

curacy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. E.H. Green and F.V. Montgomery. Coated Chippings for Rolled Asphalt. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 456, 1972.
2. J.F. Nixon. Sprinkle Treatment of Asphalt Concrete in England or "Chipping Asphalt." Texas State Department of Highways and Public Transportation, Austin, Rept. SS20.1, Aug. 1976.
3. C.H. Hughes, Sr., and J.A. Epps. Sprinkle Treatment: How, Why, and Where. Texas State Department of Highways and Public Transportation, Austin, and Texas Transportation Institute, Texas A&M Univ., College Station, Cooperative Res. Project 2-0-74-214, Dec. 1975.
4. J.F. Nixon, T.R. Kennedy, D. Husatace, and J. Underwood. Sprinkle Treatment for Skid Resistant Surfaces. Texas State Department of Highways and Public Transportation, Austin, Res. Rept. 510-1F, Dec. 1976.
5. T.R. Kennedy. Sprinkle Mix Experience in the State of Virginia. Texas State Department of Highways and Public Transportation, Austin, Rept. SS20.3, Sept. 1976.
6. C.L. Huisman and L. Zearley. Evaluation of 1977 Iowa Asphaltic Concrete Sprinkle Treatments. FHWA, Rept. FHWA-DP-50-1, June 1978 and May 1981.
7. W.L. Russell. The Uniformity of Distribution of Coated Chippings by Mechanical Spreaders. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 83, 1967.
8. J.P. Underwood. Sprinkle Treatment Placement: IH 20, Roscoe, Texas. FHWA, Rept. FHWA-DP-50-6a, Feb. 1981.
9. Federal-Aid Highway Program Manual. FHWA, Vol. 6, Chapter 2, Section 4, Subsection 3, 1973.
10. Energy Requirements for Roadway Pavement. The Asphalt Institute, College Park, MD, Nov. 1979.

Publication of this paper sponsored by Committee on Characteristics of Bituminous-Aggregate Combinations to Meet Surface Requirements.

Notice: The Transportation Research Board does not endorse products or manufacturers. Trade and manufacturers' names appear in this paper because they are considered essential to its object.

Evaluation of Moisture Effects on Asphalt Concrete Mixtures

THOMAS W. KENNEDY, FREDDY L. ROBERTS, AND KANG W. LEE

Water-induced damage of asphalt concrete mixtures has produced serious pavement distress, poor pavement performance, and increased pavement maintenance in the United States as well as in other areas of the world. This damage is mainly attributable to stripping of asphalt cement from aggregate and, in some cases, possibly to softening of the asphalt matrix. In an attempt to reduce the magnitude of the problem, various antistripping additives have been incorporated into asphalt mixtures. Unfortunately, there has been no way to evaluate their potential effectiveness or to evaluate proposed aggregate-asphalt combinations to determine their water susceptibility. Research results that describe how to determine the extent, nature, and severity of moisture-related damage to asphalt concrete mixtures used in pavements are presented. In addition, the causes of mechanisms that cause deterioration are discussed and related to those mixture and environmental factors associated with moisture damage. Included are evaluations of several testing techniques used to distinguish between aggregate-asphalt combinations that are susceptible to moisture damage and those that are not. Test methods included (a) the indirect tensile test on dry and wet cylindrical specimens, (b) the Texas freeze-thaw pedestal test, and (c) the Texas boiling test. Results of these evaluations show that both the Texas freeze-thaw pedestal test and the boiling test can be used to differentiate between known stripping and nonstripping asphalt mixtures. In addition, the tests can be used to evaluate the individual components of mixtures to determine which are water susceptible. A discussion is also presented of the most common treatments considered for use in alleviating the adverse moisture effects on pavement, adding antistripping agents or lime slurry, and pretreating stripping-prone aggregates. It is recommended that the Texas boiling test, which is simple and easy to conduct, be used for initial short-term screening and the Texas freeze-thaw pedestal test be used for final and long-term evaluations. However, if the mixture has high air voids content, it should be evaluated by using the indirect tensile test on dry and wet specimens.

Moisture-induced damage of asphalt concrete mixtures has produced serious distress, reduced performance

and safety, and increased pavement maintenance in the United States as well as in other areas in the world. This damage is attributable to stripping of asphalt cement from aggregate and possibly, in some cases, to softening of the asphalt cement (1). Unfortunately, there has been no reliable way to evaluate proposed aggregate-asphalt combinations to determine their water susceptibility.

In response to this problem, the Center for Transportation Research (CTR) and the Texas State Department of Highways and Public Transportation (TSDHPT) through their cooperative research program initiated a project to study water-induced damage to asphalt mixtures in Texas. This study included an evaluation both of proposed test methods for ascertaining the water susceptibility of asphalt concrete mixtures and of the effectiveness of antistripping additives.

Several testing techniques were selected to determine whether they could accurately identify asphalt mixtures that are moisture susceptible. The tests finally selected for detailed laboratory evaluation and development were (a) the indirect tensile test on dry and wet specimens, (b) the Texas freeze-thaw pedestal test, and (c) the Texas boiling test.

The indirect tensile test was developed by Anagnos and Kennedy (2) and has been used extensively to characterize asphalt materials. The Texas freeze-thaw pedestal test (3) is based on a procedure suggested by Plancher (4). The Texas boiling test (5) is a synthesis of the several boiling tests

used by several state agencies, including one from TSDHPT.

The test procedures and the findings of studies to evaluate the effectiveness of these testing techniques are summarized in this paper.

MOISTURE-INDUCED DAMAGE OF ASPHALT CONCRETE MIXTURES

The moisture-induced damage of asphalt concrete mixtures may show up in several forms of distress on flexible pavements. These distresses can be categorized by the mode of failure as follows (6):

1. Stripping is the physical separation of the asphalt cement and the aggregate produced by the loss of adhesion between the asphalt cement and aggregate surface, primarily due to the action of water or water vapor. The stripping is accentuated by the presence of aggregate surface coatings and smooth aggregate surface texture.

2. Softening is a general loss of stability of a mixture due to a loss of cohesion caused by the action of moisture within the asphalt or asphalt matrix.

PRACTICES TO LIMIT WATER DAMAGE

Antistripping Additives

During recent years, various antistripping additives have been incorporated into asphalt mixtures to reduce the magnitude of the stripping problem. Suitable additives are blended with the bituminous binder before the mixing operation. These chemical antistripping additives act as surfactants and allow the asphalt in the presence of mechanical agitation to coat the aggregate particles more evenly and, at the same time, to displace adsorbed water on or near the surface of aggregate particles (1).

Tentative test results indicate that additives may be more successful when applied directly on the aggregate than when added to the binder (5). However, blending the additive with the binder is more economical and is the accepted practice of highway engineers. Therefore, chemical antistripping agents are usually added to the asphalt binder at a rate of 0.5 to 1.0 percent by weight of asphalt (5).

In the past, hydrated lime has been used successfully as an antistripping additive. Chemically hydrated lime is a strongly alkaline substance and has great neutralizing power (7). The calcium from the lime replaces hydrogen, sodium, potassium, and so forth, on the aggregate surfaces. This calcium-rich surface then reacts with a long chain of organic acids to form water-resistant surfaces (5). Hydrated lime is usually applied directly on the aggregate in slurry form. It has been added to asphalt or to the aggregate in a dry form, but in such applications the results are not as dramatic as those from slurry applications. Usually 1 percent lime by weight of the aggregate, never more than 2 percent, is added (7).

Aggregate Pretreatment

Several techniques for pretreating aggregates to improve the adhesion between asphalt and aggregate have been developed (5), including the following:

1. Preheating the aggregate to evaporate the water vapor;
2. Weathering the aggregate in a stockpile to allow the outermost adsorbed water molecules to be partly replaced or covered by organic contamination, such as fatty acids from the air; and
3. Washing the aggregate to remove surface coat-

ing, especially when the aggregate has a low sand equivalent value (1).

In addition to these pretreatments, it has been observed that aggregates precoated with asphalt and salvaged bituminous surface and base materials are superior to virgin aggregate in resisting water damage (5).

In many cases, the most reliable solution is to avoid using siliceous and rhyolite aggregates in asphalt concrete mixtures. Generally, field experience has shown that mixtures that incorporate these aggregates experience the most serious water-damage problem (1). When their use is unavoidable, pretreatment by crushing has been shown to be an effective treatment in one Texas district.

TESTS CURRENTLY IN USE

Numerous attempts have been made to develop tests that aid the engineer in identifying asphalt concrete mixtures that are susceptible to moisture damage. Among these are Tex-218-F (method of test for film stripping), AASHTO T-182-70 and ASTM D1864 (coating and stripping of bitumen-aggregate mixtures), and AASHTO T-105-77 and ASTM D1075-75 (effect of water on cohesion of compacted bituminous mixtures).

Unfortunately, none of these tests has been sufficiently reliable to gain general acceptance. A primary problem has been a lack of correlation between test results and field performance. Some recent testing techniques that have demonstrated the potential to detect moisture damage in asphalt concrete mixtures are described below. These techniques are evaluated and their results are discussed later in this paper.

Indirect Tensile Test on Dry and Wet Specimens

Indirect Tensile Test

The indirect tensile test developed by Kennedy (2) involves loading a cylindrical specimen with static or repeated compressive loads acting parallel to and along the vertical diametrical plane. The compressive load is distributed through 13-mm (0.5-in.) wide steel loading strips that are curved at the interface to fit the specimen. This method of loading produces a fairly uniform tensile stress perpendicular to the plane of the applied load and along the vertical diametrical plane that ultimately causes the specimen to fail by splitting along the vertical diameter. Estimates of tensile strength, modulus of elasticity, and Poisson's ratio can be calculated from the applied load and corresponding vertical and horizontal deformations.

The test equipment was the same as that used in previous studies at CTR and included a loading frame, loading head, and Material Testing Systems' closed-loop electrohydraulic system to apply load and to control deformation rate. The loading rate of 51 mm/min (2 in./min) was applied. The vertical deformations were monitored by a direct-current (DC) linear variable differential transducer (LVDT) positioned on the upper platen, and horizontal deformations were measured by using a device consisting of two cantilevered arms with strain gauges attached (2).

The properties calculated from the test results were tensile strength and static modulus of elasticity. To evaluate the effects of moisture conditioning on the stripping and nonstripping mixtures, two additional parameters--tensile strength ratio (TSR) and modulus of elasticity ratio (MER)--are defined as follows:

$$TSR = S_{T_{wet}} / S_{T_{dry}} \quad (1)$$

where

$S_{T_{wet}}$ = tensile strength of the wet specimen (kPa) and
 $S_{T_{dry}}$ = tensile strength of the dry specimen (kPa).

$$MER = E_{swet} / E_{sdry} \quad (2)$$

where

E_{swet} = modulus of elasticity of wet specimen (kPa) and
 E_{sdry} = modulus of elasticity of dry specimen (kPa).

Moisture Conditioning Methods

To evaluate the changes in engineering properties of asphalt concrete mixtures when subjected to the effects of water, specimens were tested in both dry and wet conditions. Specimens tested dry were cured at 24°C (75°F) for 2 days before testing. Specimens tested wet were conditioned by immersing the specimen in distilled water at room temperature [24°C (75°F)], applying a vacuum, and then subjecting the specimen to further conditioning as described by Lee, Kennedy, and Roberts (5) and summarized in Table 1. All specimens were tested at 24°C (75°F). The moisture-conditioning technique was developed by Lottman (8), who studied the loss of basic engineering properties as an indication of moisture susceptibility of asphalt concrete mixtures.

This testing procedure was slightly modified to make it possible to evaluate the water susceptibility of asphalt concrete mixtures based on the results from a preliminary study conducted at the CTR (5). All aggregate combinations weighed 900 g and were batched by dry weight by using the field job-mix formula for each mixture. Cylindrical specimens with a diameter of 10 (4.0 in.) and a height of about 50.80 mm (about 2.0 in.) were compacted according to Texas test method Tex-206-F. However, different compaction efforts were applied to each mixture to obtain void contents between 6 and 8 percent so that the water could penetrate easily.

Texas Freeze-Thaw Pedestal Test

The Texas freeze-thaw pedestal test (3), although empirical in many respects, is fundamentally designed to maximize the effects of bond and to minimize the effects of mechanical properties of the mixture such as gradation, density, and aggregate interlock by using a uniform aggregate size. Three

categories of materials can be used in this test. The category is defined by aggregate type and size:

Aggregate Type	Interval Between Sieves
Natural	No. 20 and No. 35
Natural	No. 40 and No. 80
Crushed	No. 20 and No. 35.

To perform the Texas freeze-thaw pedestal test, the proper amount of aggregate is weighed and mixed with asphalt. After the optimum asphalt content is determined from the Texas mixture design procedure, the initial specimen is prepared at the optimum asphalt content plus 2 percent, and the asphalt percent is adjusted depending on the absorption characteristics of the mixture or the individual aggregate being tested.

After initial mixing, the mixture is reheated and remixed two more times every hour and then cooled to room temperature for at least 30 min. The mixture is then heated for an additional 20 min, placed in a cylindrical mold, and compacted at a constant load of 27.6 kN (6,200 lb) for 20 min. This reheating and remixing procedure was designed to produce an asphalt with a viscosity similar to that of an aged asphalt after 5 years of field service.

Each briquet specimen is cylindrical and has a diameter of 41.33 mm (1.627 in.) and a height of 19.05 mm (0.750 in.). The briquet is extracted from the mold and allowed to cool, the height is measured, and the briquet cured at ambient temperature for 3 days before being subjected to freeze-thaw cycling. The specimen is then placed on a stress pedestal in a jar covered with 12.7 mm (0.5 in.) of distilled water, placed in a temperature-controlled room, and subjected to thermal cycling, which consists of 12 hr at -12°C (10°F) followed by 12 hr at 49°C (120°F). At the end of each cycle, the surface of the specimen is inspected to determine whether the briquet has failed by cracking. The number of freeze-thaw cycles required to induce cracking in the briquet is the test result that is used as a measure of water susceptibility.

Most aggregate mixtures consist of materials from several sources that are blended naturally or by the contractor to satisfy a grading requirement. These individual components may vary in size, shape, surface texture, and chemical composition. Thus, it is desirable to first evaluate the mixture and then, if stripping is detected, it may also be desirable to evaluate individual components. In evaluating the mixture, the individual components should be included in the mixture in proportion to their weight. Another approach would be to include the components in proportion to their surface area because stripping is a surface phenomenon. However, until additional work is done on the importance of surface area, it is recommended that the components be proportioned by weight.

Table 1. Summary of conditioning procedure for dry and wet specimens.

Procedure	Vacuum Time ^a	Soaking Time After Vacuum	Freeze		Thaw		No. of Cycles	Remarks
			Temperature (°F)	Time (hr)	Temperature (°F)	Time (hr)		
26VS	30 min	30 min	—	—	—	—	—	—
26VS+SOAK(7)	2 days	7 days	—	—	—	—	—	—
26F/TH	30 min	30 min	0	15	140	24	1	Plastic bag for freezing period
26TC	30 min	30 min	0	4	120	4	18	After thermal cycles 54°F water bath for 3 hr
Dry	—	—	—	—	—	—	—	2 days at 75°F

Note: All wet specimens are moisture-conditioned after 2 days of dry curing at 75°F.

^aAll specimens 26 in. in height.

Texas Boiling Test

The Texas boiling test is a synthesis of several boiling tests used in several state agencies (5). In the test, a visual rating is made of the extent of stripping of asphalt cement from the aggregate after a sample has been subjected to the action of water at elevated temperatures for a specified time. The rating is made after the mixture has been cooled in the beaker and then poured on a clean surface.

To perform the test, the asphalt cement is heated at 103°C (325°F) for 24 to 26 hr. The unwashed individual aggregate of 100 or 300 g of mixture is also heated at 103°C (325°F) for 1 to 1.5 hr. At the appropriate time, asphalt is added to the aggregate and the materials are mixed manually on a hot table. The mixture is then allowed to cool at room temperature for 2 hr.

A 1000-mL beaker is filled approximately half-full with distilled water and heated to boiling. The mixture is dumped in the beaker and boiled for 10 min. Any floating asphalt cement is skimmed off the surface of the water. After boiling, the beaker is removed from the heat and cooled to room temperature, the water is then poured off, and the mixture is emptied onto a paper towel.

The degree of stripping is visually rated by a panel of three graders. Each observation should be matched with a rating performed at the end of the boiling period. The mixture should also be examined on the day after drying. When dried out, some mixtures show evidence of a stripping of the fines that is not apparent when the mixture is still wet.

Most aggregate mixtures consist of materials from several sources that are blended naturally or by the

contractor to satisfy a grading requirement. Because these individual components vary in size, shape, surface texture, and chemical composition, the mixture is evaluated by using the fraction called for in the job-mix formula used for construction of the pavement. To have the same asphalt film thickness on the individual aggregate components, the standard procedure suggests that the aggregate-asphalt mixture contain the optimum asphalt for the design according to Tex-204-F and that the percentage of asphalt be increased or decreased by 1 percent depending on the characteristics of the individual aggregate.

EVALUATION OF ASPHALT-AGGREGATE MIXTURES

The primary purpose of this investigation was to evaluate laboratory testing techniques that show evidence of being able to detect asphalt mixtures that are susceptible to moisture damage in the field. The test methods selected and discussed briefly in the previous section are the indirect tensile tests on dry and wet specimens, the Texas freeze-thaw pedestal test, and the Texas boiling test. The materials selected and test results from each method are discussed below.

Materials

Aggregates from eight projects were used to determine whether any of the selected testing techniques could differentiate between asphalt-aggregate mixtures known to strip and those that do not strip. Of these eight projects, four had previously experienced stripping problems and four had not. The stripping mixtures were from the Waco, Lufkin,

Table 2. Location and description of stripping aggregates.

District	Aggregate Type	Producer and/or Source	Aggregate Proportion (%)
Waco	Coarse gravel	Waco Sand and Gravel Company (Bosqueville pit)	65.0
	Washed sand	Waco Sand and Gravel Company (Bosqueville pit)	21.0
	Field sand	Pendeley River Sand, Inc. (Pendeley pit)	14.0
Lufkin	Crushed limestone	Gifford-Hill	27.0
	Pea gravel	Crocket Sand and Gravel Company	15.0
	Coarse sand	Midway Material Company	15.0
	Local fine sand	Dickerson pit	43.0
Houston (Harris County)	Gravel screenings	Lone Star, Eagle Lake	63.3
	Crushed limestone	Texas Crushed Stone Company	10.3
	Local field sand	Harris County	26.4
Yoakum	Lone Star coarse aggregate	Lone Star, Eagle Lake	43.0
	Lone Star Gem sand	Lone Star, Eagle Lake	12.2
	Styles coarse sand	Styles	13.3
	Tanner Walker sand	Tanner Walker	31.5

Table 3. Location and description of nonstripping aggregates.

District	Aggregate Type	Producer and/or Source	Aggregate Proportion (%)
Lubbock	Crushed caliche	Long pit, Lubbock	100.0
Houston (Galveston County)	Crushed limestone	Texas Crushed Stone Company (Georgetown)	55.0
	Limestone screenings	Texas Crushed Stone Company (Georgetown)	20.0
	Field sand	Flora pit (Alvin)	25.0
Austin	Crushed limestone	Southwest Materials Company	39.0
	Crushed limestone	Southwest Materials Company	22.0
	Limestone screenings	Texas Crushed Stone Company	22.0
	Local sand	Centex Materials (Sheppard pit)	17.0
Atlanta	Coarse slag	Gifford-Hill	60.0
	Slag screenings	Gifford-Hill	15.0
	Local sand	Panola County	12.0
	Wilson red sand	Shelby County	13.0

Yoakum, and Houston (Harris County) districts. The stripping mixtures contained siliceous river gravel or sand (see Table 2). The nonstripping mixtures were from the Lubbock, Houston (Galveston County), Austin, and Atlanta districts. These nonstripping aggregates were crushed limestone, caliche, and slag (see Table 3).

The asphalt cements used in the laboratory mixtures are the same as those used for the construction of corresponding pavements. The asphalts consisted of asphalt grades AC-10 and AC-20 produced by Exxon, Vickers, Cosden, and Texaco.

Test Results and Analysis

The aggregates and asphalt cements were combined in the proportion used in the field and tested to de-

termine resistance to stripping. The test results from each technique are analyzed below.

Indirect Tensile Test on Dry and Wet Specimens

The TSR and MER reflect the change in property caused by the presence of moisture and directly reflect the moisture susceptibility of each mixture (5). Summaries of the individual test results for each method are given in Tables 4-6.

Values of TSR ranged from 0.16 to 0.91 for the stripping mixtures and from 0.10 to 1.25 for the nonstripping mixtures (Table 6). Specimens were tested after moisture conditioning by using the four techniques given in Table 1, and the results are shown in Figure 1 and Tables 5 and 6. In general, test method 26VS appears to be less severe than the other three test methods. The most severe testing techniques were methods 26F/TH and 26TC. However, because of overlap of data, it is not possible to use these test methods to differentiate between stripping-prone mixtures and nonstripping mixtures as shown in Figure 1. This result is contrary to that reported by Lottman (8) and Epps and others (9), but it was consistent for all materials tested.

Values of MER ranged from 0.15 to 1.17 for stripping mixtures and from 0.07 to 1.90 for nonstripping ones. The range of these values is a little wider than the range of values for TSR but is in the same general range. As with the TSR results, there is overlap of results for the various conditioning techniques, and one technique could not be singled out that could consistently be used to differentiate between stripping and nonstripping mixtures.

TEXAS FREEZE-THAW PEDESTAL TEST

Results from the Texas freeze-thaw pedestal test

Table 4. Static indirect tensile test results: unconditioned specimens for stripping and nonstripping mixtures.

District	Air Voids (%)	Tensile Strength, S_T (psi)	Static Modulus of Elasticity, E_S (psi)
Stripping Materials			
Waco	6.8	75	38,100
Lufkin	10.9	49	28,500
Houston (Harris County)	7.1	50	23,200
Yoakum	5.8	101	55,200
Nonstripping Materials			
Lubbock	7.9	75	39,800
Houston (Galveston County)	7.9	66	42,900
Austin	7.7	49	20,100
Atlanta	7.7	54	22,100

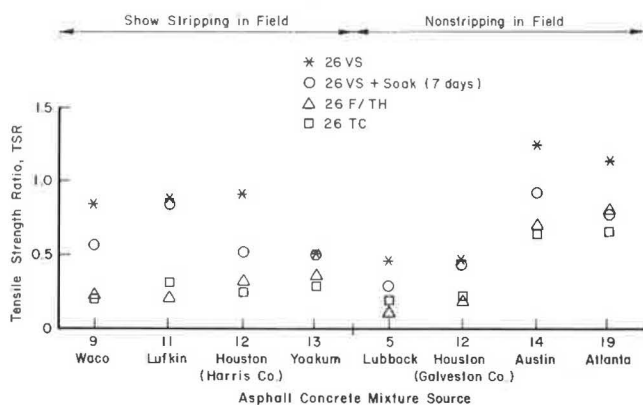
Table 5. Static indirect tensile test results: conditioned specimens for stripping mixtures.

District	Moisture Conditioning Technique	Air Voids Content (%)		Moisture Content (%)	Tensile Strength, S_T (psi)	Static Modulus of Elasticity, E_S (psi)	Wet/Dry Ratio	
		Before Conditioning	After Conditioning				TSR	MER
Waco	4VS	6.9	7.0	1.8	74	31,400	0.99	0.82
	4F/TH	7.0	6.7	2.6	59	24,900	0.79	0.65
	4VS+SOAK(7)	7.2	6.8	1.5	78	42,400	1.04	1.11
	26VS	7.2	7.0	3.0	54	20,700	0.73	0.54
	26F/TH	7.4	8.2	3.9	16	8,800	0.21	0.23
	26TC	7.5	7.8	3.3	15	5,800	0.20	0.15
	26VS+SOAK(7)	7.6	7.3	3.8	42	35,900	0.56	0.94
	4VS	10.6	10.6	0.7	51	27,300	1.05	0.96
	4F/TH	10.3	10.5	2.3	46	22,100	0.95	0.77
	4VS+SOAK(7)	10.7	10.8	2.2	55	24,100	1.14	0.85
Lufkin	15F/TH	11.4	12.6	4.7	21	9,000	0.44	0.32
	15TC	11.4	11.8	3.7	29	14,800	0.60	0.52
	15VS+SOAK(7)	11.3	11.7	4.2	45	34,100	0.94	1.20
	26VS	11.4	11.9	5.4	43	18,300	0.88	0.64
	26F/TH	11.4	13.6	6.5	10	4,800	0.20	0.17
	26TC	11.4	12.0	5.2	15	6,900	0.31	0.24
	26VS+SOAK(7)	11.7	12.1	5.8	41	28,300	0.84	0.99
	4VS	7.2	7.2	0.6	55	23,600	1.11	1.02
	4F/TH	7.2	7.1	2.2	44	18,900	0.89	0.82
	4VS+SOAK(7)	6.8	6.8	1.7	49	26,400	0.99	1.14
Houston (Harris County)	15F/TH	7.1	7.3	3.1	24	13,800	0.47	0.59
	15TC	7.3	7.4	2.8	21	11,900	0.41	0.51
	15VS+SOAK(7)	6.7	6.4	2.8	43	29,600	0.87	1.28
	26VS	7.0	6.9	3.8	45	27,100	0.91	1.17
	26F/TH	6.8	7.1	3.8	16	14,800	0.32	0.64
	26TC	6.6	6.9	3.3	12	9,000	0.25	0.39
	26VS+SOAK(7)	6.8	7.1	4.2	26	12,100	0.52	0.52
	4VS	—	—	0.3	103	52,600	1.01	0.95
	4F/TH	—	—	1.3	109	58,800	1.07	1.06
	4VS+SOAK(7)	—	—	1.1	100	45,600	0.99	0.83
Yoakum	26VS	4.7	6.7	2.8	51	13,800	0.51	0.25
	26F/TH	4.6	5.3	2.3	36	18,900	0.36	0.34
	26TC	4.9	5.6	2.0	29	11,500	0.29	0.21
	26VS+SOAK(7)	3.9	5.7	3.3	51	28,000	0.50	0.51

Table 6. Static indirect tensile test results: conditioned specimens for nonstripping mixtures.

District	Moisture Conditioning Technique	Air Voids Content (%)		Moisture Content (%)	Tensile Strength, S_T (psi)	Static Modulus of Elasticity, E_S (psi)	Wet/Dry Ratio	
		Before Conditioning	After Conditioning				TSR	MER
Lubbock	4VS	7.7	—	1.9	88	41,100	1.18	1.03
	4F/TH	8.7	12.5	8.0	25	7,500	0.34	0.19
	4VS+SOAK(7)	8.1	11.9	7.2	27	9,500	0.37	0.24
	26VS	7.6	8.6	6.8	34	9,800	0.46	0.25
	26F/TH	7.1	14.6	10.3	7	2,700	0.10	0.07
	26TC	7.2	13.3	7.8	13	5,500	0.17	0.14
	26VS+SOAK(7)	6.5	11.0	8.5	22	9,000	0.29	0.23
	4VS	7.6	7.8	1.2	70	36,200	1.06	0.84
	4F/TH	7.9	8.5	2.8	49	25,100	0.73	0.58
Houston (Galveston County)	4VS+SOAK(7)	7.8	8.2	2.2	70	34,100	1.06	0.79
	15F/TH	6.6	8.7	4.4	24	7,700	0.37	0.18
	15TC	6.6	7.6	3.3	33	13,200	0.51	0.31
	15VS+SOAK(7)	8.4	9.6	4.8	36	26,700	0.54	0.62
	26VS	7.8	8.8	5.0	31	9,900	0.47	0.23
	26F/TH	7.7	10.2	6.3	12	5,300	0.18	0.12
	26TC	7.9	9.8	5.8	13	6,000	0.20	0.14
	26VS+SOAK(7)	8.1	9.5	6.0	30	26,800	0.45	0.63
	4VS	7.5	7.7	1.4	53	28,500	1.09	1.42
Austin	4F/TH	8.2	8.3	3.1	36	16,700	0.73	0.83
	4VS+SOAK(7)	7.7	7.6	2.6	55	23,200	1.13	1.15
	15F/TH	8.4	8.5	4.4	29	13,100	0.60	0.68
	15TC	8.7	9.0	3.1	30	13,700	0.61	0.68
	15VS+SOAK(7)	7.2	7.1	3.6	41	17,100	0.84	0.85
	26VS	6.9	9.0	4.3	61	38,200	1.25	1.90
	26F/TH	6.6	6.6	4.2	34	17,200	0.69	0.86
	26TC	6.6	7.3	3.9	31	15,800	0.64	0.78
	26VS+SOAK(7)	7.1	7.2	5.2	44	22,600	0.91	1.12
Atlanta	4VS	7.1	7.3	1.2	55	22,800	1.02	1.03
	4F/TH	9.8	9.9	3.0	57	18,300	1.07	0.83
	4VS+SOAK(7)	6.7	6.8	2.2	65	25,200	1.21	1.14
	26VS	7.8	10.1	4.0	61	26,000	1.14	1.17
	26F/TH	5.8	6.2	4.0	43	8,500	0.80	0.38
	26TC	7.0	7.1	4.0	35	9,600	0.66	0.44
	26VS+SOAK(7)	8.3	8.2	5.7	41	9,200	0.77	0.41

Figure 1. TSR for various moisture conditioning techniques.

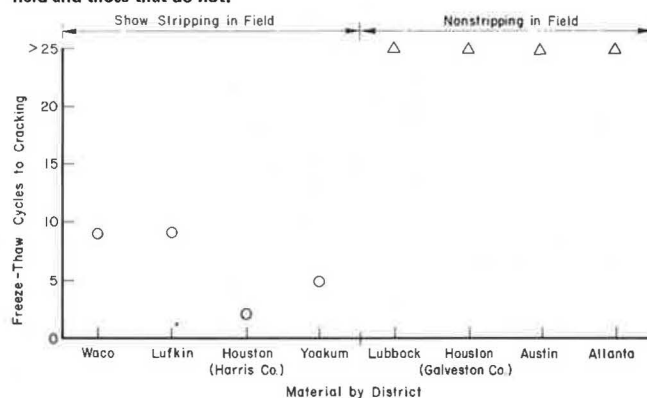


show that the stripping materials cracked in less than 10 cycles whereas the nonstripping materials sustained more than 25 cycles to failure (see Figure 2). In fact, several mixtures sustained more than 100 cycles. It has been concluded that the division between mixtures that strip in the field and those that do not is probably between 10 and 20 cycles. If such is the case, the Texas freeze-thaw pedestal test offers significant potential for use in detecting these asphalt concrete mixtures that may strip in the field.

In addition to evaluating mixtures, the test has also been used to evaluate the individual components of a mixture to evaluate their water susceptibility.

The test results for several individual aggregates are given in Table 7. The gravel screenings and sands vary in the number of cycles to cracking

Figure 2. Texas freeze-thaw pedestal test results for mixtures that strip in the field and those that do not.



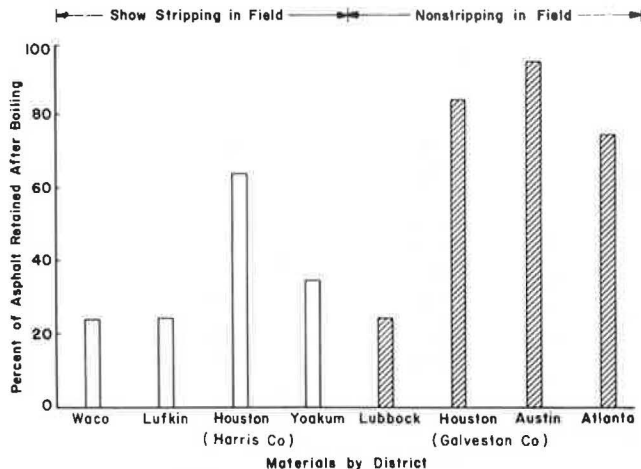
from one for the Lone Star gravel screenings to more than 25 for the Dickerson fine sand. All of the crushed limestone products exhibited excellent resistance to stripping. However, no pattern was obvious for the sandy materials.

Texas Boiling Test

The estimation of stripping based on visual examination of mixtures after boiling is shown in Figure 3 for each of the eight mixtures described in Tables 2 and 3. The mixtures that stripped in the field all showed more than 35 percent stripping after boiling. The nonstripping mixtures all retained more than 75 percent asphalt-coated particles except for the Lubbock caliche.

The Lubbock caliche may be a moisture-susceptible

Figure 3. Texas boiling test results for mixtures that strip in the field and those that do not.



material. Test results from project 183 (10) showed that, if exposed to sufficient water, this material swelled and showed significant loss of strength. Because Lubbock is a relatively dry area (1), no serious stripping has been observed in the field. However, there have been recent reports that stripping of this caliche has occurred at the lower section of an underpass where the water had accumulated. This additional evidence lends credence to the boiling-test results, which show that the Lubbock caliche could strip under wet conditions.

Thus, it is currently believed that the division between stripping and nonstripping mixtures lies between 65 and 75 percent retained asphalt, as shown by boiling-test results. If this is the case, the Texas boiling test offers significant potential for use in detecting asphalt concrete mixtures that may strip in the field. Because this test is quicker and simpler to run than the Texas freeze-thaw pedestal test, it may be more favorable for use in the field, especially because the boiling test uses a sample of the full-graded mixture. The boiling test

Table 7. Freeze-thaw pedestal test results for specimens from stripping mixes.

District	Individual Aggregate and Design Mixture	No. of Cycles to Cracking						Coefficient of Variation (%)	Mixture Proportion (%)
		Specimen No.			Range	Mean	SD		
		1	2	3					
Waco	Waco washed sand	5	7	6	2	6	1.00	16.7	21.0
	Pendeley field sand	14	14	14	0	14	0.00	0.0	14.0
Lufkin	Design mixture	8	9	9	1	9	0.58	6.7	100.0
	Crushed limestone	>25	>25	>25	a	>25	a	a	27.0
	Pea gravel	8	8	8	0	8	0.00	0.0	15.0
	Midway coarse sand	5	5	4	1	5	0.58	12.4	15.0
	Dickerson fine sand	>25	>25	>25	a	>25	a	a	43.0
	Design mixture	9	9	9	0	9	0.00	0.0	100.0
Houston (Harris County)	Lone Star gravel screenings	1	2	1	1	1	0.58	43.3	63.3
	Texas crushed stone and crushed lime- stone	>25	>25	>25	a	>25	a	a	10.3
	Harris County field sand	8	8	8	0	8	0.00	0.0	26.4
Yoakum	Design mixture	2	2	3	1	2	0.58	24.7	100.0
	Lone Star coarse aggre- gate	3	3	4	1	3	0.58	17.3	43.0
	Lone Star Gem sand	3	2	3	1	3	0.58	21.6	12.2
	Styles coarse sand	4	3	2	2	3	1.00	33.3	13.3
	Tanner Walker sand	12	12	12	0	12	0.00	0.0	31.5
	Design mixture	5	5	5	0	5	0.00	0.0	100.0

a Could not be calculated.

Table 8. Texas boiling test results for individual aggregates and design mixtures that stripped.

			Asphalt Retained After Boiling (%)								
District	Individual Aggregate and Design Mixture	Asphalt Content (%)	Panel of Graders			Range	Mean	SD	Coefficient of Variation (%)	Mix Proportion (%)	
			1	2	3						
Waco	Coarse river gravel (9D)	2.3	55	40	25	30	40	15.0	37.5	65.0	
	Washed sand (9F)	6.3	5	10	5	5	7	2.9	43.5	21.0	
	Field sand (9E)	6.3	5	1	1	4	2	2.3	98.6	14.0	
Lufkin	Design mixture	4.3	50	25	10	40	28	20.2	71.3	100.0	
	Crushed limestone (11C)	5.0	60	60	60	0	60	0.0	0.0	27.0	
	Pea gravel (11D)	3.0	50	30	40	20	40	10.0	25.0	15.0	
	Coarse field sand (11E)	7.0	80	65	70	15	72	7.6	10.6	15.0	
	Fine field sand (11F)	7.0	85	90	80	10	85	5.0	5.9	43.0	
	Design mixture	5.0	60	40	20	40	40	20.0	50.0	100.0	
Houston (Harris County)	Gravel screenings (12B)	2.3	30	40	40	10	37	5.8	15.8	63.3	
	Crushed limestone (12A)	4.3	80	65	70	15	72	7.6	10.6	10.3	
	Field sand (12C)	6.3	85	90	75	15	83	7.6	9.1	26.4	
	Design mixture	4.3	70	50	50	20	57	11.5	20.3	100.0	
Yoakum	Coarse river gravel (13A)	3.0	15	15	10	5	13	2.9	21.8	43.0	
	Fine river gravel (13B)	5.0	50	45	45	5	47	2.9	6.2	12.2	
	Coarse field sand (13C)	7.0	20	10	5	15	12	7.6	65.1	13.3	
	Fine field sand (13D)	8.0	90	90	95	5	92	2.9	3.2	31.5	
	Design mixture	5.0	70	50	40	30	53	15.3	28.7	100.0	

has also been used to evaluate the individual components of these aggregate mixtures to determine their water susceptibility. Test results for each of the individual aggregates are included in Tables 8 and 9.

Use of Moisture Tests to Evaluate Materials

The results of this study indicated a possible correlation between the Texas freeze-thaw pedestal test and the Texas boiling test. Such a relation would be useful to those agencies that are not equipped to conduct the freeze-thaw pedestal test and indirect tensile tests. Even though there is no well-defined relation between moisture tests, a fair correlation was observed. Some of the limitations of the test and a proposed method for using them to evaluate the moisture susceptibility of asphalt-aggregate mixtures are discussed below.

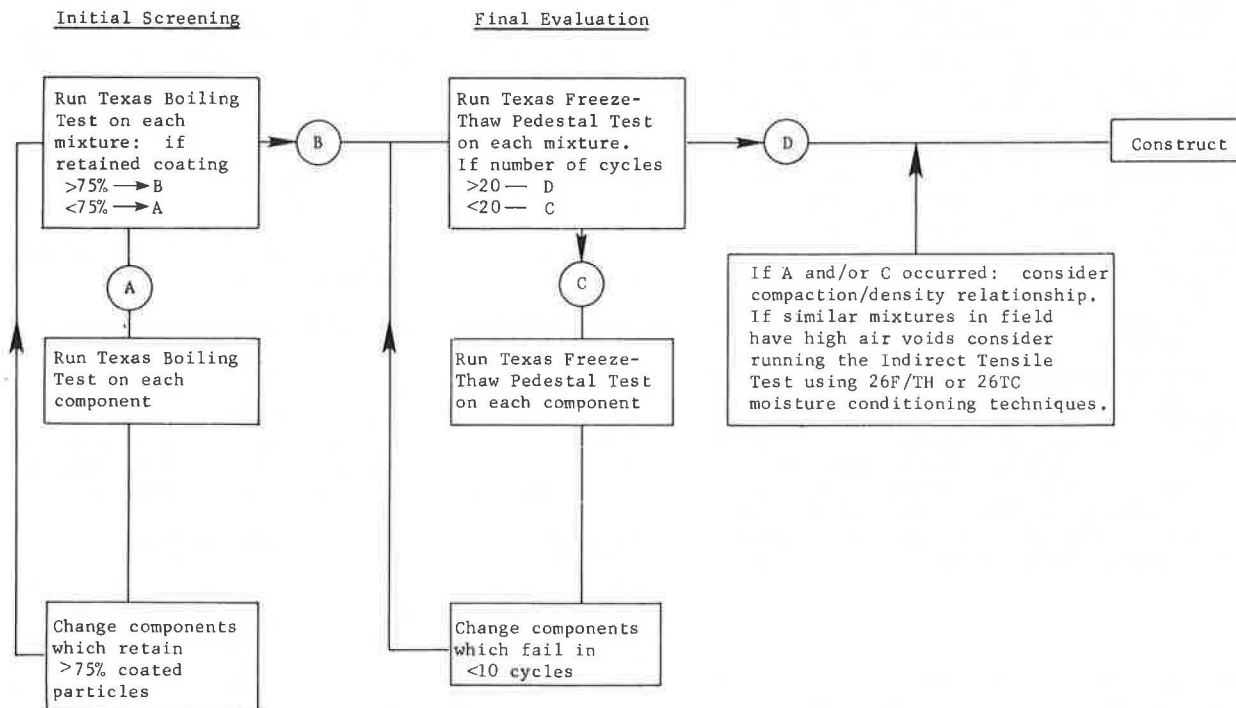
Suggested Methodology

Preliminary test results indicate that both the Texas freeze-thaw pedestal test and the Texas boiling test offer great potential in detecting stripping-prone aggregate-asphalt combinations in the laboratory. To implement these moisture tests for field use, a methodology for performing them and evaluating the results is essential. Figure 4 shows a flow diagram that contains a suggested methodology for the examination of the moisture susceptibility of asphalt-aggregate combinations. The Texas boiling test, which is simple and uses a sample of the mixture, is suggested for field control and as an initial screening test in detecting stripping-prone mixtures. This test can be performed on specimens being prepared for use in selecting the mixture design. If the mixture is identified as highly water

Table 9. Texas boiling test results for individual aggregates and design mixtures of nonstripping materials.

			Asphalt Retained After Boiling (%)								
District	Individual Aggregate and Design Mixture	Asphalt Content (%)	Panel of Graders			Range	Mean	SD	Coefficient of Variation (%)	Mix Proportion (%)	
			1	2	3						
Lubbock	Crushed caliche (5A)	9.0	70	50	50	20	57	11.5	20.3	100.0	
Houston (Galveston County)	Crushed limestone (12E)	5.0	75	85	95	20	85	10.0	11.8	55.0	
	Crushed limestone screens (12F)	5.0	70	60	90	30	73	15.3	20.9	20.0	
Austin	Flora field sand (12G)	7.0	75	50	50	25	58	14.4	24.7	25.0	
	Design mixture	6.0	80	75	95	20	83	10.4	12.5	100.0	
	Crushed limestone (14I and 14J)	3.4	90	90	95	5	92	2.9	3.2	61.0	
	Crushed limestone (14K)	4.4	95	95	99	4	36	2.3	2.4	22.0	
Atlanta	Local field sand (14L)	7.4	75	55	70	20	67	10.4	15.6	17.0	
	Design mixture	5.4	95	95	99	4	96	2.3	2.4	100.0	
	Gifford-Hill slag (19A and 19B)	5.5	90	95	99	9	95	4.5	4.8	75.0	
	Panola local sand (19C)	7.5	85	85	95	10	88	5.8	6.6	12.0	
	Wilson red sand (19D)	6.5	60	60	80	20	67	11.5	17.3	13.0	
	Design mixture	7.5	80	80	75	5	78	2.9	3.7	100.0	

Figure 4. Suggested methodology for selecting and performing moisture tests.



susceptible, each component of the mixture will be examined to determine which component contributes to stripping. After either eliminating the moisture-susceptible component or reducing the quantity, the new mix can be tested to determine whether it passes the test. This initial screening can probably detect most of the aggregates and mixtures that will cause problems in the field. However, once a contract has been let and the contractor has selected materials for the mixture, a final evaluation is suggested.

In the final evaluation, the mixture that passed the initial screening is examined by using the Texas freeze-thaw pedestal test. If tests on the mixture show adverse moisture effects, the testing should be expanded to determine which component contributes to the stripping. After modification of the mixture design, including perhaps the addition of an anti-stripping additive or a change in the amount or type of aggregate in the mixture, the new mix should be tested again to evaluate the effect of each treatment investigated.

After the final evaluation, it may also be desirable to consider the effect of compaction and density on the potential for moisture damage, especially if there has been difficulty in achieving proper field compaction with the aggregates selected. If typical mixtures of these materials show high air void contents, these mixtures should be evaluated by using the indirect tensile test on both dry and wet specimens to evaluate the effect of water penetrating into the mixture. In a recent study on I-10 at Columbus, Texas, a mixture that was a combination of water-susceptible aggregates showed no distress because the low air voids kept water from penetrating into the mix. Two other mix designs composed of similar materials failed dramatically when water successfully penetrated the mixture (11). Tests at the CTR indicate that the 26F/TH and 26TC moisture-conditioning techniques most often provide results that can be used to detect stripping mixtures.

Limiting Values for Each Test

As noted earlier, based on results in Figure 3 a limiting retention value of 75 percent is suggested for use in distinguishing between stripping and nonstripping mixtures in the Texas boiling test. Hence, any mixture or individual aggregate should retain more than 75 percent coated aggregate or undergo further evaluation.

When a mixture is to be evaluated by using the Texas freeze-thaw pedestal test, the mixture should sustain at least 20 cycles or the individual aggregate should sustain at least 10 cycles before it is placed on the road in a mixture (Figure 2). If the mixture of these materials is usually placed with a high air voids content, the indirect tensile test on dry and wet specimens should probably be run. Lottman (8) recommends a tensile strength ratio of 0.70 or higher to ensure that the susceptibility of the mixture is not so great as to affect its performance. However, for data available in this investigation, there was no single value of TSR that would permit a distinction between susceptible and non-susceptible mixtures for all moisture conditioning techniques. However, for the 26F/TH and 26TC techniques, a TSR greater than 0.5 indicates general acceptability and is suggested for use at the present time.

SUMMARY

Several testing techniques were used to evaluate the moisture susceptibility of eight Texas asphalt con-

crete mixtures with known field performance. The results indicate that both the Texas freeze-thaw pedestal test and the Texas boiling test were able to differentiate fairly well between stripping and nonstripping asphalt concrete mixtures.

It is suggested that the Texas boiling test be used for a quick evaluation of asphalt-aggregate mix in the field. Because this test is very severe, it is suggested that the Texas freeze-thaw pedestal test be used for final and long-term evaluation of those mixtures that strip in the boiling test. When similar mixtures have a high air voids content in the field, it is desirable to evaluate the mixture by using the static indirect tensile test.

CONCLUSIONS

General

Both the Texas freeze-thaw pedestal test and the Texas boiling test are laboratory tests that have been used to differentiate between asphalt mixtures that are known to strip in the field and those that do not strip. However, the indirect tensile test results could not be used to differentiate clearly between stripping and nonstripping mixtures.

Texas Freeze-Thaw Pedestal Test

All four of the known stripping mixtures cracked in less than 10 cycles, whereas the nonstripping mixtures all sustained more than 25 cycles without cracking. In addition, the individual components that contributed to the stripping were identifiable. Hence, this procedure offers excellent potential for use in detecting asphalt concrete mixtures that may be prone to water damage. Furthermore, the evidence indicates that somewhere between 10 and 20 cycles to cracking is the borderline between stripping and nonstripping mixtures.

Texas Boiling Test

All four of the known stripping mixtures retained less than 65 percent coated particles, whereas the nonstripping mixtures, except for the Lubbock caliche, retained more than 75 percent coated particles. This caliche material appears to be moisture susceptible if exposed to sufficient water even though it generally does not strip in the field. Hence, the boiling test also offers good potential for use in detecting mixtures that may strip in the field. In addition, the boiling test offers good potential for use in field laboratories as a quality control test. Even though this test can be used to evaluate the individual components, its best use is with the complete mixture prepared either in the laboratory or directly from the plant.

Indirect Tensile Test on Dry and Wet Specimens

Tensile test results for all of the moisture-conditioning techniques do not differentiate equally between the stripping and nonstripping mixtures. In general, the 26F/TH and 26TC techniques do a better job of differentiating, but neither of these methods is as effective as the pedestal and boiling tests.

Use of Moisture Tests to Evaluate Materials

A methodology for using these test methods to evaluate the moisture susceptibility of asphalt-aggregate mixtures was presented. The Texas boiling test, which is simple and easy to conduct, is recommended for use in the initial screening. If a mixture retains less than 75 percent coated aggregates and

needs further evaluation, the Texas freeze-thaw pedestal test should be performed to provide additional data. If the specimen of mixture fails in less than 20 cycles, the water-susceptible component should be identified, the mixture modified, and a new mix evaluated.

When similar mixtures have high air void content in the field, they can be evaluated by using the static indirect tensile test to determine the effect of those voids on the moisture susceptibility of the mixtures.

Treatment to Prevent Moisture Damage

Available techniques for limiting water damage to asphalt concrete mixtures include using antistripping additives, precoating the aggregates, and incorporating design and construction controls to ensure dense field mixtures. Both the Texas freeze-thaw pedestal test and the Texas boiling test can be used to evaluate the effectiveness of antistripping additives and pretreatment of aggregates with the antistripping additives (3,5).

RECOMMENDATIONS

Immediate

1. The Texas freeze-thaw pedestal test and the Texas boiling test can begin to be used to detect those asphalt concrete mixtures that might suffer water damage in the field.

2. It is suggested that the Texas boiling test be used for initial screening.

3. After initial screening the Texas freeze-thaw pedestal test can be used for final and long-term evaluation.

4. Potential treatments can also be evaluated by using either test; however, each aggregate-asphalt combination should be tested. If any component of a mixture is changed, the mixture should be rechecked.

Long-Term

Other aggregate mixtures with known field performance characteristics should be tested and the results evaluated to strengthen confidence in using the Texas freeze-thaw pedestal test and the Texas boiling test as a means of differentiating between stripping and nonstripping mixtures.

ACKNOWLEDGMENT

The research described in this paper was carried out at the CTR, Bureau of Engineering Research, at the University of Texas at Austin. We are grateful for the support of TSDHPT and FHWA.

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily

reflect the official views or policies of FHWA. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. R.B. McGennis, R.B. Machemehl, and T.W. Kennedy. Moisture Effects on Asphalt Concrete Mixtures. Center for Transportation Research, Univ. of Texas at Austin, Res. Rept. 253-1 (in preparation).
2. J.N. Anagnos and T.W. Kennedy. Practical Method for Conducting the Indirect Tensile Test. Center for Highway Research, Univ. of Texas at Austin, Res. Rept. 98-10, Aug. 1972.
3. T.W. Kennedy, F.L. Roberts, and K.W. Lee. Evaluation of Moisture Susceptibility of Asphalt Mixtures Using the Texas Freeze-Thaw Pedestal Test. Assn. of Asphalt Paving Technologists, Symposium on Antistripping Additives in Paving Mixtures, Kansas City, MO, Feb. 1982.
4. H.G. Plancher, R.L. Miyake, and J.C. Petersen. A Simple Laboratory Test to Indicate the Susceptibility of Asphalt-Aggregate Mixtures to Moisture Damage During Repeated Freeze-Thaw Cycling. Proc., Canadian Technical Asphalt Assn. Meeting, Victoria, British Columbia, 1980.
5. K.W. Lee, T.W. Kennedy, and F.L. Roberts. The Prediction and Evaluation of Moisture Damages on Asphalt Concrete Mixtures in Pavement Systems. Center for Transportation Research, Univ. of Texas at Austin, Res. Rept. 253-5 (in preparation).
6. K. Majidzadeh and F.N. Brovold. State of the Art: Effect of Water on Bitumen-Aggregate Mixtures. HRB, Special Rept. 98, 1968.
7. Hydrated Lime in Asphalt Paving. National Lime Assn., Arlington, VA, Bull. 325, n.d.
8. R.P. Lottman. Predicting Moisture-Induced Damage to Asphalt Concrete. NCHRP, Rept. 192, 1978.
9. J.A. Epps, J.W. Button, R.R. Valdez, and D.N. Little. Development Work on a Test Procedure to Identify Water-Susceptible Asphalt Mixtures. Texas A&M Univ., College Station, Res. Rept. 287-1, Nov. 1980.
10. J.N. Anagnos, F.L. Roberts, and T.W. Kennedy. Evaluation of the Effect of Moisture Conditioning on Blackbase Mixtures. Center for Transportation Research, Univ. of Texas at Austin, Res. Rept. 183-13, Oct. 1981.
11. T.W. Kennedy, R.B. McGennis, and F.L. Roberts. Investigation of Premature Distress in Conventional Asphalt Materials on Interstate 10 at Columbus, Texas. Center for Transportation Research, Univ. of Texas at Austin, Res. Rept. 313-1, Aug. 1982.

Publication of this paper sponsored by Committee on Flexible Pavement Construction.