test To Determine Tack Coat Adequacy," Research Report 0-4129, Center for Transportation Infrastructure Systems, The University of Texas at El Paso, El Paso, Texas.

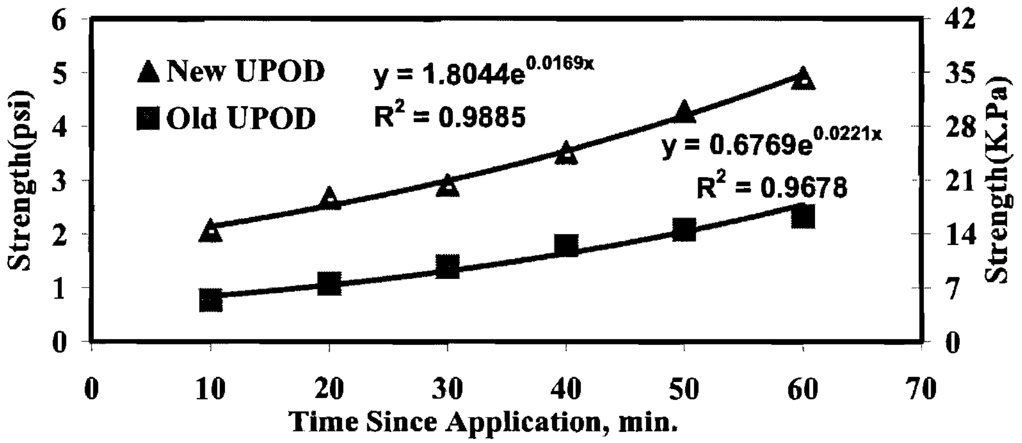
APPENDIX A: COMPARISON TEST RESULTS BETWEEN NEW AND OLD UPOD

A.1 UPOD Results for CSS1-h at 0.04 gal/yd² Application Rate

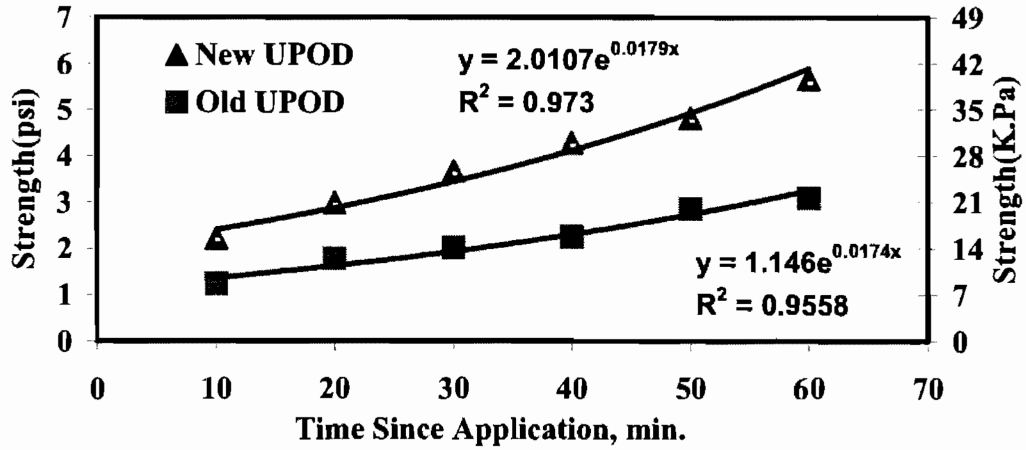
Residual Application Rate, gal/yd²	Temp. °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old (Prototype) UPOD
0.04	50	10	1.15	0.46
		20	1.38	0.62
		30	1.65	0.66
		40	1.68	0.69
		50	1.84	0.77
		60	1.84	0.77
	77	10	2.07	0.77
		20	2.68	1.08
		30	2.91	1.39
		40	3.52	1.78
		50	4.28	2.08
		60	4.9	2.32
	95	10	2.22	1.24
		20	2.99	1.78
		30	3.67	2.01
		40	4.29	2.24
		50	4.82	2.86
		60	5.67	3.09
	140	10	5.13	2.16
		20	5.67	2.39
		30	5.97	2.55
		40	6.12	2.63
		50	6.43	2.78
		60	6.58	3.01



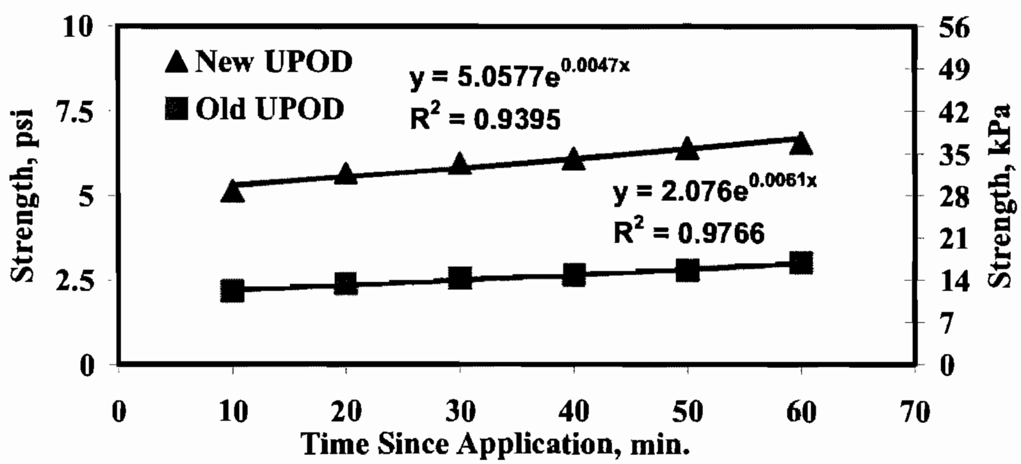
A.2 UPOD Results for CSS1-h at 50°F at 0.04 gal/yd² Application Rate



A.3 UPOD Results for CSS1-h at 77°F at 0.04 gal/yd² Application Rate



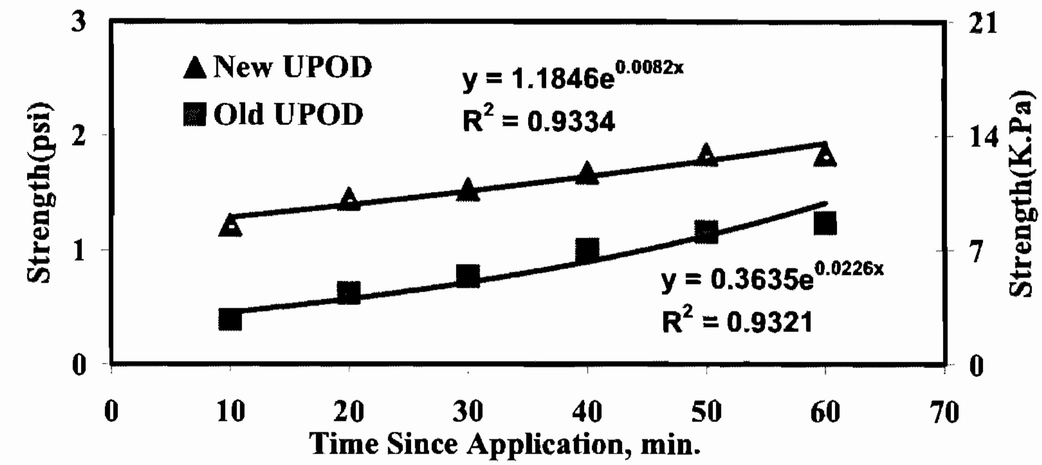
A.4 UPOD Results for CSS1-h at 95°F at 0.04 gal/yd² Application Rate



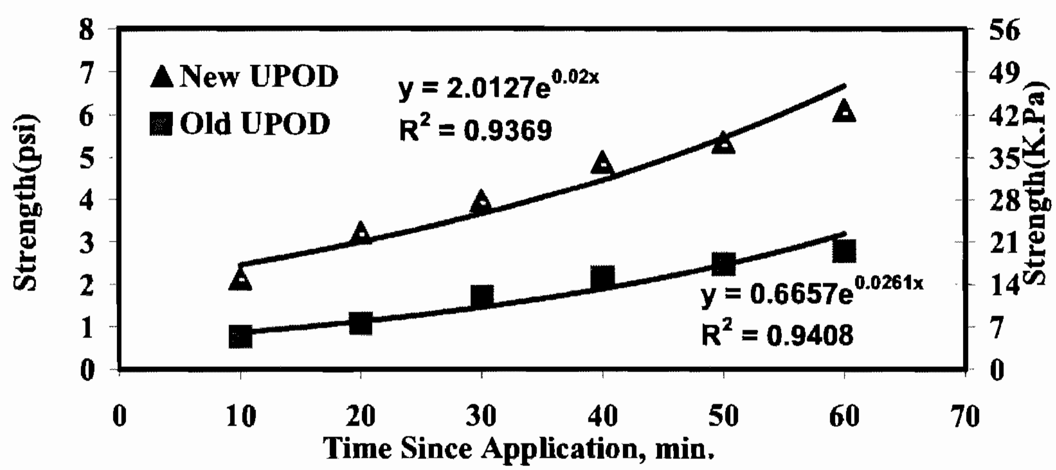
A.5 UPOD Results for CSS1-h at 140°F at 0.04 gal/yd² Application Rate

A.6 UPOD Results for CSS1-h at 0.1 gal/yd² Application Rate

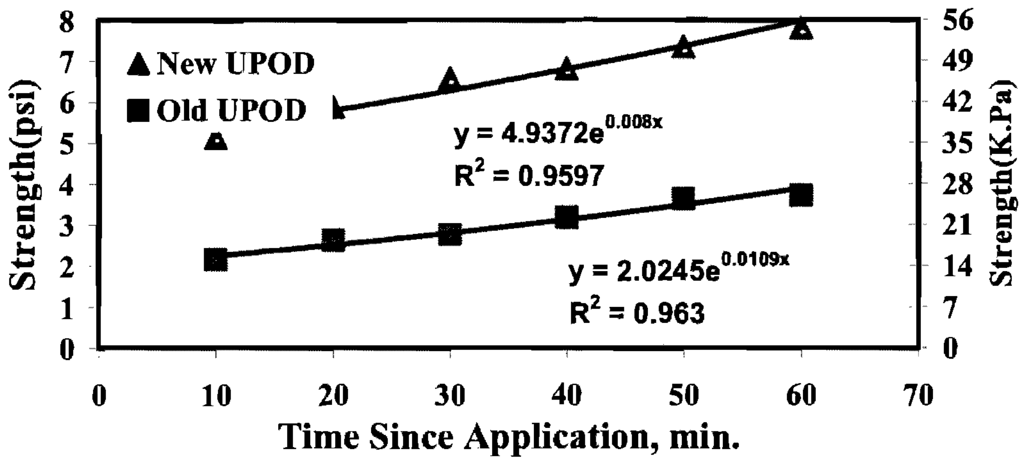
Residual Application Rate gal/yd²	Temperature °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old UPOD
0.1	50			
		10	1.22	0.39
		20	1.45	0.62
		30	1.53	0.77
		40	1.68	1
		50	1.84	1.16
		60	1.84	1.24
	77	10	2.14	0.77
		20	3.22	1.08
		30	3.98	1.7
		40	4.9	2.16
		50	5.36	2.47
		60	6.12	2.78
	95	10	5.13	2.16
		20	5.89	2.63
		30	6.58	2.78
		40	6.81	3.17
		50	7.35	3.63
		60	7.81	3.71
	140	10	6.58	2.36
		20	7.2	2.55
		30	7.5	2.78
		40	7.81	3.32
		50	7.81	3.63
		60	8.27	3.71



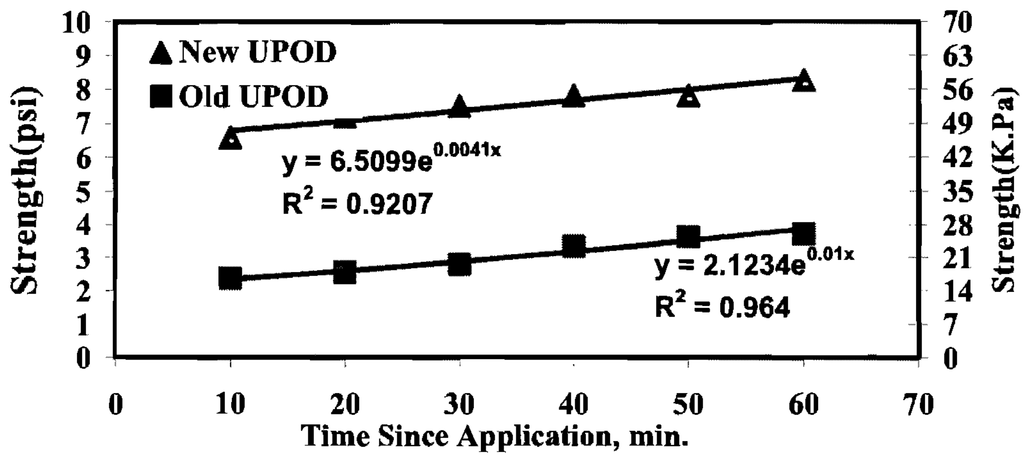
A.7 UPOD Results for CSS1-h at 50°F at 0.1 gal/yd² Application Rate



A.8 UPOD Results for CSS1-h at 77°F at 0.1 gal/yd² Application Rate



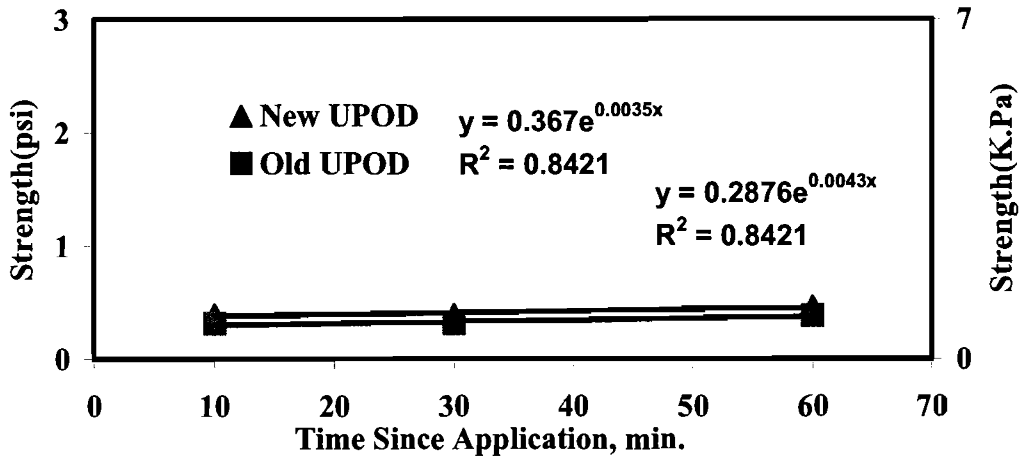
A.9 UPOD Results for CSS1-h at 95°F at 0.1 gal/yd² Application Rate



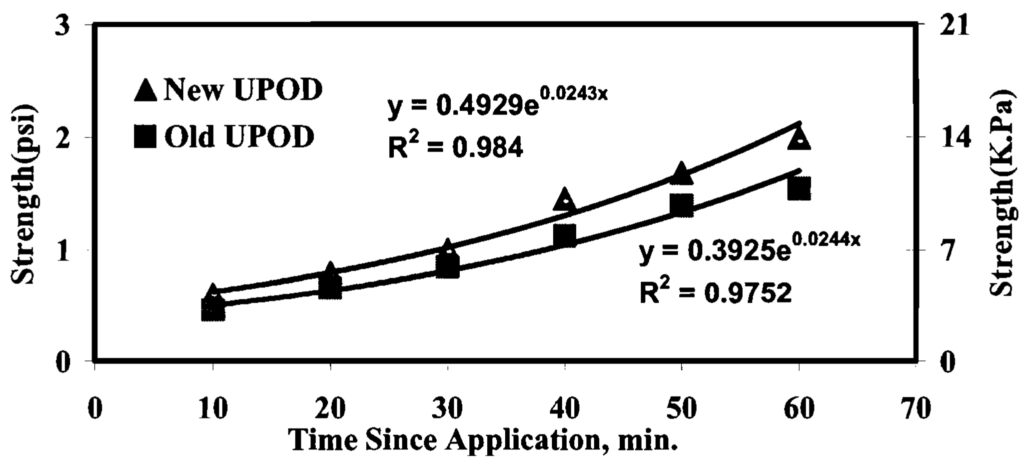
A.10 UPOD Results for CSS1-h at 140°F at 0.1 gal/yd² Application Rate

A.11 UPOD Results for SS1-h at 0.04 gal/yd² Application Rate

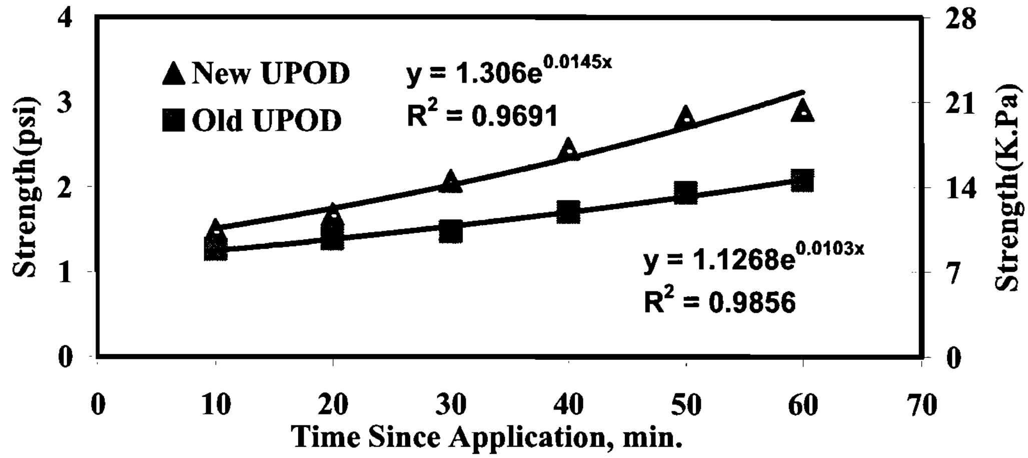
Residual Application Rate gal/yd²	Temperature °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old UPOD
0.04	50	10	0.39	0.31
		30	0.39	0.31
		60	0.46	0.38
	77	10	0.61	0.46
		20	0.8	0.66
		30	1	0.85
		40	1.45	1.12
		50	1.68	1.39
		60	1.99	1.54
	95	10	1.49	1.27
		20	1.68	1.39
		30	2.07	1.47
		40	2.45	1.7
		50	2.83	1.93
		60	2.91	2.08
	140	10	2.45	1.54
		20	2.53	1.7
		30	2.68	1.81
		40	2.91	2.01
		50	3.06	2.16
		60	3.37	2.39



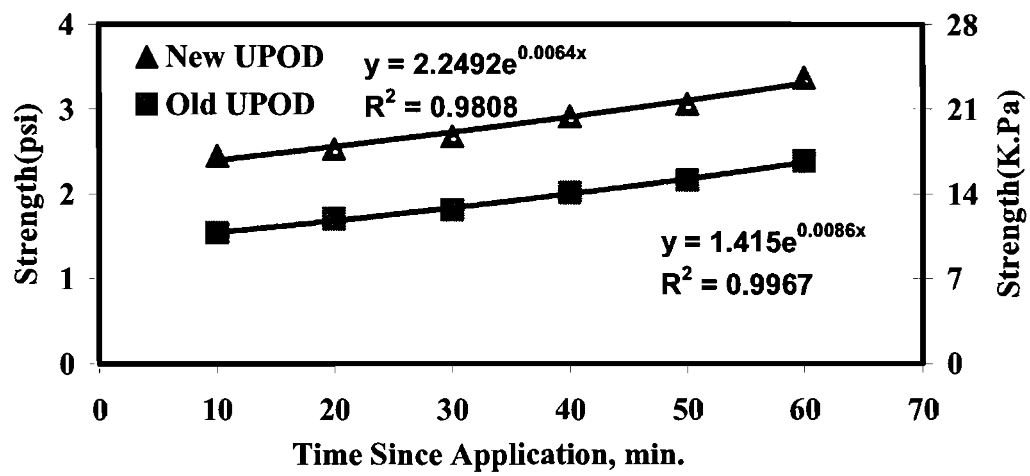
A.12 UPOD Results for SS1-h at 50°F at 0.04 gal/yd² Application Rate



A.13 UPOD Results for SS1-h at 77°F at 0.04 gal/yd² Application Rate



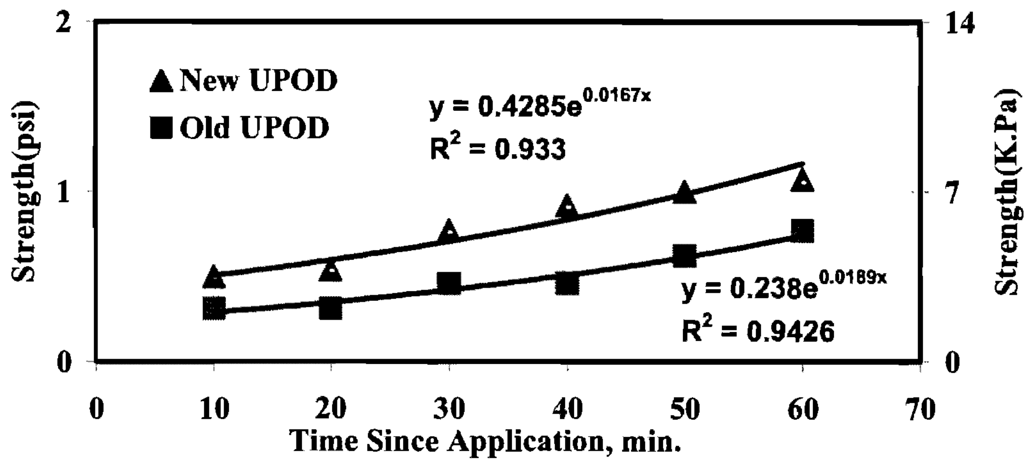
A.14 UPOD Results for SS1-h at 95°F at 0.04 gal/yd² Application Rate



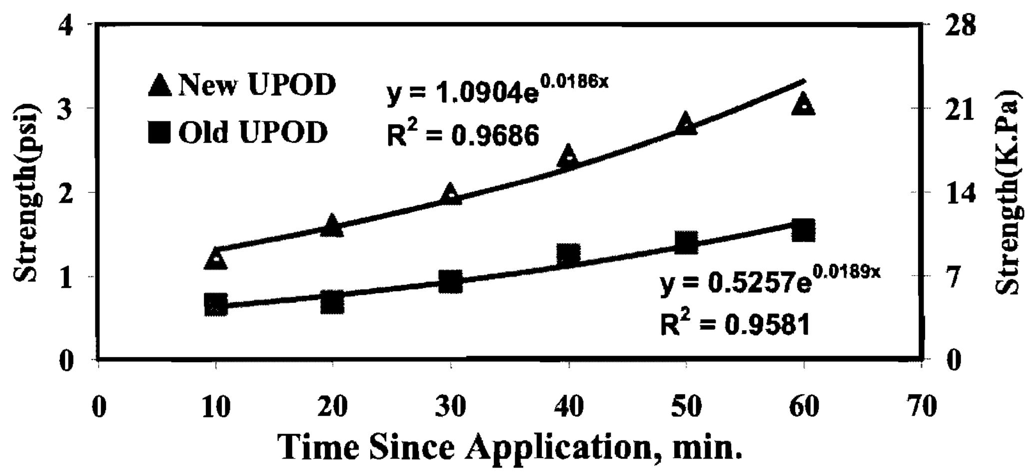
A.15 UPOD Results for SS1-h at 140°F at 0.04 gal/yd² Application Rate

A.16 UPOD Results for SS1-h at 0.1 gal/yd² Application Rate

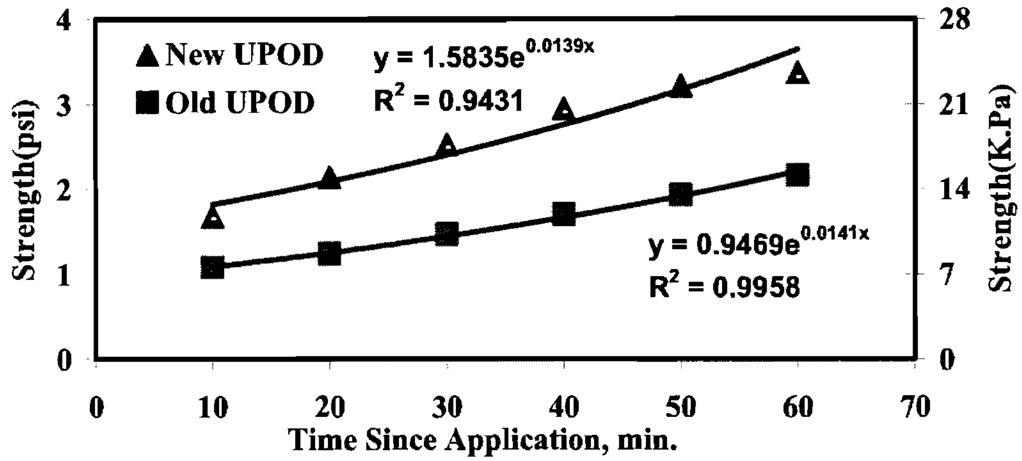
Residual Application Rate gal/yd²	Temperature °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old UPOD
0.1	50	10	0.5	0.31
		20	0.54	0.31
		30	0.77	0.46
		40	0.92	0.46
		50	1	0.62
		60	1.07	0.77
	77	10	1.22	0.66
		20	1.61	0.69
		30	1.99	0.93
		40	2.45	1.24
		50	2.83	1.39
		60	3.06	1.54
	95	10	1.68	1.08
		20	2.14	1.24
		30	2.53	1.47
		40	2.95	1.7
		50	3.22	1.93
		60	3.37	2.16
	140	10	3.52	1.24
		20	3.83	1.31
		30	4.13	1.54
		40	4.44	1.93
		50	4.75	2.32
		60	4.75	2.63



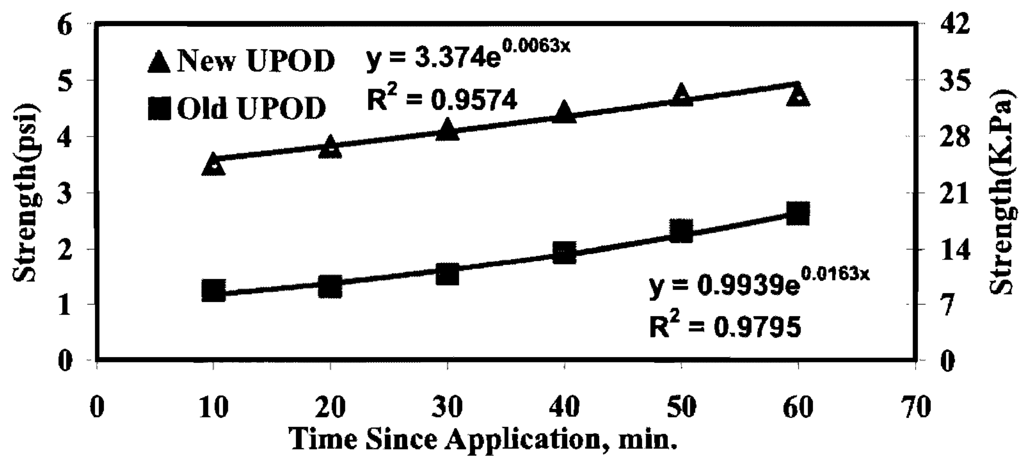
A.17 UPOD Results for SS1-h at 50°F at 0.1 gal/yd² Application Rate



A.18 UPOD Results for SS1-h at 77°F at 0.1 gal/yd² Application Rate



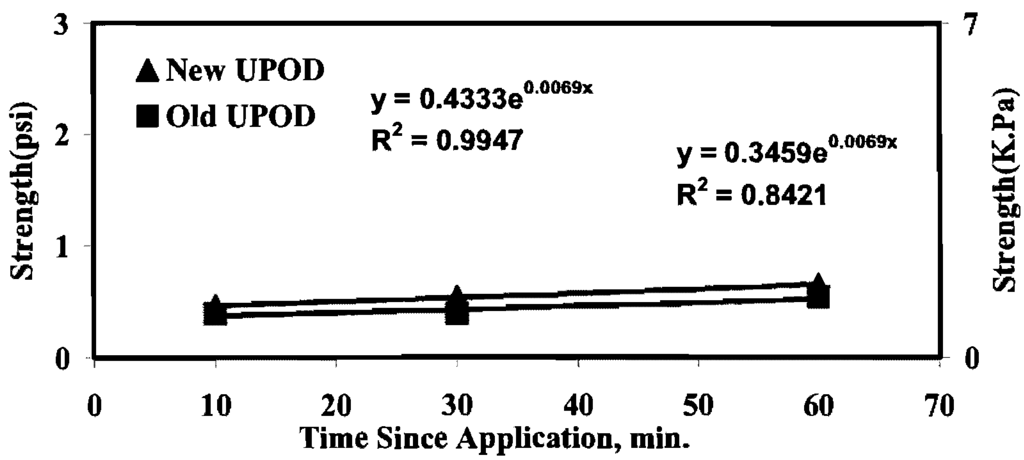
A.19 UPOD Results for SS1-h at 95°F at 0.1 gal/yd² Application Rate



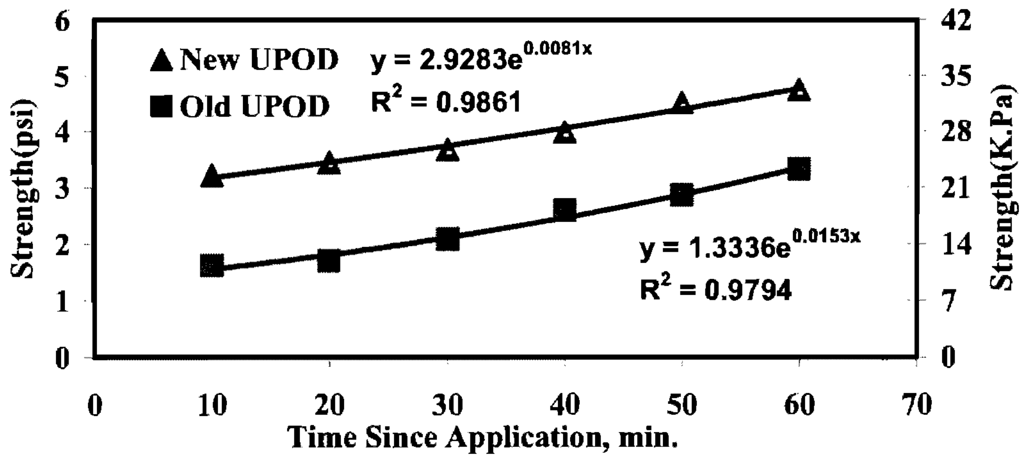
A.20 UPOD Results for SS1-h at 140°F at 0.1 gal/yd² Application Rate

A.21 UPOD Results for PG64-22 at 0.04 gal/yd² Application Rate

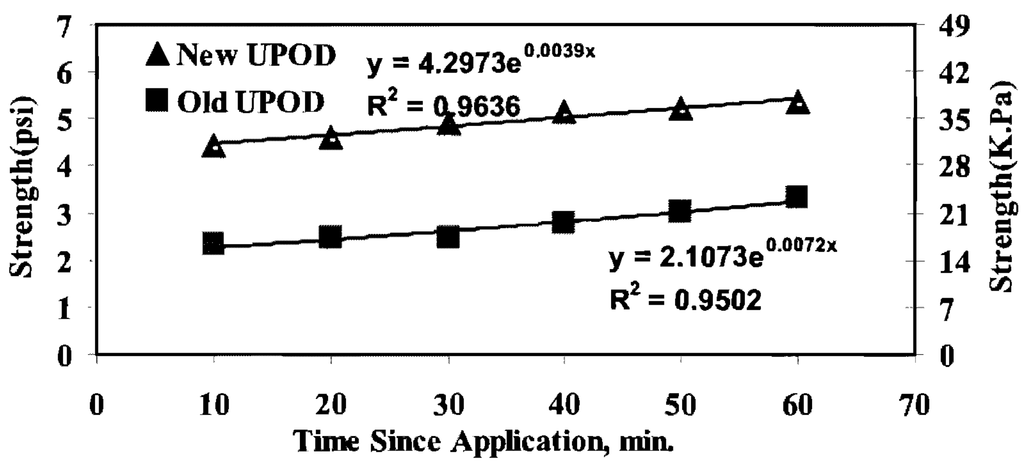
Residual Application Rate gal/yd²	Temperature °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old UPOD
0.04	50	10	0.46	0.39
		30	0.54	0.39
		60	0.65	0.54
	77	10	3.22	1.62
		20	3.44	1.7
		30	3.67	2.08
		40	3.98	2.59
		50	4.52	2.86
		60	4.75	3.32
	95	10	4.44	2.32
		20	4.59	2.47
		30	4.9	2.47
		40	5.13	2.78
		50	5.21	3.01
		60	5.36	3.32



A.22 UPOD Results for PG64-22at 50°F at 0.04 gal/yd² Application Rate



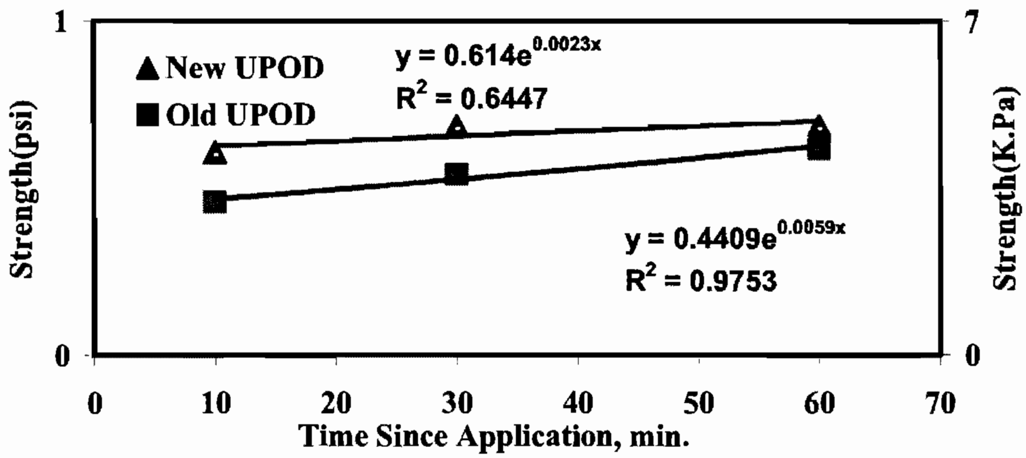
A.23 UPOD Results for PG64-22at 77°F at 0.04 gal/yd² Application Rate



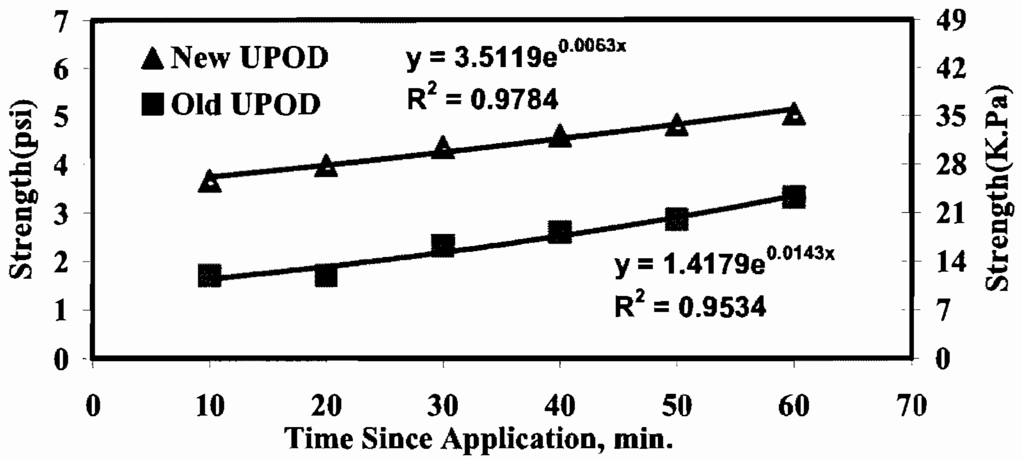
A.24 UPOD Results for PG64-22at 95°F at 0.04 gal/yd² Application Rate

A.25 UPOD Results for PG64-22 at 0.1 gal/yd² Application Rate

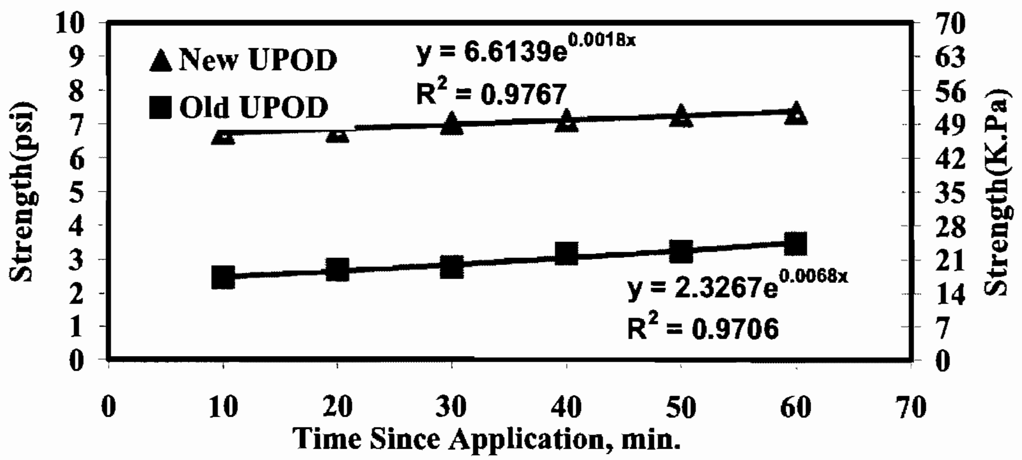
Residual Application Rate gal/yd²	Temperature °F	Set time min	Avg. Cohesive Strength, psi	
			New UPOD	Old UPOD
0.1	50	10	0.61	0.46
		30	0.69	0.54
		60	0.69	0.62
	77	10	3.67	1.7
		20	3.98	1.7
		30	4.36	2.32
		40	4.59	2.59
		50	4.82	2.86
		60	5.05	3.32
	95	10	6.74	2.47
		20	6.81	2.7
		30	7.04	2.78
		40	7.12	3.17
		50	7.27	3.24
		60	7.35	3.47



A.26 UPOD Results for PG64-22at 50°F at 0.1 gal/yd² Application Rate



A.27 UPOD Results for PG64-22at 77°F at 0.1 gal/yd² Application Rate



A.28 UPOD Results for PG64-22at 95°F at 0.1 gal/yd² Application Rate

APPENDIX B: TEX-243-F, TACK COAT ADHESION TEST

Overview

Effective Date: May 2006

Use this test method to evaluate the adhesive properties of tack coat for roadway use at the project site.

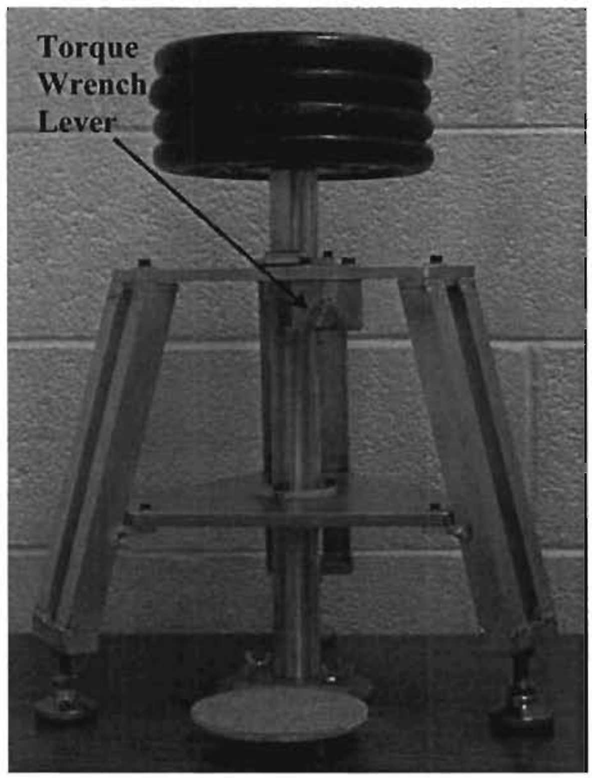
Units of Measurement

The values given in parentheses (if provided) are not standard. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Apparatus

Use the following apparatus:

- Tack Coat Pull Off Device (as shown in figure below)
- Torque wrench, 150 lb-in capacity
- Handheld non-contact infrared thermometer capable of measuring from 40°F (4°C) to 350°F (177°C) with an accuracy of ± 2°F (± 1°C), with a LCD display capable of displaying the maximum temperature, adjustable emissivity in increments of 0.01 or a fixed emissivity equal to or greater than 0.95 and a minimum 6:1 distance to spot ratio.
- Pocket weather meter capable of measuring wind speed (0.7 to 89 mph) and ambient temperature (5°F [-15°C] to 122°F [50°C]).



Tack Coat Pull Off Device

Materials

- Utility cutting knife
- Moisture bearing foam
- Double sided tape

Procedure

Follow these steps to prepare the testing apparatus for use and to perform the tack coat adhesion test.

Preparing Tack Coat Pull Off Device for Use	
Preparing Apparatus	
Step	**Action**
1	Cut a circular piece of double-sided tape approximately 5 in. (127 mm) in diameter.
2	Attach the double-sided tape from Step 1 to the contact plate of the testing apparatus. Remove any excess double-sided tape with a utility cutting knife.
3	Cut a circular piece of the moisture bearing foam approximately 5 in. (127mm) in diameter.
4	Attach the smooth and slick textured side of the moisture bearing foam from step 3 to the double-sided tape. Remove any excess moisture bearing foam
5	Fasten the contact plate with the double-sided tape and moisture bearing foam to the bottom of the testing device using wing nuts (placed diagonally of each other).
Performing Field Test	
6	Select a test section of pavement coated with tack coat. NOTE: Select an area of approximately 2 ft^2 (0.2 m^2) in size.
7	a. Record relevant information as suggested in the Data Sheet:
8	Allow tack coat to cure for approximately 30 minutes.
9	Position the testing device onto the test section selected in Step 6.
10	Let the contact plate (prepared according to Steps 1-5) fall into the test area by rotating torque wrench lever in counter-clockwise direction.
11	Place 40 lb. (18 kg) load on top of the testing device and hold in place for approximately 10 min.
12	Remove the load from the testing device after approximately 10 min.
13	Connect the torque wrench to the testing device.
14	Apply torque until the contact plate completely separates from the pavement surface.
15	Record the maximum torque required to completely separate the contact plate from the pavement surface.

Calculations

Calculate the adhesive strength of the applied tack coat material by multiplying the Toque with the appropriate calibration Factor.

UPOD No.	**Calibration Factor, psi**
1	**0.079**
2	**0.072**
3	**0.085**
4	**0.085**
5	**0.081**
6	**0.075**

Acceptance Criterion

Compare the measured adhesive strength with the provided nomographs. If the measured tack coat strength is less than 1.0 psi then the tack coat should be rejected regardless of tack coat type, application rate, and pavement temperature.

Tex-243-F Tack Coat Adhesion Test Data Sheet

District: ________________ Existing Mix Type or Surface: _____________

County: ________________ Overlay Mix Type: ______________________

Highway:________________ Contractor: _____________________________

Lot Number: _____________ Date Tested: ____________________________

Location Mark: ____

____

Comments: ____

Tack Coat Type: _________

Estimated Application Rate:_______ gal/yd^2 Measured Application Rate:____ gal/yd^2

Break Time:_______________

Circle- Field Lab

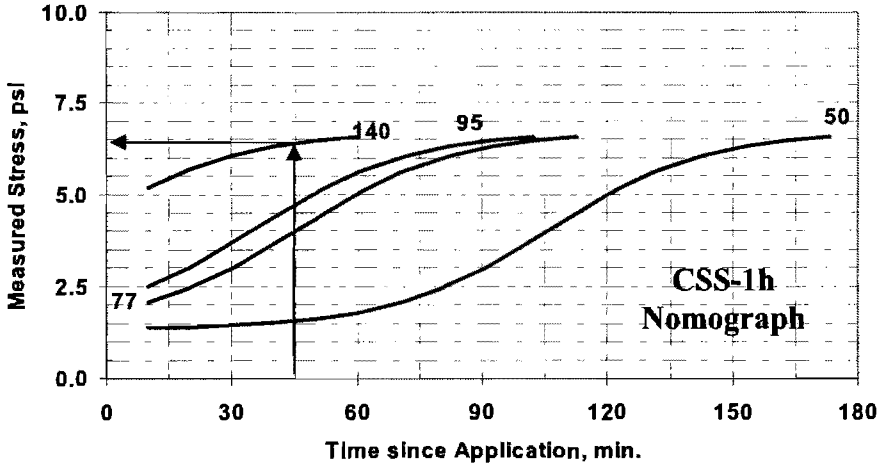
Trials	Application Quality*	Ambient Temperature, °F	Wind Velocity, mph	Pavement Temperature, °F	Tested Time, min.	(Measured Torque-3), in-lbs
1						
2						
3						
4						
5						
6						

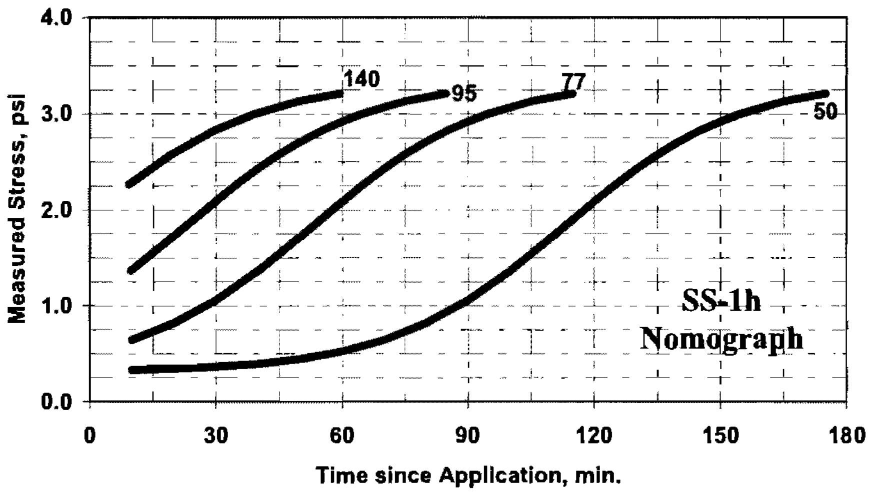
Application Quality*

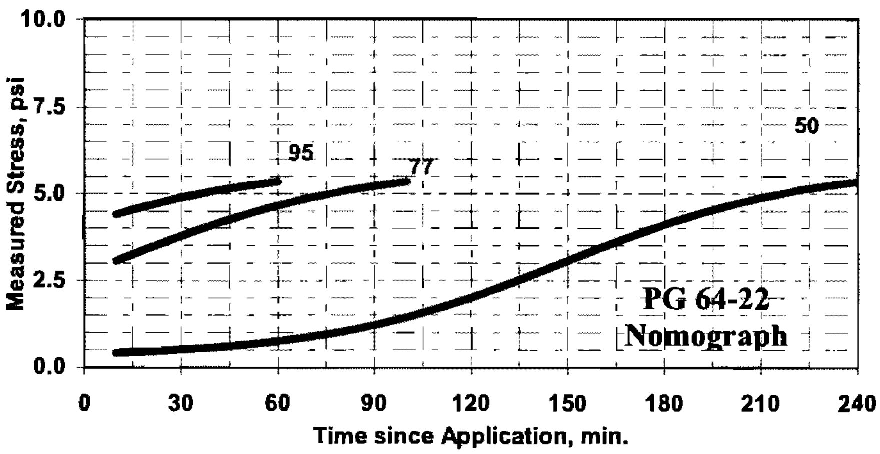
A. Proper Coverage on Existing Surface
B. Proper Coverage on Milled Surface
C. Delivery Vehicle Tracking
D. Material Transfer Device Tracking
E. Small Nozzle Opening
F. Application on Oxidized Asphalt
G. Excessive Unbroken Tack
H. Uneven Distribution

Boot Heel Evaluation

Adhesive Quality: ___ Good ___ Fair ____Poor


10.0
7.5
5.0
2.5
0.0
Measured Stress, psi
0
30
60
90
120
150
180
Time since Application, min.
140
95
50
77
CSS-1h
Nomograph


4.0
3.0
2.0
1.0
0.0
Measured Stress, psi
0
30
60
90
120
150
180
Time since Application, min.
140
95
77
50
SS-1h
Nomograph


10.0
7.5
5.0
2.5
0.0
Measured Stress, psi
0
30
60
90
120
150
180
210
240
Time since Application, min.
95
77
50
PG 64-22
Nomograph