Comparison Study of Moisture Damage Test Methods for Evaluating Antistripping Treatments in Asphalt Mixtures

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Moisture damage is a major problem for asphalt concrete pavements constructed throughout much of the United States, as well as other areas in the world. A number of test methods and procedures have been developed to evaluate the moisture damage potential of asphalt-aggregate mixtures; however, these different test methods and variations do not yield the same results. A study of the relationships among various moisture damage test values for a range of mixtures using different antistripping additives compared two basic moisture damage test methods, that is, the wet-dry indirect tensile test (the Lottman test) and the boiling test. A number of variations of the wet-dry indirect tensile test were also compared. On the basis of the results of the test program, the moisture susceptibility test methods are ranked in the decreasing order of severity: (a) original Lottman method, (b) modified Lottman method, and (c) Tunnicliff-Root method. Correlations have been obtained between the moisture damage test values of the modified Lottman method and the other test methods. The relationships between the boiling test results and the wet-dry indirect tensile strength ratio values have also been established.

Moisture damage is a major problem for asphalt pavements constructed throughout much of the United States. The seriousness of the problem, which has been studied for decades, is evidenced by the large number of research efforts conducted in the United States during the past 10 to 15 years.

As a result of the research, a number of tests and test procedures have been developed to evaluate the moisture damage potential of asphalt-aggregate mixtures. Unfortunately, although a limited number of basic tests are currently used, many variations of each test and many different acceptance criteria are being used. It is also apparent that these different tests and test variations do not yield the same results and thus do not predict the same amount of moisture damage potential.

In recognition of these factors, research was undertaken to evaluate the relationships between various moisture damage test values for a range of mixtures and antistripping agents. Two basic moisture susceptibility test methods were selected for laboratory evaluation, that is, the wet-dry indirect tensile test (the Lottman test) and the boiling test. However, a number of variations of the wet-dry indirect tensile test were compared.

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EXPERIMENTAL PROGRAM

The objective of this study was to evaluate the relationships between various moisture damage test methods for a range of mixture and antistripping agents. To achieve the objective, the experimental program used aggregates and asphalts from eight highway districts in Texas (Figure 1), and 13 commercially available antistripping additives and the hydrated lime. Two basic moisture damage tests were performed on treated and untreated mixtures, which were plant mixtures (mixed in the plant and compacted in the laboratory) and laboratory mixtures (mixed and compacted in the laboratory).

Materials

Plant Mixtures

Loose samples of the hot asphalt mixtures used in actual field construction were obtained at the eight asphalt mixing plants. The loose samples were reheated and compacted in the laboratory using a compaction procedure that produced an air

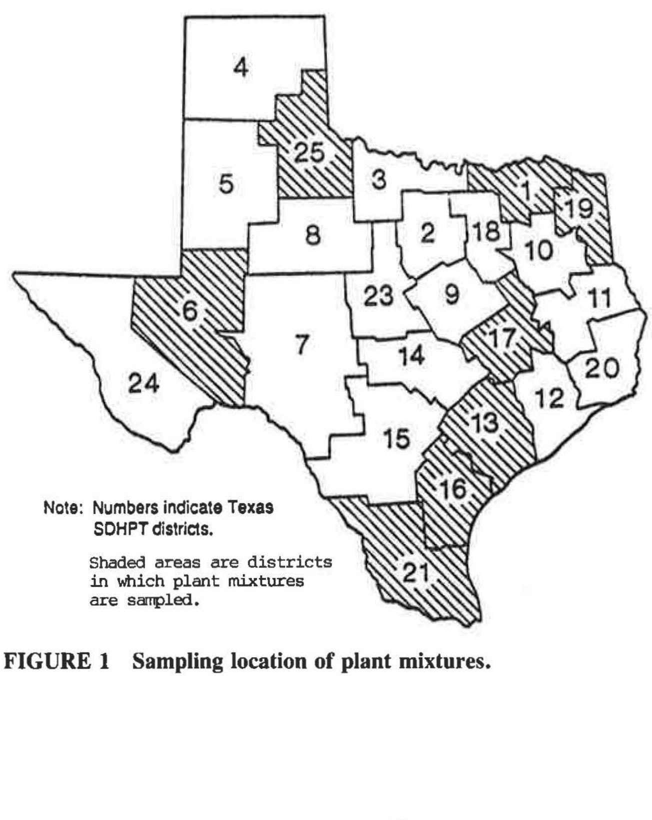


FIGURE 1 Sampling location of plant mixtures.

void content of about 7 percent. The types of aggregate and the source and amount of asphalt cement for the plant mixtures are summarized in Table 1. Two or more liquid antistripping additives and hydrated lime were used in each type of plant mixture with identical raw material sources (aggregates and asphalt cement). Fourteen antistripping additives, including hydrated lime, were used in the eight plant mixtures. The actual additive dosages are summarized in Table 2. The percentage of lime is by the total weight of dry aggregates, whereas the percentage of liquid additives is by the weight of asphalt cement.

Laboratory Mixtures

The asphalt cements, aggregates, liquid antistripping additives, and hydrated lime were obtained at the asphalt mixing plants. In the laboratory these materials were prepared and mixed using the laboratory mixing procedures in accordance with the mixture design established for the plant mixture. The asphalt cement and additive dosages are summarized in Table 3 for the laboratory-prepared mixtures. The laboratory additive dosage levels are essentially the same as those for the plant mixtures. The liquid additives were blended with the

TABLE 1 SUMMARY OF MATERIALS FOR PLANT MIXTURES

Location of Field Project	Aggregates	Asphalt	Asphalt Content, % Field +	Design ++
Dist. 17	.Processed gravel 55% .Washed sand 25% .Coarse sand 10% .Fine sand 10%	.AC-20 .Texas Gulf Refinery	4.9	4.9
Dist. 16	.Field sand 20% .Limestone Screenings 22% .Coarse Limestone 58%	.AC-20 .Gulf States Refinery	5.1	4.3
Dist. 13	.Crushed gravel 50% .Limestone 10% .Limestone screenings 20% .Field Sand 20%	.AC-20 .Texas Fuels & Asphalt Refinery	5.0	5.0
Dist. 6	.Rhyolite 56% .Screening 37% .Field Sand 7%	.AC-20 .American Petrofina Refinery	6.2	6.2
Dist. 25	.Coarse Aggr. 20% .Inter. aggr. 34% .Screening 46%	.AC-20 .Diamond Shamrock Refinery	5.2	5.2
Dist. 1	.Coarse sandstone 55% .Unwashed screenings 30% .Field sand 15%	.AC-20 .Total Petroleum Refinery	5.5	6.0
Dist. 19	.Coarse Aggregate 20% .Inter. Aggregate 40% .Screening 20% .Field sand 20%	.AC-20 .Lion Oil Refinery	5.6	5.3
Dist. 21	.Coarse Aggregate 35% .Uncrushed aggregate 20% .Screening 25% .Field sand 20%	.AC-10 .Texas Fuel & Asphalt Coastal Refinery	5.2	5.2

\+ Actual asphalt content used for the plant mixtures.
++ Laboratory design optimum asphalt content for the mixture design.

TABLE 2 SUMMARY OF ANTISTRIPPING ADDITIVE DOSAGES FOR PLANT-PREPARED MIXTURES

Location of Field Project	Additives	Additive Dosage*, %
District 17	.Control	0
	.Lime	1.5
	.BA 2000	1.0
	.Perma-Tac	1.0
District 16	.Control	0
	.Lime	1.0
	.Aquashield	0.5
	.Dow Anti-Strip	0.41
	.Pavebond LP	0.5
District 13	.Control	0
	.Lime	2.0
	.BA 2000	1.0
	.Perma-Tac Plus	1.0
District 6	.Control	0
	.Lime	1.0
	.Pavebond LP	1.0
	.Perma-Tac	1.0
	.Unichem	0
District 25	.Control	0
	.Lime	1.0
	.Aquashield II	1.0
	.Fina-A	1.0
	.Perma-Tac	1.0
	.Unichem	1.0
District 1	.Control	0
	.Lime	1.5
	.ARR-MAZ	0.75
	.Dow Anti-Strip	0.45
	.Fina-A	1.0
	.Indulin AS-1	1.0
	.Pavebond Special	1.0
	.Perma-Tac Plus	1.0
District 19	.Control	0
	.Lime	1.0
	.ARR-MAZ	1.0
	.Aquashield II	0.8
	.BA 2000	0.5
	.Perma-Tac	1.0
District 21	.Control	0
	.Lime	1.0
	.ARR-MAZ	1.0
	.Aquashield II	0.41
	.Dow Anti-Strip	0.5
	.Fina-B	0.41
	.Pavebond LP	1.0
	.Perma-Tac	1.0

* The percentage of lime is by the total weight of dry aggregates; percentage of liquid additives is by the weight of asphalt cement.

TABLE 3 SUMMARY OF ASPHALT CONTENT AND ADDITIVE DOSAGES FOR LABORATORY-PREPARED MIXTURES

SDHPT District	Additives	Additive Dosage, * %	Asphalt Content,* * %
17	.Control	0	
	.Lime	1.5	4.9
	.BA 2000	1.0	
	.Perma-Tac	1.0	
16	.Control	0	
	.Lime	1.0	
	.Aquashield	0.5	4.3
	.Dow Anti-Strip	0.41	
	.Pavebond LP	0.5	
13	.Control	0	
	.Lime	2.0	5.0
	.BA 2000	1.0	
	.Perma-Tac Plus	1.0	
	.Control	0	
	.Lime	1.0	
6	.Pavebond LP	1.0	6.2
	.Perma-Tac	1.0	
	.Unichem	0	
25	.Control	0	
	.Lime	1.0	
	.Aquashield II	1.0	5.2
	.Fina-A	1.0	
	.Perma-Tac	1.0	
	.Unichem	1.0	
1	.Control	0	
	.Lime	1.5	
	.ARR-MAZ	0.75	
	.Dow Anti-Strip	0.45	6.0
	.Fina-A	1.0	
	.Indulin AS-1	1.0	
	.Pavebond Special	1.0	
	.Perma-Tac Plus	1.0	
19	.Control	0	
	.Lime	1.0	5.3
	.ARR-MAZ	1.0	
	.Aquashield II	0.8	
	.BA 2000	0.5	
	.Perma-Tac	1.0	
21	.Control	0	
	.Lime	1.0	
	.ARR-MAZ	1.0	
	.Aquashield II	0.41	5.2
	.Dow Anti-Strip	0.5	
	.Fina-B	0.41	
	.Pavebond LP	1.0	
	.Perma-Tac	1.0	

* The percentage of hydrated lime is based on the total weight of dry aggregates: the percentage of liquid additive is based on the weight of the asphalt cement.

* * Asphalt content is percent by weight of total mixture.

preheated asphalt; however, the hydrated lime was placed on the aggregates in a slurry form for all of the lime-treated laboratory mixtures. The specimens were compacted using a procedure that produced an air void content of about 7 percent.

Moisture Susceptibility Test Methods

The two basic moisture susceptibility test methods compared were the wet-dry indirect tensile test, often referred to as the Lottman test, and the boiling test. There are, however, variations of the wet-dry indirect tensile test. Thus, the following specific test methods were selected for evaluation.

Wet-Dry Indirect Tensile Test

The indirect tensile test (*1, 2*) was used by Lottman et al. (*3, 4*) for measuring the potential for moisture damage in asphalt mixtures (Figure 2). Subsequently, several techniques for moisture conditioning were developed as modifications of the original Lottman procedure. All methods, however, use the indirect tensile test to determine the tensile strength ratio (*TSR*) of wet and dry specimens as follows:

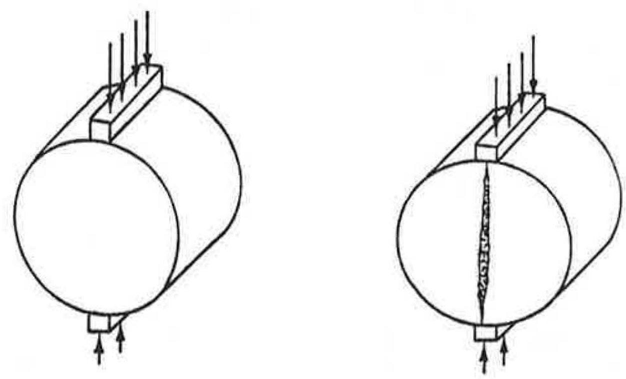
$$TSR = \frac{S_T(\text{Conditioned})}{S_T(\text{Unconditioned})} \tag{1}$$

where S_T is the indirect tensile strength.

The wet-dry indirect tensile test methods selected for evaluation were as follows:

- Tex-531-C method, a modified Lottman (*5*),
- Modified Tex-531-C method,
- Original Lottman method (*3*), and
- Tunnicliff-Root method (*6, 7*).

The test procedures are described below and are summarized in Table 4.



(a) Compressive load being applied. (b) Specimen failing in tension.

FIGURE 2 Indirect tensile test loading and failure.

TABLE 4 SUMMARY OF MOISTURE-CONDITIONING PROCEDURE

	Test Method	
Tex-531-C	Original Lottman	Tunnicliff-Root
.Vacuum saturation to 60-80% filled voids.	.Vacuum saturation using 26-in Hg for 30 min.	.Vacuum saturation to 60-80% filled voids.
.Freezing at 0 F for 15 hours.	.Conditioning at 77 F (water bath) for 30 min.	.Soaking at 140 F (water bath) for 24 hours.
.Thawing at 140 F (water bath) for 24 hours.	.Freezing at 0 F for 15 hours.	.Conditioning at 77 F (water bath) for 3 hours prior to testing.
.Conditioning at 77 F(water bath) for 3 hours prior to testing.	.Thawing at 140 F(water bath) for 24 hours.	
	.Conditioning at 77 F (water bath) for 3 hours prior to testing.	

Tex-531-C Method The test method currently used by the Texas State Department of Highways and Public Transportation (SDHPT), the Tex-531-C method, utilizes laboratory-compacted specimens with air void contents of approximately 7 percent. A group of specimens were prepared and compacted using the design aggregates and asphalt. Half of the specimens were tested dry or unconditioned. The other half were conditioned by vacuum saturation with water. A partial vacuum (approximately 15 to 17 in. of mercury) was applied long enough to achieve a degree of saturation of about 70 percent.

The conditioned specimens were placed in a freezer at 0°F for 15 hr, and then placed in a 140°F water bath for 24 hr. After a complete freeze-thaw cycle, the moisture-conditioned specimens were cooled to room temperature in a 77°F water bath for approximately 3 hr before testing. All of the specimens were tested to determine their indirect tensile strength. The ratio of the conditioned strength to the unconditioned (dry) tensile strength is calculated using Equation 1.

Modified Tex-531-C Method The Tex-531-C method includes a procedure to account for asphalt absorption. This procedure requires an additional 2 days for curing. Thus, it would be desirable to eliminate this extra time. The mixing and compaction procedures of the Tex-531-C method, with cure and without cure, are summarized in Table 5. The conditioning and testing procedures of the compacted specimens were exactly the same as for the Tex-531-C method.

Original Lottman Method In the original Lottman method, the laboratory specimens were fabricated and compacted in the same fashion as for the modified Tex-531-C method. The conditioned specimens, however, were partially saturated under a vacuum of 26 in. of mercury for 30 min rather than for a period of time required to achieve a specified degree of saturation. Subsequently, the wet specimens were placed in a 77°F water bath for 30 min before being subjected to a freeze-thaw cycle. The specimens were frozen at 0°F for 15 hr and then thawed in a 140°F water bath for 24 hr. After a complete freeze-thaw cycle, the wet specimens were cooled to room temperature in a 77°F water bath for approximately 3 hr before testing. All of the wet and dry specimens were then tested to determine their indirect tensile strength.

TABLE 5 SUMMARY OF MIXING AND COMPACTION PROCEDURE

Procedure	Test Method	
	Tex-531-Method with Cure (Method A)	Modified Tex-531-C Method without Cure (Method B)
Mixing	. Mixing at 300 F . Cooling at room temperature for 2.5 hours . Curing at 140 F for 15 hours	. Mixing at 275 F
Molding	. Heating at 250 F for 2 hours . Compacting specimens to 7.0 +/- 1.0% air voids . Cooling the specimens to room temperature	. (Same as Method A)

Tunnicliff-Root Method In the Tunnicliff-Root procedure, the freeze cycle (0°F for 15 hr) used in the Tex-531-C method was eliminated because it was felt that the freeze cycle could cause additional specimen damage over and above that produced by the moisture (*6, 7*). The laboratory specimens were fabricated and compacted to about 7 percent air voids as in the Tex-531-C method. Half of the specimens were partially vacuum-saturated with water to 55 to 80 percent saturation. The conditioned specimens were soaked in a 140°F water bath for 24 hr and then cooled to room temperature in a 77°F water bath for approximately 3 hr before testing. The wet and dry specimens were then tested to determine their indirect tensile strength.

Texas Boiling Test

The Texas boiling test (*5, 8*) involved a visual determination of the extent of stripping of the asphalt from aggregate surfaces after the mixture had been subjected to the action of boiling water for a specified time. To perform this test, an asphalt mixture was prepared at 325°F and boiled in distilled water for 10 min. After boiling, the mixture was allowed to cool, the water was drained, and the mixture was allowed to dry. The mix was examined the following day to estimate the degree of stripping present in the mixture. The stripping test results were reported as the percentage of asphalt retained after boiling.

Laboratory Testing Program

Moisture susceptibility tests were performed on both the laboratory and plant mixtures. The following tests were conducted on all laboratory mixtures:

- Four wet-dry indirect tensile test methods, and
- Texas boiling test.

Because in plant-prepared mixtures no option exists to account for curing, the procedure is the same with or without cure. Thus, the following tests were used for the plant-mixed and laboratory-compacted samples:

- Three of the wet-dry indirect tensile tests, and
- Texas boiling test.

The treated and untreated mixtures were compacted in the laboratory, and the specimens were prepared for the dry and/or wet conditioning. Eighteen laboratory-mixed and 12 plant-mixed specimens were prepared for each treatment (or control). Any of the specimens that had air voids outside the 6 to 8 percent range were discarded, and new specimens were prepared and compacted.

The Texas boiling test was performed on the loose laboratory-prepared mixtures and the reheated plant mixtures.

Engineering Properties Analyzed

The engineering properties analyzed were the indirect tensile strength, tensile strength ratio, and percentage of asphalt retained (boil test).

Tensile Strength

The indirect tensile strength is the maximum tensile stress the specimen can withstand. For 4-in.-diameter specimens and the load-deformation information obtained from the static test, tensile strength can be calculated from the following relationship:

$$S_T = \frac{0.156P}{t} \tag{2}$$

where

S_T = tensile strength (psi),
P = the maximum load carried by the specimen (lb), and
t = thickness or height of the specimen (in.).

Tensile Strength Ratio

The tensile strength ratio was defined in Equation 1.

Boil Value

The boiling test value is expressed as the percentage of asphalt retained after boiling. The value is visually estimated by two independent operators according to the degree of stripping present in the mixture.

EXPERIMENTAL RESULTS

The test results obtained for the laboratory-prepared mixtures and the plant-mixed/laboratory-compacted mixtures are summarized as follows.

Wet-Dry Indirect Tensile Test Results

Laboratory Mixture

The four test methods (Tex-531-C with cure, Tex-531-C without cure, original Lottman, and Tunnicliff-Root) were conducted for the laboratory mixture. Tensile strength ratios (TSRs) were obtained for these test methods by dividing the average tensile strength of the three wet specimens by the average tensile strength of the three dry specimens. These TSR values are summarized in Table 6.

Plant Mixture

Three test methods (Tex-531-C without cure, original Lottman, and Tunnicliff-Root) were used to evaluate the plant mixture. TSRs were obtained for these test methods by dividing the average tensile strength of the three wet specimens by the average tensile strength of the three dry specimens. These TSR values are summarized in Table 7.

Texas Boiling Test Results

Laboratory Mixture

For the boiling test, the boiled mixture was allowed to dry and examined the following day. The percentage of asphalt retained after boiling was estimated independently by two operators at different times. The average value of the two ratings was reported as the degree of stripping present in the mixture. The test results are summarized in Table 8.

Plant Mixture

Representative loose plant mixtures were used for the boiling test. The same procedure was followed as described for the laboratory mixture. These test results are also summarized in Table 8.

Comparison of Moisture Damage Test Values

Because of the concern with asphalt absorption during the mixing stage of sample preparation in the laboratory, the effect of curing on the moisture susceptibility of the laboratory mixture was analyzed and is discussed first here for the modified Lottman (Tex-531-C) procedure.

Effect of Curing for Modified Lottman (Tex-531-C) Procedure

The results from the Tex-531-C method with and without cure are compared in Figures 3–10 for the eight projects. Test values from the Tex-531-C method with cure and the Tex-531-C method without cure are essentially equal with the exception of the values for lime-treated material in District 19. The test values for all laboratory mixtures are compared in Figure 11. These data indicate that curing the laboratory mixtures does not have a significant effect on the estimated moisture susceptibility values (TSR values). Thus, the time required for testing in the laboratory can possibly be shortened significantly. The linear regression relationship between the two sets of TSR values approximates the line of equality, and the R^2 value of .86 indicates a reasonably good correlation.

TABLE 6 SUMMARY OF TSR TEST RESULTS FOR LABORATORY MIXTURES

District	Additive Name	Tensile Strength Ratio (TSR) Tex-531-C with Cure	Tex-531-C w/o Cure	Original Lottman	Tunnicliff-Root
	No Additive	0.51	0.51	0.47	0.52
17	Lime	1.18	1.19	1.12	1.23
	BA 2000	0.82	0.96	0.88	1.09
	Perma-Tac	0.82	0.94	0.91	0.97
	No Additive	0.44	0.47	0.44	0.53
	Lime	0.74	0.83	0.77	0.93
16	Aquashield	0.56	0.62	0.60	0.70
	Dow	0.53	0.58	0.45	0.68
	Pavebond LP	0.60	0.55	0.57	0.67
	No Additive	0.43	0.55	0.53	0.70
13	Lime	1.42	1.27	1.22	1.26
	BA 2000	0.64	0.66	0.79	0.29
	Perma-Tac	0.61	0.69	0.78	0.88
	No Additive	0.20	0.23	0.15	0.32
	Lime	0.78	0.62	0.58	0.78
6	Pavebond LP	0.40	0.35	0.26	0.42
	Perma-Tac	0.49	0.37	0.30	0.42
	Unichem	0.37	0.42	0.30	0.54
	No Additive	0.67	0.62	0.46	0.64
	Lime	1.30	1.23	0.93	1.07
25	Aquashield II	1.19	1.23	0.82	1.01
	Fina-A	0.98	1.18	0.82	1.01
	Perma-Tac	1.03	0.97	0.70	0.86
	Unichem	0.92	1.02	0.72	0.87
	No Additive	0.74	0.96	0.80	1.01
	Lime	1.06	1.22	1.14	1.24
	ARR-MAZ	1.14	1.26	1.14	1.29
1	Dow	0.70	0.85	0.82	0.95
	Fina-A	1.10	1.10	1.10	1.20
	Indulin AS-1	1.07	1.14	1.17	1.22
	PVBD Special	1.21	1.37	1.50	1.42
	Perma-Tac Plus	1.15	1.15	0.94	1.13
	No Additive	1.12	1.07	0.93	0.98
	Lime	1.07	1.53	1.45	1.64
19	ARR-MAZ	1.19	1.09	0.99	1.20
	Aquashield II	1.25	1.24	1.11	1.36
	BA2000	1.16	1.07	1.22	1.30
	Perma-Tac	0.93	1.17	1.03	1.03
	No Additive	0.24	0.28	0.22	0.77
	Lime	1.04	1.06	1.04	21.07
	ARR-MAZ	0.52	0.48	0.39	0.55
21	Aquashield II	0.73	0.76	0.54	0.74
	Dow	0.35	0.37	0.30	0.37
	Fina-B	0.45	0.88	0.59	0.78
	Pavebond LP	0.51	0.55	0.53	0.58
	Perma-Tac	0.47	0.52	0.39	0.49

TABLE 7 SUMMARY OF TSR TEST RESULTS FOR PLANT-MIXED/ LABORATORY-COMPACTED MIXTURES

		Tensile Strength Ratio (TSR)		
District	Additive Name	Tex-531-C Method	Original Lottman	Tunnicliff-Root
17	No Additive	0.64	0.51	0.61
	Lime	1.18	1.01	1.09
	BA 2000	1.07	0.98	1.01
	Perma-Tac	0.51	0.43	0.50
16	No Additive	0.79	0.72	0.87
	Lime	1.02	0.87	1.01
	Aquashield	0.87	0.76	0.87
	Dow	0.75	0.72	0.87
	Pavebond LP	0.77	0.75	0.90
13	No Additive	1.03	1.02	0.98
	Lime	1.03	1.02	0.97
	BA 2000	1.08	0.96	0.99
	Perma-Tac	1.00	0.98	0.96
6	No Additive	0.47	0.38	0.54
	Lime	0.54	0.43	0.66
	Pavebond LP	0.83	0.66	0.80
	Perma-Tac	0.78	0.65	0.85
	Unichem	0.64	0.61	0.78
25	No Additive	0.60	0.44	0.64
	Lime	0.89	0.76	0.90
	Aquashield II	0.60	0.48	0.63
	Fina-A	0.85	0.79	0.96
	Perma-Tac	0.76	0.63	0.76
	Unichem	0.75	0.67	0.78
1	No Additive	1.06	0.97	1.07
	Lime	1.12	1.27	1.12
	ARR-MAZ	1.10	1.23	1.16
	Dow	0.97	0.95	0.96
	Fina-A	1.12	1.20	1.15
	Indulin AS-1	1.10	1.22	1.19
	PVBD Special	1.15	1.24	1.19
	Perma-Tac Plus	1.02	1.07	1.12
19	No Additive	0.73	0.75	0.80
	Lime	1.11	1.16	1.21
	ARR-MAZ	1.12	1.08	1.08
	Aquashield II	1.16	1.24	1.17
	BA 2000	1.21	1.26	1.27
	Perma-Tac	1.01	1.14	1.15
21	No Additive	0.23	0.28	0.26
	Lime	0.17	0.19	0.19
	ARR-MAZ	0.39	0.41	0.40
	Aquashield II	0.47	0.53	0.50
	Dow	0.30	0.30	0.29
	Fina-B	0.56	0.65	0.56
	Pavebond LP	0.51	0.59	0.51
	Perma-Tac	0.42	0.49	0.44

TABLE 8 SUMMARY OF TEXAS BOILING TEST RESULTS

District	Additive Name	Asphalt Retained After Boiling, %	
		Lab Mix	Plant Mix
	No Additive	50.0	52.5
17	Lime	85.0	94.0
	BA 2000	92.5	92.5
	Perma-Tac	90.0	50.0
	No Additive	77.5	82.5
	Lime	75.0	82.5
16	Aquashield	77.5	85.0
	Dow	77.5	85.0
	Pavebond LP	77.5	85.0
	No Additive	77.5	77.5
13	Lime	96.5	96.5
	BA 2000	97.5	96.5
	Perma-Tac	96.5	95.0
	No Additive	50.0	70.0
	Lime	72.5	72.5
6	Pavebond LP	60.0	85.0
	Perma-Tac	65.0	80.0
	Unichem	67.5	85.0
	No Additive	50.0	77.5
	Lime	85.0	87.5
25	Aquashield II	96.5	77.5
	Fina-A	94.0	94.0
	Perma-Tac	90.0	92.5
	Unichem	94.0	87.5
	No Additive	82.5	90.0
	Lime	92.5	92.5
	ARR-MAZ	90.0	97.5
1	Dow	82.5	91.5
	Fina-A	92.5	95.0
	Indulin AS-1	92.5	96.5
	PVBD Special	92.5	95.0
	Perma-Tac Plus	92.5	95.0
	No Additive	85.0	85.0
	Lime	94.0	90.0
19	ARR-MAZ	92.5	90.0
	Aquashield II	92.5	94.0
	BA 2000	92.5	96.5
	Perma-Tac	92.5	90.0
	No Additive	37.5	25.0
	Lime	81.0	37.5
	ARR-MAZ	55.0	57.5
21	Aquashield II	77.5	67.5
	Dow	57.5	52.5
	Fina-B	80.0	75.0
	Pavebond LP	65.0	67.5
	Perma-Tac	55.0	61.0

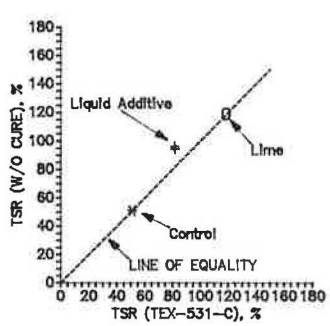


FIGURE 3 Effect of curing on TSR values for Tex-531-C procedure, District 17 (river gravel aggregate).

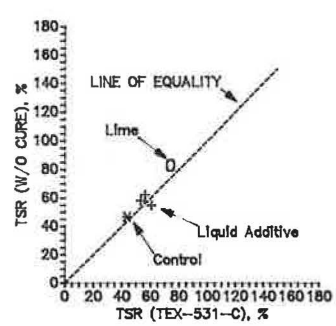


FIGURE 4 Effect of curing on TSR values for Tex-531-C procedure, District 16 (limestone aggregate).

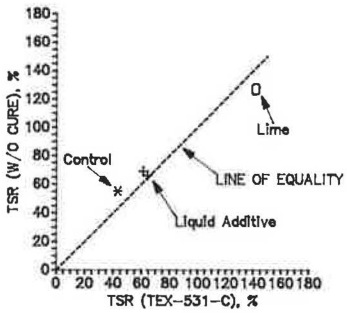


FIGURE 5 Effect of curing on TSR values for Tex-531-C procedure, District 13 (crushed gravel aggregate).

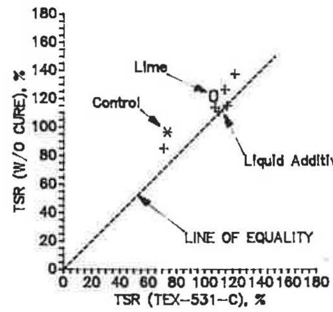


FIGURE 8 Effect of curing on TSR values for Tex-531-C procedure, District 1 (crushed sandstone aggregate).

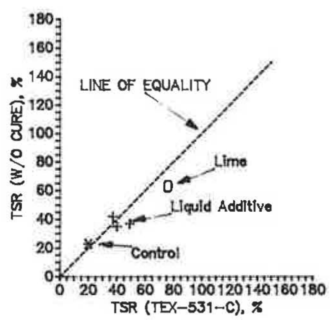


FIGURE 6 Effect of curing on TSR values for Tex-531-C procedure, District 6 (rhyolite aggregate).

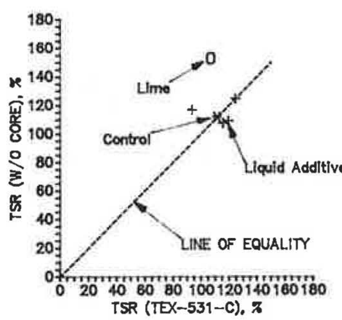


FIGURE 9 Effect of curing on TSR values for Tex-531-C procedure, District 19 (crushed gravel aggregate).

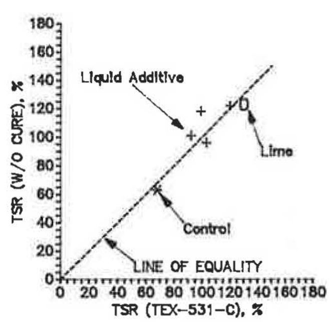


FIGURE 7 Effect of curing on TSR values for Tex-531-C procedure, District 25 (crushed gravel aggregate).

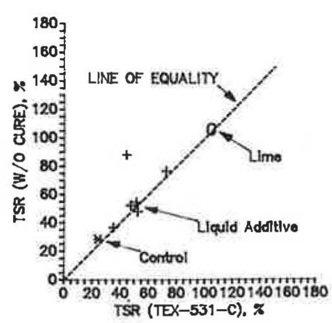


FIGURE 10 Effect of curing on TSR values for Tex-531-C procedure, District 21 (crushed gravel aggregate).

Comparison of Tensile Strength Ratios

The TSR values obtained using the various wet-dry indirect tensile test methods were evaluated and compared.

Comparisons of the TSR values for laboratory mixtures are shown in Figures 12–19 for the modified Lottman (Tex-531-C), the original Lottman, and the Tunnicliff-Root test methods. All tests were compared to the modified Lottman procedure used by the Texas SDHPT. As shown in the figures, the original Lottman test procedure was more severe than the other test methods evaluated as evidenced by the lower TSR values. The TSR values for the Tunnicliff-Root procedure tended to be approximately equal to or slightly less than the TSR values for the modified Lottman procedure.

For the plant mixture, the results were similar to the results obtained for the laboratory mixtures (Figures 20–27). Thus, the test methods, ranked in decreasing order of severity are as follows:

1. Original Lottman,
2. Modified Lottman, and
3. Tunnicliff-Root.

The severity of the original Lottman test is attributed to the high degree of saturation of the specimens produced by

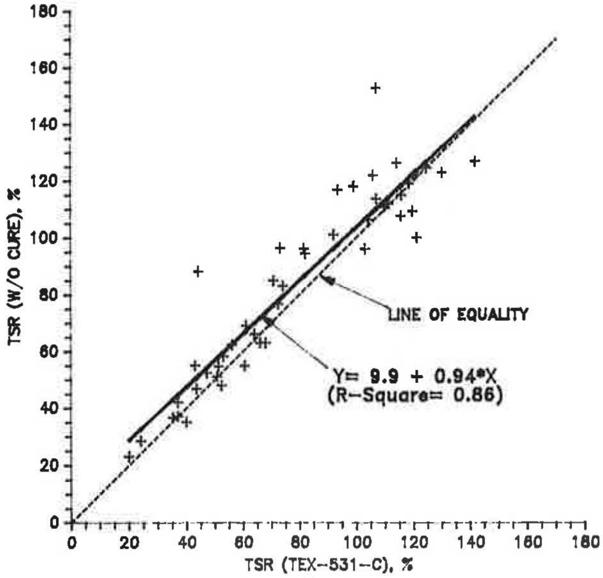


FIGURE 11 Effect of curing on TSR values for Tex-531-C procedure, all projects.

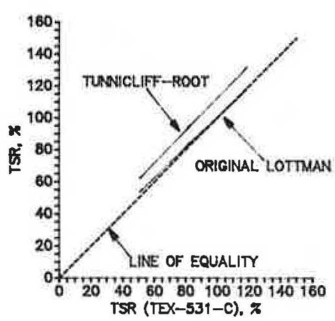


FIGURE 12 Comparison of TSR values for laboratory mixtures, District 17 (river gravel aggregate).

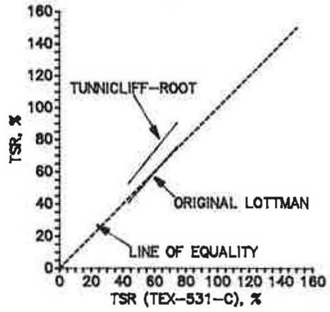


FIGURE 13 Comparison of TSR values for laboratory mixtures, District 16 (limestone aggregate).

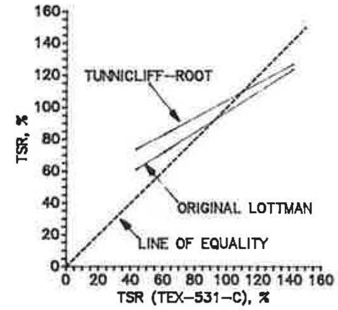


FIGURE 14 Comparison of TSR values for laboratory mixtures, District 13 (crushed gravel and limestone).

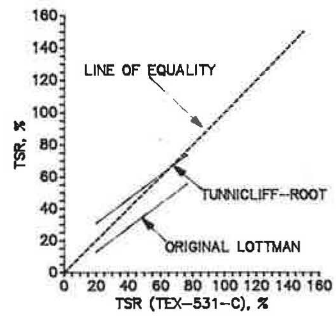


FIGURE 15 Comparison of TSR values for laboratory mixtures, District 6 (rhyolite aggregate).

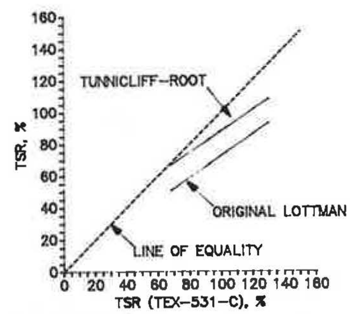


FIGURE 16 Comparison of TSR values for laboratory mixtures, District 25 (crushed gravel aggregate).

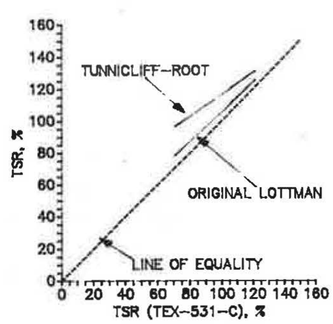


FIGURE 17 Comparison of TSR values for laboratory mixtures, District 1 (crushed sandstone aggregate).

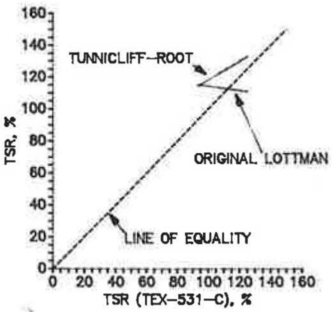


FIGURE 18 Comparison of TSR values for laboratory mixtures, District 19 (crushed gravel aggregate).

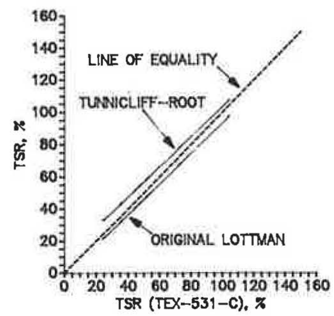


FIGURE 19 Comparison of TSR values for laboratory mixtures, District 21 (crushed gravel aggregate).

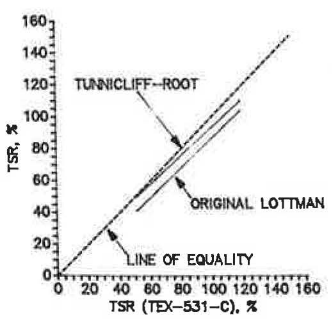


FIGURE 20 Comparison of TSR values for plant mixtures, District 17 (river gravel aggregate).

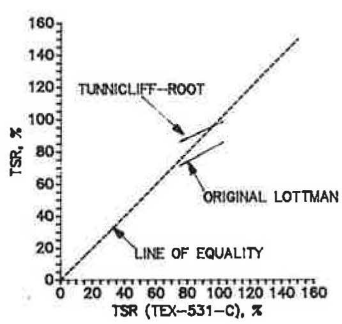


FIGURE 21 Comparison of TSR values for plant mixtures, District 16 (limestone aggregate).

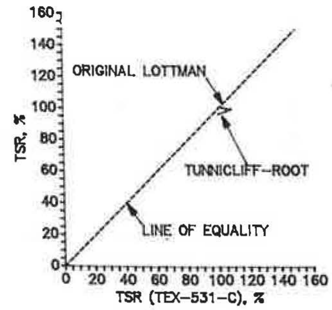


FIGURE 22 Comparison of TSR values for plant mixtures, District 13 (crushed gravel and limestone).

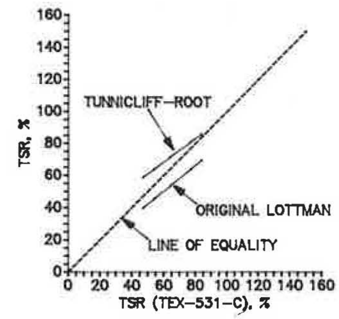


FIGURE 23 Comparison of TSR values for plant mixtures, District 6 (rhyolite aggregate).

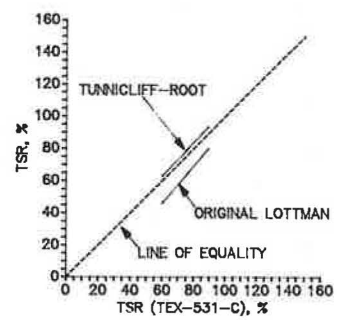


FIGURE 24 Comparison of TSR values for plant mixtures, District 25 (crushed gravel aggregate).

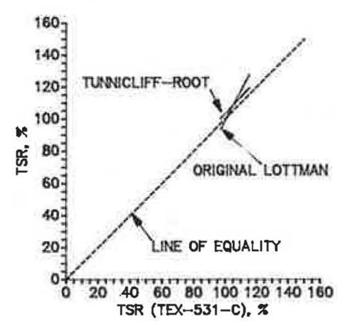


FIGURE 25 Comparison of TSR values for plant mixtures, District 1 (crushed sandstone aggregate).

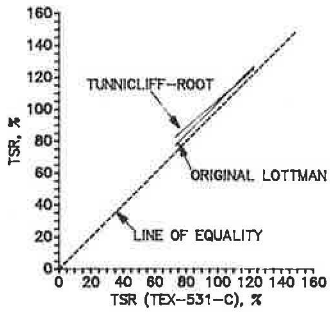


FIGURE 26 Comparison of TSR values for plant mixtures, District 19 (crushed gravel aggregate).

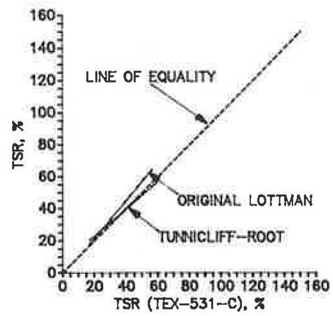


FIGURE 27 Comparison of TSR values for plant mixtures, District 21 (crushed gravel aggregate).

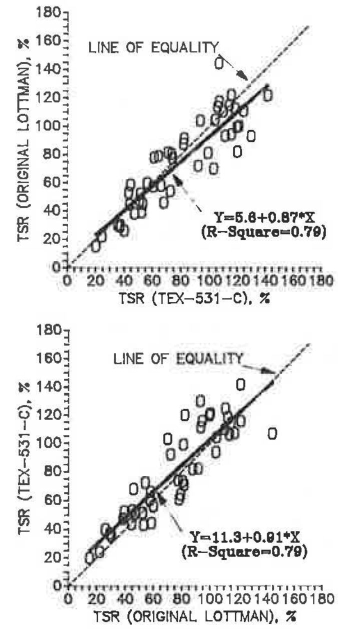


FIGURE 28 Correlation of original Lottman TSR values with Tex-531-C TSR values, laboratory mixtures.

the vacuum saturation procedure. In the modified Lottman test (Tex-531-C), the degree of saturation is controlled between 60 and 80 percent and thus results in less damage. In the Tunnicliff-Root method, the degree of saturation is also controlled between 55 and 80 percent, but no freeze cycle is used, and the specimens are conditioned with only a warm (140°F) water bath; thus, damage due to freezing is eliminated.

Correlations of TSR Values with Modified Lottman TSR Values

Laboratory Mixtures The laboratory mixture TSR values for the original Lottman and Tunnicliff-Root methods were correlated with the modified Lottman (Tex-531-C) TSR values as shown in Figures 28 and 29. For each comparison (e.g., the original Lottman versus the modified Lottman) there are two correlation relationships shown for the two sets of data. One regresses the original Lottman data on the modified Lottman data. The other regresses the modified Lottman data on the original Lottman data. These correlations are reasonably good. The R^2 values range from .67 to .79.

Plant Mixtures The TSR values for the original Lottman and Tunnicliff-Root procedures are compared with the modified Lottman TSR values as shown in Figures 30 and 31. For each comparison, two regression equations are shown as previously discussed. The R^2 values are very high, ranging from .91 to .95. Excellent correlations are obtained between the original Lottman, the Tunnicliff-Root, and the modified Lottman methods for the plant mixtures.

Laboratory and Plant Mixtures Combining the TSR values from the laboratory and plant mixtures for all eight proj-

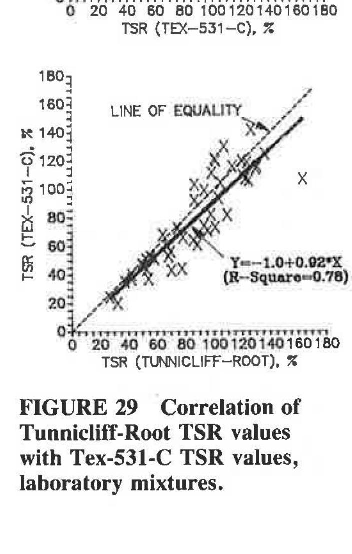


FIGURE 29 Correlation of Tunnicliff-Root TSR values with Tex-531-C TSR values, laboratory mixtures.

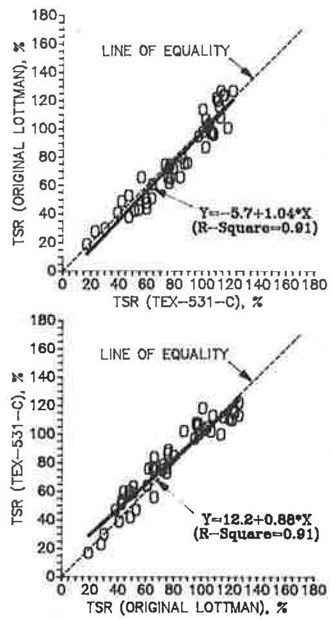


FIGURE 30 Correlation of original Lottman TSR values with Tex-531-C TSR values, plant mixtures.

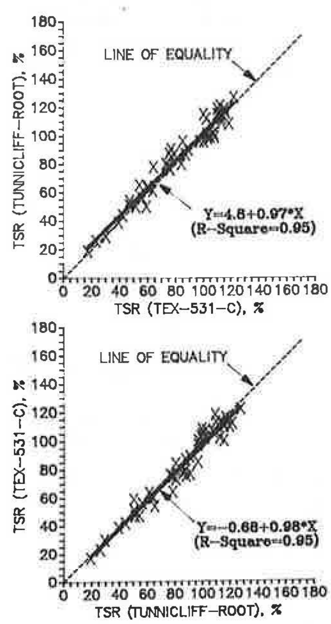


FIGURE 31 Correlation of Tunnicliff-Root TSR values with Tex-531-C TSR values, plant mixtures.

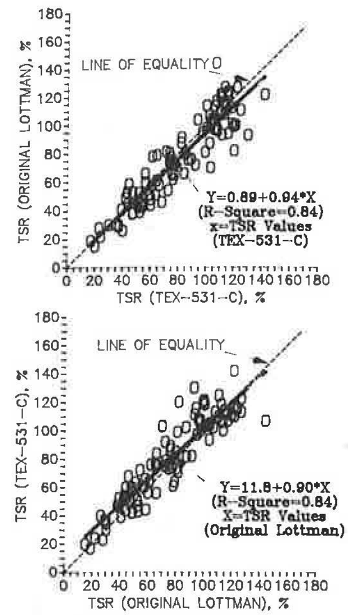


FIGURE 32 Correlation of original Lottman TSR values with Tex-531-C TSR values, all projects.

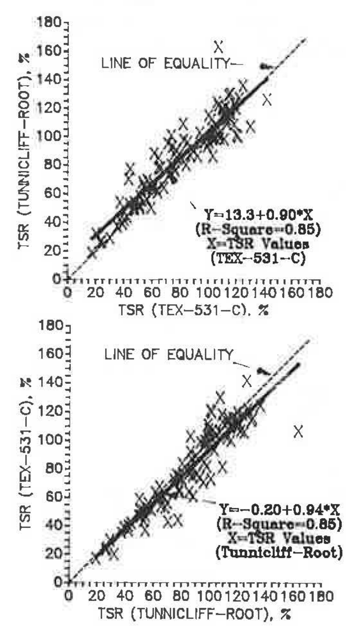


FIGURE 33 Correlation of Tunnicliff-Root TSR values with Tex-531-C TSR values, all projects.

ects produces correlations between the TSR values for both the original Lottman and Tunnicliff-Root procedures and the modified Lottman values, as shown in Figures 32 and 33. The correlation equations are also summarized in Table 9 for the comparisons between the original Lottman, the Tunnicliff-Root, and the modified Lottman methods. Good correlations appear, with the R^2 values ranging from .84 to .85. Therefore, the TSR values for the modified Lottman procedure can be estimated using the TSR values obtained from either the original Lottman or the Tunnicliff-Root procedures, and vice versa, according to the equations in Table 9.

Comparison of Boil Values with TSR Values

Two types of correlations were developed between the boiling test results and the TSR values; the first regresses the TSR values on the boil values (Figures 34–37 and 38–40), and the

TABLE 9 SUMMARY OF CORRELATION EQUATIONS OF TSR VALUES FOR VARIOUS TEST METHODS

Correlation	Correlation Equation	R^2 Value
Original Lottman	C (TSR) = 0.89 + 0.94*A(TSR)	0.84
vs.	or	
Modified Lottman	A (TSR) = 11.8 + 0.90*C(TSR)	0.84
Tunnicliff-Root	D (TSR) = 13.3 + 0.90*A(TSR)	0.85
vs.	or	
Modified Lottman	A (TSR) = 0.20 + 0.94*D(TSR)	0.85

A(TSR) = TSR values of the modified Lottman (Tex-531-C) method, %
C(TSR) = TSR values of the original Lottman method, %
D(TSR) = TSR values of the Tunnicliff-Root method, %

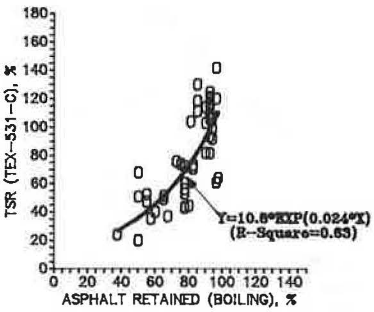


FIGURE 34 Correlation of Tex-531-C TSR values with boiling test results, laboratory mixtures.

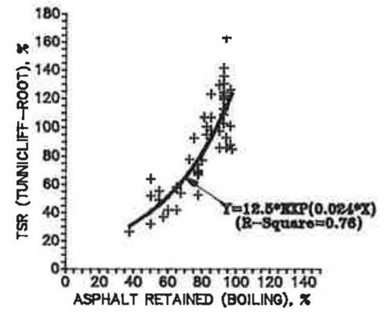


FIGURE 37 Correlation of Tunnicliff-Root TSR values with boiling test results, laboratory mixtures.

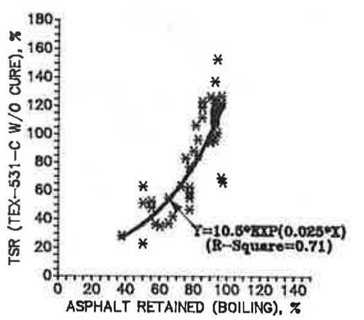


FIGURE 35 Correlation of Tex-531-C (without cure) TSR values with boiling test results, laboratory mixtures.

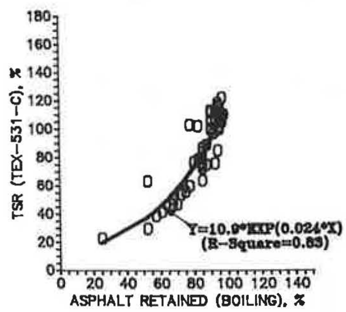


FIGURE 38 Correlation of boiling test results with Tex-531-C TSR values, plant mixtures.

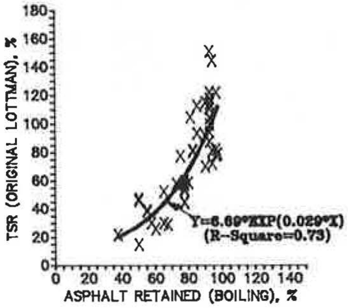


FIGURE 36 Correlation of original Lottman TSR values with boiling test results, laboratory mixtures.

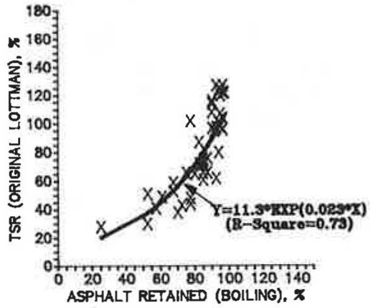


FIGURE 39 Correlation of boiling test results with original Lottman TSR values, plant mixtures.

second regresses the boil values on the TSR values (Figures 41–44 and 45–47). The correlation relationships were developed using the logarithmic transformation of the TSR data and correlating it with the boil values using linear regression.

Laboratory Mixtures The relationships between the boiling test results and each of the three TSR test methods for the laboratory mixture are shown in Figures 34–37 and 41–44. The R^2 values range from .63 to .76.

Plant Mixtures The relationships between the boiling test results and each of the three TSR test methods are shown

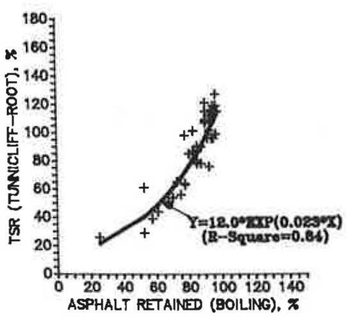


FIGURE 40 Correlation of boiling test results with Tunnicliff-Root TSR values, plant mixtures.

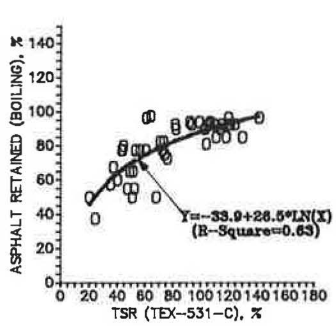


FIGURE 41 Correlation of Tex-531-C TSR values with boiling test results, laboratory mixtures.

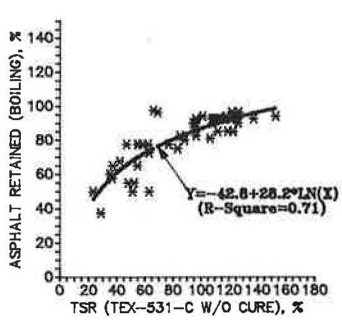


FIGURE 42 Correlation of Tex-531-C (without cure) TSR values with boiling test results, laboratory mixtures.

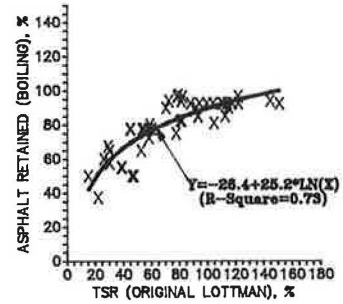


FIGURE 43 Correlation of original Lottman TSR values with boiling test results, laboratory mixtures.

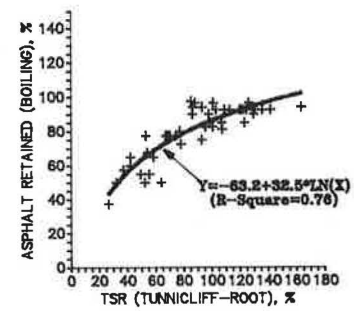


FIGURE 44 Correlation of Tunnicliff-Root TSR values with boiling test results, laboratory mixtures.

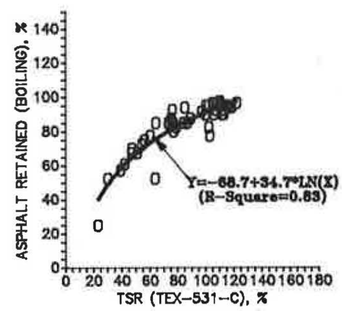


FIGURE 45 Correlation of Tex-531-C TSR values with boiling test results, plant mixture.

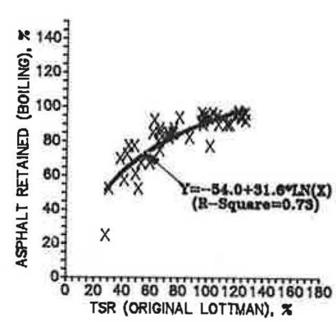


FIGURE 46 Correlation of original Lottman TSR values with boiling test results, plant mixtures.

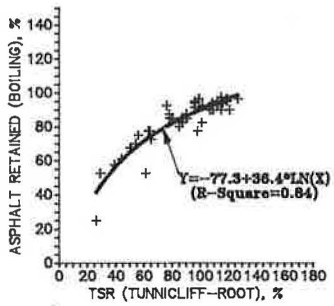


FIGURE 47 Correlation of Tunnicliff-Root TSR values with boiling test results, plant mixtures.

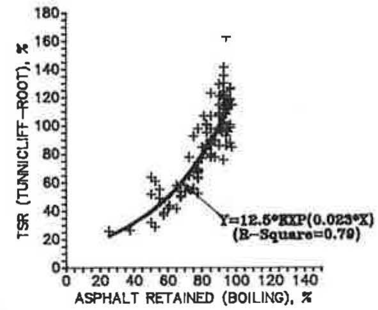


FIGURE 50 Correlation of boiling test results with Tunnicliff-Root TSR values, all projects.

in Figures 38–40 and 45–47. The R^2 values range from .73 to .84.

Laboratory and Plant Mixtures The correlations between the boiling test results and the TSR values were developed using the test values from both the laboratory and plant mixtures for all eight projects. The first type of correlation is shown in Figures 48–50, and the second type is shown in Figures 51–53 for each of the three TSR test methods. The R^2 values range from .71 to .79. Therefore, the correlations are reasonably good between the TSR values and the boil values using the logarithmic transformation of the TSR data.

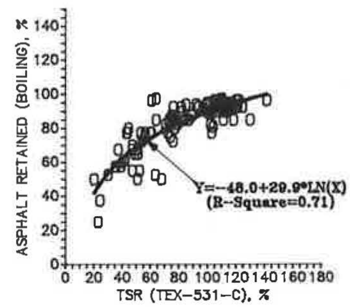


FIGURE 51 Correlation of Tex-531-C TSR values with boiling test results, all projects.

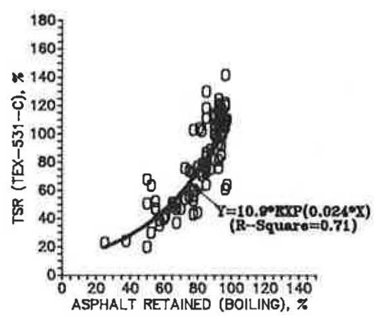


FIGURE 48 Correlation of boiling test results with Tex-531-C TSR values, all projects.

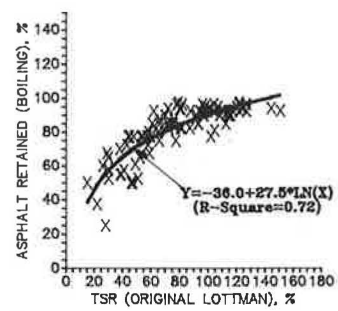


FIGURE 52 Correlation of original Lottman TSR values with boiling test results, all projects.

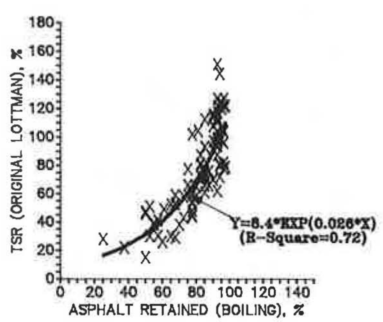


FIGURE 49 Correlation of boiling test results with original Lottman TSR values, all projects.

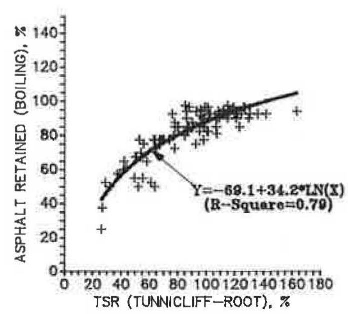


FIGURE 53 Correlation of Tunnicliff-Root TSR values with boiling test results, all projects.

CONCLUSIONS

The conclusions based on the data and analyses from this study are summarized.

- The moisture susceptibility test methods in the decreasing order of severity were as follows:

  1. Original Lottman method,
  2. Tex-531-C method, and
  3. Tunnicliff-Root method.

- Good correlations were obtained between the TSR values of the modified Lottman and both the original Lottman and the Tunnicliff-Root procedures. The R^2 values ranged from .84 to .85.
- With regard to the asphalt absorption during the mixing stage of sample preparation in the laboratory, the effect of curing on TSR values specified by the modified Lottman procedure was not significant. Thus, the time required for testing moisture damage could possibly be shortened significantly.
- The correlations between the boiling test results and the TSR values were reasonably good. The R^2 values ranged from .71 to .79.
- Because the various test methods produce different levels of damage as measured by the tensile strength ratios, the acceptance criteria should be different for evaluating the moisture damage potential of asphalt-aggregate mixtures.

ACKNOWLEDGMENTS

Funding for this research was provided by the Texas SDHPT and FHWA. The study was conducted at the Center for Transportation Research of the University of Texas, Austin. The research reported here was part of the second author's Ph.D. dissertation on the evaluation of stripping and moisture damage in asphalt pavements.

REFERENCES

1. T. W. Kennedy. Characterization of Asphalt Pavement Materials Using the Indirect Tensile Test. *Proc., Association of Asphalt Paving Technologists*, Vol. 46, 1977.
2. J. N. Anagnos and T. W. Kennedy. *Practical Method for Conducting the Indirect Tensile Test.* Research Report 98-10. Center for Highway Research, University of Texas, Austin, Aug. 1972.
3. R. P. Lottman. *Predicting Moisture-Induced Damage to Asphalt-Concrete.* Report 192. NCHRP, 1978.
4. R. P. Lottman. Laboratory Test Method for Predicting Moisture-Induced Damage to Asphalt Concrete. In *Transportation Research Record 843*, TRB, National Research Council, Washington, D.C., 1982.
5. *Manual of Testing Procedures.* Bituminous Section. Texas State Department of Highways and Public Transportation, Austin, 1983.
6. D. G. Tunnicliff and R. E. Root. Antistripping Additives in Asphalt Concrete for Effectiveness of Antistripping Additives. *Proc., Association of Asphalt Paving Technologists*, Vol. 53, 1983.
7. D. G. Tunnicliff and R. E. Root. *NCHRP Report 274: Use of Antistripping Additives in Asphaltic Concrete Mixtures—Laboratory Phase.* TRB, National Research Council, Washington, D.C., 1984.
8. T. W. Kennedy, F. L. Roberts, and K. W. Lee. Evaluating Moisture Susceptibility of Asphalt Mixtures Using the Texas Boiling Test. In *Transportation Research Record 968*, TRB, National Research Council, Washington, D.C., 1984.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Materials.