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STRIPPING OF ASPHALT CONCRETE PHYSICAL TESTING

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Because of the test complexity and lack of a strong correlation with stripping performance, the freeze-thaw stress pedestal test is not recommended. The boil and indirect tensile tests, in combination, offer a viable, although, imperfect, system for stripping evaluation. The lack of a strong correlation with reported field performance detracts from both tests. However, the imprecise and subjective nature of the reported performance and the correlations obtained by others are mitigating factors.

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PHYSICAL TESTING

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Sponsored by
The State of Alabama Highway Department
in Cooperation with
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Federal Highway Administration

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The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of Alabama Highway Department or the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, or regulation.

ABSTRACT

The freeze-thaw stress pedestal test, the boil test and the indirect tensile test were evaluated for assessing the stripping potential of typical Alabama asphalt concrete mixes and the effectiveness of antistripping additives. This was accomplished by testing surface and base/binder mixes with five aggregate combinations, two sources of asphalt cement and three antistripping additives.

Because of the test complexity and lack of a strong correlation with stripping performance, the freeze-thaw stress pedestal test is not recommended. The boil and indirect tensile tests, in combination, offer a viable, although, imperfect, system for stripping evaluation. The lack of a strong correlation with reported field performance detracts from both tests. However, the imprecise and subjective nature of the reported performance and the correlations obtained by others are mitigating factors.

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INTRODUCTION

Stripping in asphalt concrete has long been recognized as a cause of premature pavement damage. In 1938 Hubbard wrote, "It (stripping) has been observed ever since asphalt paving came into existence" (1). Yet, after many years of research and application there is no consensus regarding stripping. Tunnicliff and Root (2), in a recent extensive study of stripping, found no nationwide agreement as to the severity, the causes, test procedures for predicting or remedies for stripping.

This lack of consensus is not surprising considering the complexity of the problem. Stripping was initially considered a separation of asphalt coatings from aggregate surfaces (3). This is still considered the dominant failure mode, but some have added that stripping may also result from a loss of cohesion in the asphalt cement (4). Compounding the complexity of the problem are the numerous factors that can influence stripping of an asphalt concrete mixture, i.e., coarse and fine aggregate properties, asphalt cement properties, mix design, construction conditions, environment and traffic.

Two recent studies (2 and 5) exemplify the complexity of stripping and the futility of precise treatment. As a result analysis, prediction and treatment of stripping is often somewhat simplistic. An illustration of this is the policy of the Georgia Department of Transportation that requires antistripping in all asphalt concrete. Specifically, evolution and application of evaluation and prediction procedures have been characterized by the following:

1. Selection of simplified testing procedures,
2. Selection of limiting criteria without strong positive correlation with documented field performance and

3. Required testing of each proposed aggregate, asphalt cement and antistripping additive combination because specific interactions render generalizations regarding individual components invalid.

The conclusions and recommendations resulting from this study reflect these characteristics.

OBJECTIVES

The study reported herein is concerned with the physical aspects of stripping and is part of a total study which also includes chemical aspects of the process. The following two, of three objectives of the total study,were addressed:

(1) To develop and/or recommend laboratory test procedures to determine stipping potential of asphalt-aggregate mixtures; and

(2) To develop a laboratory procedure to determine the type and amount of antistripping additive needed to provide satisfactory short-term and long-term resistance to moisture damage in asphalt-aggregate mixtures.

TEST PROGRAM

To accomplish study objectives a test program was designed to evaluate and modify, as necessary, available laboratory test procedures. Three types of tests were selected for evaluation (boil test, freeze-thaw stress pedestal test and indirect tensile test). These were evaluated by testing typical Alabama asphalt concrete mixes with known performance histories.

Test Procedures

Several boil test procedures, which seem to be variations of ASTM D-3625, are available. The version selected for evaluation was developed and is utilized by the Texas State Department of Highways and Public Transportation (5 and 6). The sensitivity of test results to several of the more important procedural details are presented by Wilson (7).

The freeze-thaw stress pedestal test selected for evaluation was developed at the Texas Center for Transportation Research (8 and 9). It is an adaptation of a test proposed by the Laramie Energy Technology Center (10).

The evolution of test procedures seems to be progressing toward procedures which measure strength loss for compacted specimens that have been moisture conditioned. This is a logical choice since loss of strength is the most serious consequence of stripping. An immersion-compression test has been standardized as ASTM D-1075 for measuring compressive strength loss upon soaking. However, the indirect tensile test, as reported in references 2, 5, 9 and 11-14, is currently the most favored type test and was selected for evaluation. Tensile strength and modulus are measured for control and conditioned specimens and used to compute strength (TSR) and modulus (SMR) ratios. Specific procedures evaluated were the procedure recommended by Tunnicliff and Root (2) and basically a modified Lottman procedure (11) as contained in reference 5 as Texas Test Method Tex-531-C.

Materials

Five aggregate combinations, two asphalt cement sources and three antistripping additives were sampled for testing. These represent typical materials and the aggregate combinations provide a range of reported field stripping performance from good to poor.

Aggregate

Five aggregate combinations of three to five individual aggregates were selected and labeled A-E. Each component of each mix was numbered 1-5 (e.g. the second of the three components of combination A was assigned A2). The five aggregate combinations initially selected were real surface mixes (A, B, C and E were 416 mixes and D was a 411 mix). Aggregate from the five combinations were also combined to produce mixes meeting base/binder specifications. Therefore, for each aggregate combination, A-E, there will be a surface mix and a base/binder mix. Properties of the mixes are given in Table 1.

Each mix is distinctly different in the nature of the materials but meets specifications for a surface, binder or base course. Different gradations of limestone for particular combinations were from the same source. Different types of gravel and coarse sands for particular combinations were from the same source, but the fine sands (mixes C and D) were from sources different from the gravels and coarse sands.

Aggregate combinations were selected after consultation with Alabama Highway Department central laboratory and division personnel to provide a range of field performance from good to poor. The characterization of the aggregate combination is subjective and is based on experience of field personnel with asphalt-aggregates mixes containing the aggregates. The characteri-zation is, therefore, general in nature rather than specific, and relates to the potential for stripping rather than to the performance of a particular mix.

Table 1. Mix Characteristics

Aggregate Combination A	Surface Mix	Base/Binder Mix
A1 - Screenings, Dolomitic Limestone	65%	55%
A2 - Natural Coarse Sand, Quartz	15%	-
A3 - Crushed Stone, Dolomitic Limestone	20%	45%
Asphalt Content	5.5%	4.25%
Aggregate Combination B		
B1 - Screenings, Limestone	10%	10%
B2 - Natural Coarse Sand, Quartz and Chert	20%	20%
B3 - Crushed Gravel, Chert	70%	10%
B4 - Uncrushed Gravel, Chert	-	60%
Asphalt Content	7.5%	4.5
Aggregate Combination C		
C1 - Natural Fine Sand	15%	15%
C2 - Natural Coarse Sand, Quartz	25%	-
C3 - Crushed Gravel, Quartz	60%	-
C4 - Uncrushed Gravel, Quartz	-	45%
C5 - Pit-Run Sand Gravel, Quartz	-	40%
Asphalt Content	6.25%	4.55%
Aggregate Combination D		
D1 - Natural Fine Sand	15%	10%
D2 - Coarse Washed Sand, Quartz	50%	20%
D3 - Uncrushed Gravel, Quartz and Chert	35%	70%
Asphalt Content	6.25%	4.9%
Aggregate Combination E		
E1 - Screenings, Limestone	65%	35%
E2 - Natural Coarse Sand, Quartz	10%	10%
E3 - Crushed Stone, Limestone	25%	55%
Asphalt Content	5.5%	4.15%

As results presented later will verify, factors other than aggregate composition (gradation and asphalt content) influence test results. Therefore, the lack of strong correlation of test results with expected performance was not totally unexpected, and should not be interpreted as an invalidation of the test procedures or the reported performance. Rather, it should indicate that additional procedural refinements and application to specific mixes will be necessary to improve test result-performance correlation.

Combination A. These are basically limestone mixes and have good reported performance with few signs of pavement distress attributible to stripping. Surface Mix A contains 85% crushed limestone and 15% natural sand and has been used for shoulder paving and leveling. Base/Binder Mix A contains 100% crushed limestone. The limestone is dense (specific gravity ≈ 2.8) dolomitic material with an absorption of about 1%.

Combination B. These are basically gravel mixes with variable reported performance. Before the use of antistrip additives was required, stripping damage was severe. With the use of antistrip additives, performance has improved; however, some stripping problems are still reported. Both the surface and the base/binder mixes contain 10% limestone screenings and 90% siliceous sand and gravel. The gravel and sand are from the same source; and are described as "cherty" materials (specific gravity ≈ 2.5) with relatively high absorption (3%). The surface mix contains crushed gravel and the base/binder mix contains basically uncrushed gravel (10% crushed gravel added to meet gradation requirements).

Combination C. These are siliceous gravel mixes with good reported performance. Even before the use of antistrip additives only minor stripping problems were reported. Both the surface and base/binder mixes contain 15% fine sand and 85% coarse sand and gravel from a primary source. The coarse sand and gravel are predominately sound quartz and quartzite materials (specific gravity ≈ 2.6) with relatively low absorption (1%).

Combination D. These are siliceous gravel mixes with poor reported stripping performance. The use of antistrip additives has improved performance, but gravels from this region of the state continue to be regarded as particularly susceptible to water damage. The mixes contain 10 and 15% fine sand and 90 and 85% washed sand and gravel from a primary source. The washed sand is primarily sound quartz but the coarser particles tend to be similar to the gravel. The gravel is a "cherty" material (specific gravity ≈ 2.5) with highly variable material type including light and porous particles. Absorption is relatively high at about 2.5%.

Combination E. These are basically limestone mixes with good reported stripping performance. Both the surface and base/binder mixes contain 10% natural sand and 90% crushed limestone from a primary source. The limestone has a relatively high calcium carbonate content (≈90%), a specific gravity of about 2.6 and absorption of about 1%.

Asphalt Cement

Asphalt cement was obtained from two primary Alabama sources and labeled AC1 and AC2. Both were viscosity grade AC-20. Samples were obtained from each source on several occasions which may have introduced undesirable variability. However, all material has met physical specifications and crude sources have remained relatively constant. Both sources mix crude; with the majority coming from the Gulf of Mexico.

Antistripping Additives

Three antistrip additives were used: hydrated lime and two proprietary chemical agents. The hydrated lime is high calcium and was applied at a rate of 1% by weight of aggregate. One proprietary liquid agent, labeled BA, is a metalo-amine (or polyamine) with 0.5% by weight of asphalt cement recommended dosage rate. The second proprietary liquid agent, labeled KB, is an amido-amine with 0.5 - 1% by weight of asphalt cement recommended dosage rate.

TEST RESULTS AND ANALYSIS

This section will be organized to present and discuss test data. The freeze-thaw stress pedestal test, the boil test and the indirect tensile test will be treated individually. Results from boil and indirect tensile tests will be compared.

Freeze-Thaw Stress Pedestal Test

Stress pedestal tests (8 and 9) were performed only on surface mixes with both asphalts. The stress pedestal test measures the number of freeze-thaw cycles required to cause cracking in a small briquette comprised of asphalt and fine (-#20 to + #35) size aggregate. Stripping resistance is directly related to the number of freeze-thaw cycles to cracking. Results from stress pedestal tests are summarized in Table 2 and are plotted in Figure 1 for comparison with criteria suggested in reference 9.

Examination of Figure 1 reveals that, except for combination E, the test results do not correlate well with the suggested criteria and reported field performance. In addition, for mixes A, C and E the data indicates that antistrip agents BA and KB reduces freeze thaw cycles to failure.

The primary reasons for considering the stress pedestal test was that it could be used to identify aggregate constituents, particularly sands, that were responsible for a mixes stripping potential. Individual aggregate constituents for combinations A, B and C were tested and results shown in Table 3. Comparison of these results with results for the entire mixes and reported field performances revealed no particular correlations.

Because of the absence of strong indications that the stress pedestal test would be a good predictor of stripping potential, it was eliminated

Table 2. Freeze-Thaw Cycles to Cracking - Surface Mixes

Aggregate Combination	AC1					AC2				
	Antistrip					Antistrip				
	None	HL_a	BA_b	KB_b	KB_c	None	HL_a	BA_b	KB_b	KB_c
A-Surface	15	--	--	--	--	13	>25	>25	11	--
B-Surface	16	>25	13	9	9	17	>25	17	6	7
C-Surface	15	--	--	--	--	18	>25	13	14	--
D-Surface	>25	--	>25*	>25*	>25*	>25	--	>25	>25*	>25*
E-Surface	>25	--	>25	>25	>25	>25	--	>25	>25	>25

a - 1% Hydrated Lime (Based on Aggregate Weight)
b - 0.5% Antistrip Agent (Based on Asphalt Weight)
c - 1.0% Antistrip Agent (Based on Asphalt Weight)
* - 1 of 3 Samples Cracked @ less than 25 cycles

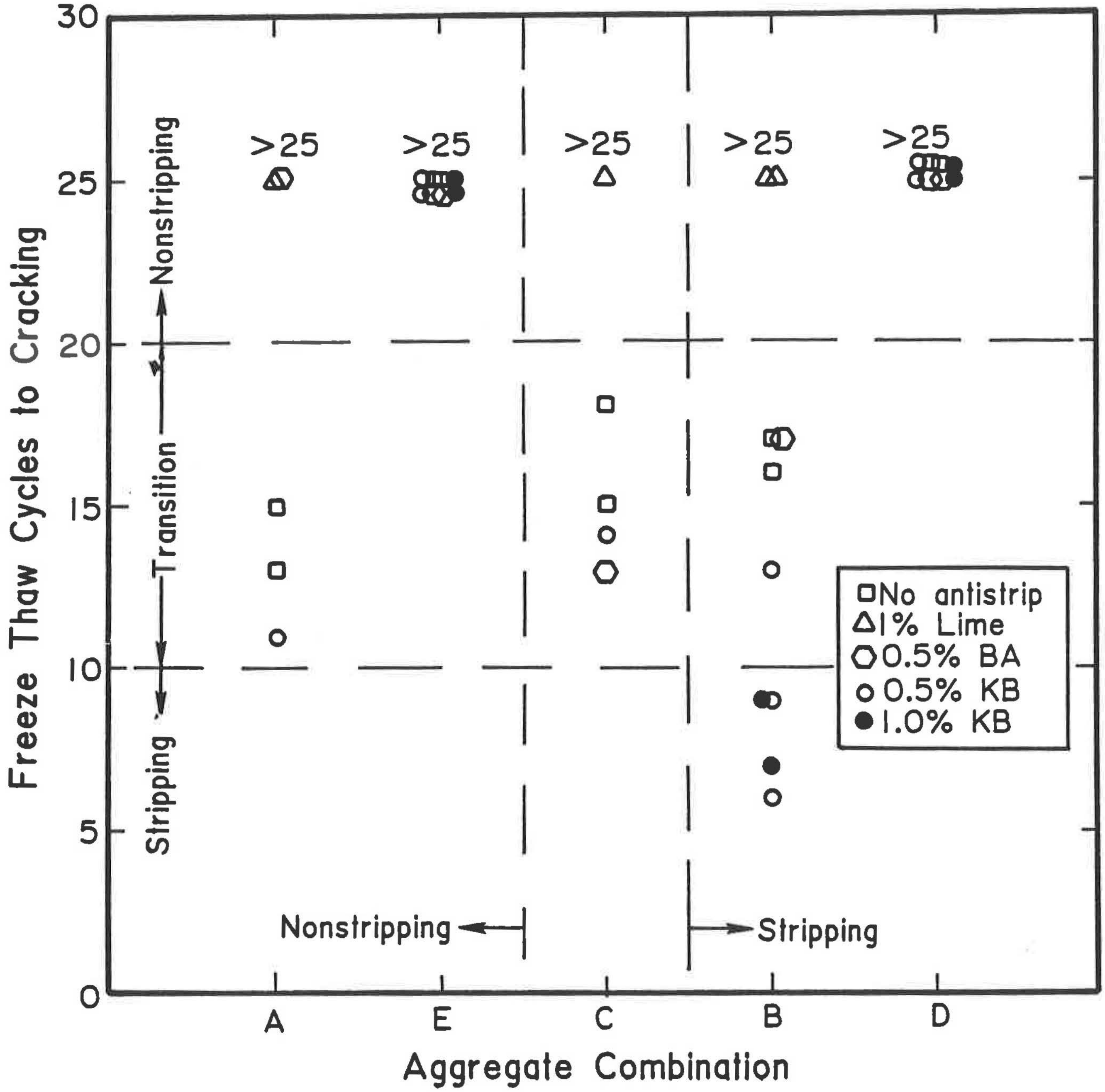

Figure 1. Prediction of Stripping with Stress Pedestal Test

Table 3. Freeze-Thaw Cycles to Cracking for Individual Aggregate Components

Aggregate (% Mix)	Cycles to Cracking
A1 (65)	9
A2 (15)	9
A3 (20)	9
B1 (10)	6
B2 (20)	>50
B3 (70)	40
C1 (15)	>50
C2 (25)	10
C3 (60)	4

Mixed with AC2

from further consideration early in the testing program. Additional factors that made the test less attractive than the boil or indirect tensile test are:

1. The time required, special equipment needed and test procedure difficulty.
2. Inability of the test to simulate important mix properties (gradation, asphalt film thickness, void content and void size).

Boil Test

Boil test results for surface mixes, base/binder mixes and individual aggregate components are summarized in Table 4. Data for surface and base/binder mixes are plotted in Figure 2 along with a 90% coating retention criteria. For the two limestone aggregate combinations (A & E), the boil test correctly predicted the low stripping potential for combination E but incorrectly for combination A. For two gravel aggregate combinations (B & D), the test correctly predicted the high stripping potential for combination B but incorrectly for combination D. For the marginal aggregate combination C, three mixes had lower and one mix had higher than 90% coating retention.

The test results for individual aggregate provided no indication that a particular aggregate component could be identified as the cause of stripping. Neither could test on coarse or fine fractions identify which size particles were more susceptible to coating loss. This apparent insensitivity may be partly due to the effects of asphalt content (asphalt film thickness) and gradation rather than particle properties (mineralogy, shape, size, porosity charge, etc).

Table 4. Boil Test Results (Percent Coating Retained) - Without Additive

Fraction / Asphalt Cement / Aggregate or Aggregate Combination	Total Sample		3/8" - #4		A Fine Fraction (typ. #40-#80)	
	AC1	AC2	AC1	AC2	AC1	AC2
A-Surface	70	70	50	40	20	15
A-Base/Binder	25	35	--	--	--	--
A1	85	50	45	25	45	25
A2	15	15	--	--	20	20
A3	40	35	40	35	--	--
B-Surface	55	60	40	40	30	40
B-Base/Binder	25	35	--	--	--	--
B1	75	40	50	35	40	30
B2	80	80	55	55	80	80
B3	75	60	45	40	30	30
C-Surface	95	75	35	40	95	95
C-Base/Binder	80	85	--	--	--	--
C1	95	95	--	--	95	95
C2	75	80	--	--	80	80
C3	75	45	25	30	25	25
D-Surface	95	95	--	--	--	--
D-Base/Binder	90	95	--	--	--	--
D1	95	90	90	90	--	--
D2	90	85	--	--	95	90
D3	45	45	--	--	90	85
E-Surface	95	90	--	--	--	--
E-Base/Binder	90	90	--	--	--	--
E1	95	85	80	75	--	--
E2	90	90	85	75	50	50
E3	30	30	--	--	80	80

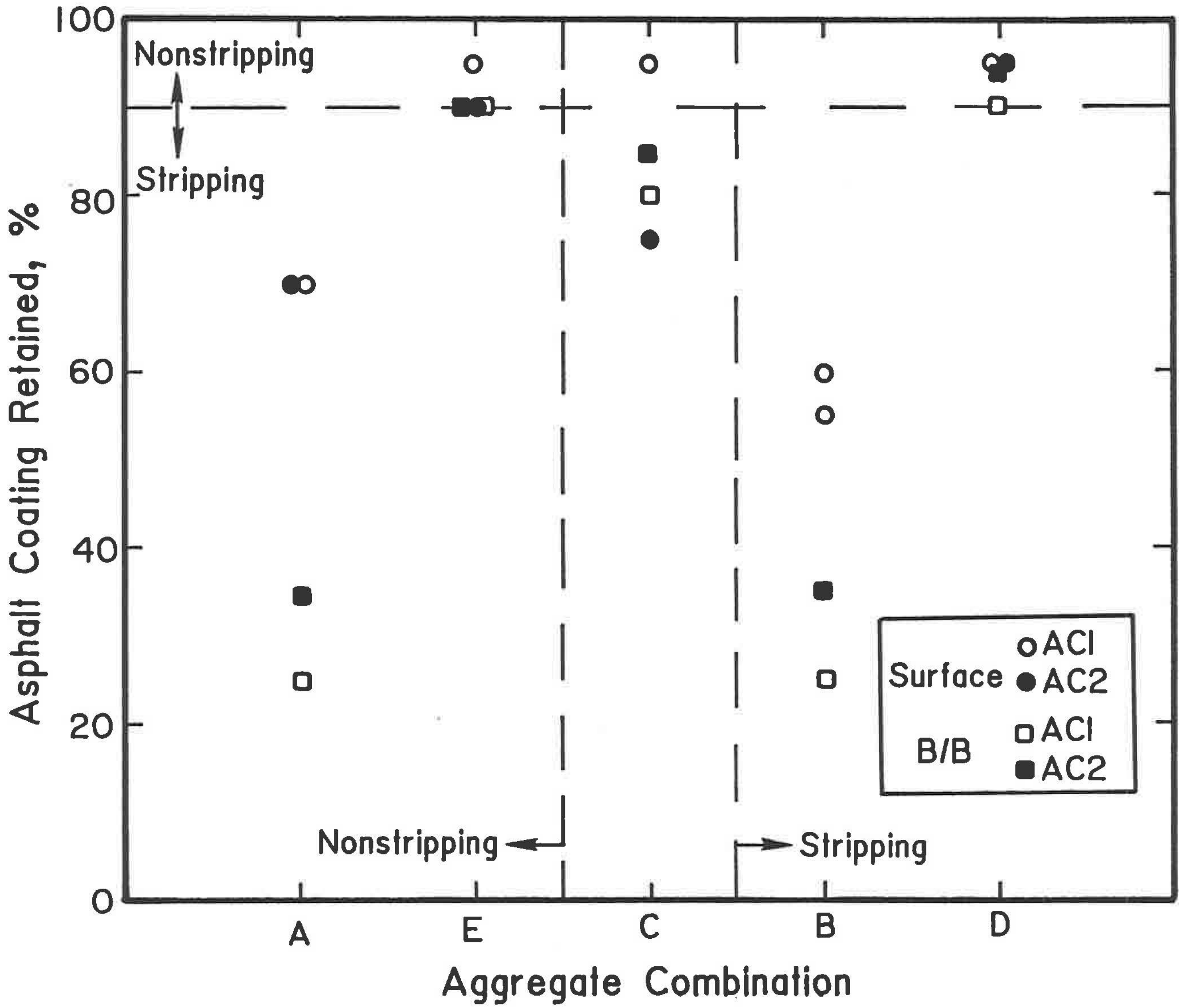

Figure 2. Prediction of Stripping with Boil Test

Tests, reported in reference 7, indicated that asphalt content influences coating retention, although, above an asphalt content sufficient to provide complete aggregate coating the effects are minimal. Aggregate size and gradation proved to significantly affect coating retention. Indications were that well graded aggregate containing fines was more resistant to coating removal. The differences between the response of the surface and base/binder mixes for combinations A & B may be, at least partly, due to differences in gradation and asphalt content. The base/binder mixes were coarser, had lower asphalt content and had lower coating retention.

Boil test results with antistrip agents are summarized in Table 5 and the effects of the various agents illustrated in Figure 3. Conclusions drawn from these data are:

1. Boil test reflect improvements in coating retention when antistrip agents included;
2. The effectiveness of antistrip agents is mix specific with asphalt cement having only nominal influence. Differences of 5-10% between AC1 and AC2 are not considered significant;
3. The liquid antistrip agents were more effective than lime in increasing coating retention. This confirms response reported in reference 3. This is most apparent for agent BA with combinations A, B and C; and
4. The liquid antistrip agents were not formulated for use with limestone aggregate and account for their relative ineffectiveness for combination A.

Table 5. Boil Test Results (Percent Coating Retained) - With Additives

Aggregate Combination	AC1					AC2				
	Antistrip					Antistrip				
	None	HL_a	BA_b	KB_b	KB_c	None	HL_a	BA_b	KB_b	KB_c
A-Surface	70	80	95	95	--	70	90	85	80	--
A-Base/Binder	25	50	60	60	--	35	50	60	50	55
B-Surface	55	70	90	60	85	60	75	90	50	80
B-Base/Binder	25	65	95	70	80	35	55	90	75	80
C-Surface	95	80	95	95	--	75	75	95	95	--
D-Surface	95	85	95	95	--	95	85	95	95	--
E-Surface	95	--	--	--	--	90	95	100	100	--

a - 1% Hydrated Lime (Based on Aggregate Weight)
b - 0.5% Antistrip Agent (Based on Asphalt Weight)
c - 1.0% Antistrip Agent (Based on Asphalt Weight)

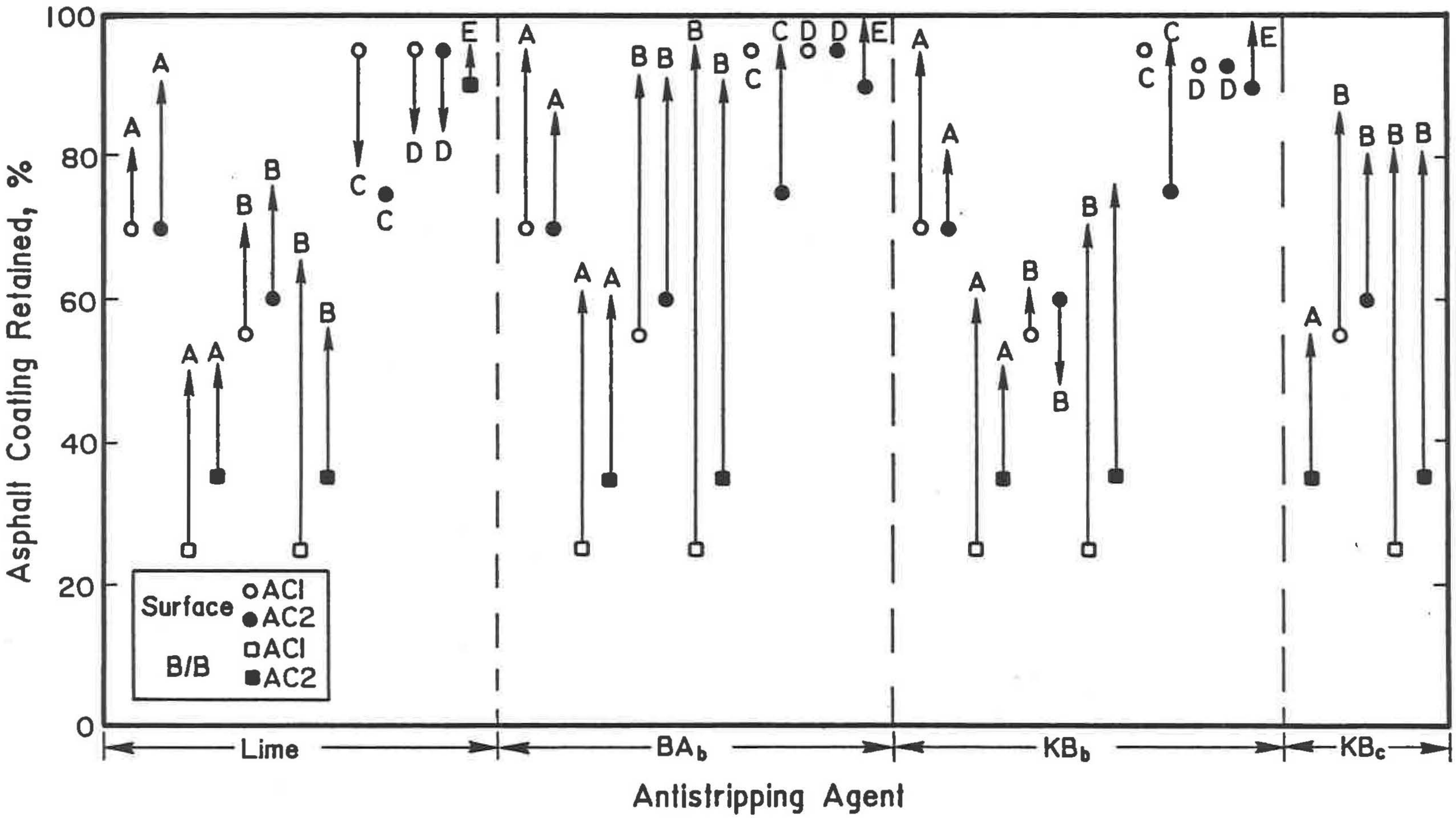

Figure 3. Effects of Antistrip Agents on Boil Test Results

Evaluation of the effectiveness of lime with the boil test is more difficult than liquid agents. When lime is used a white powdery coating (assumed due to unbound lime) often results. This reduces the luster and the intensity of the black asphalt coating which in turn reduces coating retention ratings. It is felt that the relatively poor performance of the lime may be, at least partly, due to the influence of the white powdery coating on the subjective asphalt coating retention rating. The boil test may not be a good indicator of the effectiveness of lime as an antistrip agent.

Indirect Tensile Test

Indirect tensile test results are summarized in Table 6 for surface and base/binder mixes without antistrip additives. These data can be used to examine the effects of several variables.

Figure 4 demonstrates the effects of sample preparation and moisture conditioning procedures on tensile strength loss. Tensile strength ratios (TSR) are plotted for the two conditioning procedures. The general trend, except for combination B, is that condition 2 is somewhat more severe than condition 1. Based on the comparison of the test procedures in Table 7, it appears that the one cycle of freezing (condition 1) caused a strength loss larger than strength gains resulting from mix and specimen aging.

Figure 5 demonstrates the effects of mix type on tensile strength loss. The general trend, except for combination E, is that strength loss is more severe for base/binder mixes. This is similar to the trend observed for the boil tests, particularly for combinations A & B.

Speculation is that these differences are due to the coarser gradation and lower asphalt cement content of the base binder mixes. Asphalt content

Table 6. Indirect Tensile Test Results - No Additives

Aggregate Combination		Asphalt Content (%)	Moisture Condition 1				Moisture Condition 2			
			Initial Voids (%)	Final Sat. (%)	TSR* (%)	SMR* (%)	Initial Voids (%)	Final Sat. (%)	TSR* (%)	SMR* (%)
Asphalt Cement 1										
A	Surf.	5.5	6.5	89	87	-	6.2	90	81	58
A	B/B	4.25	7.4	94	27	11	7.7	89	24	10
B	Surf.	7.5	7.0	100+	80	-	6.2	100+	81	53
B	B/B	4.5	6.6	100+	59	30	6.4	100+	76	60
C	Surf.	6.25	7.3	80	109	-	6.9	82	88	72
C	B/B	4.55	6.9	89	78	45	6.7	85	78	55
D	Surf.	6.25	7.4	88	107	76	7.5	93	98	71
D	B/B	4.9	6.6	97	83	47	6.6	98	79	44
E	Surf.	5.5	6.4	82	85	59	7.4	96	70	56
E	B/B	4.15	7.0	88	92	90	6.8	88	75	47
Asphalt Cement 2										
A	B/B	4.25	6.7	100+	41	17	6.4	100+	45	23
B	B/B	4.5	7.7	100+	52	29	7.2	100+	63	55
C	B/B	4.55	7.2	93	93	68	6.7	83	82	68
D	B/B	4.9	6.9	95	95	54	7.2	100	76	46
E	B/B	4.15	6.5	85	96	83	6.9	88	74	43

* Strength and modular ratios were computed for averages of minimum of 3 dry and 3 conditioned specimens.

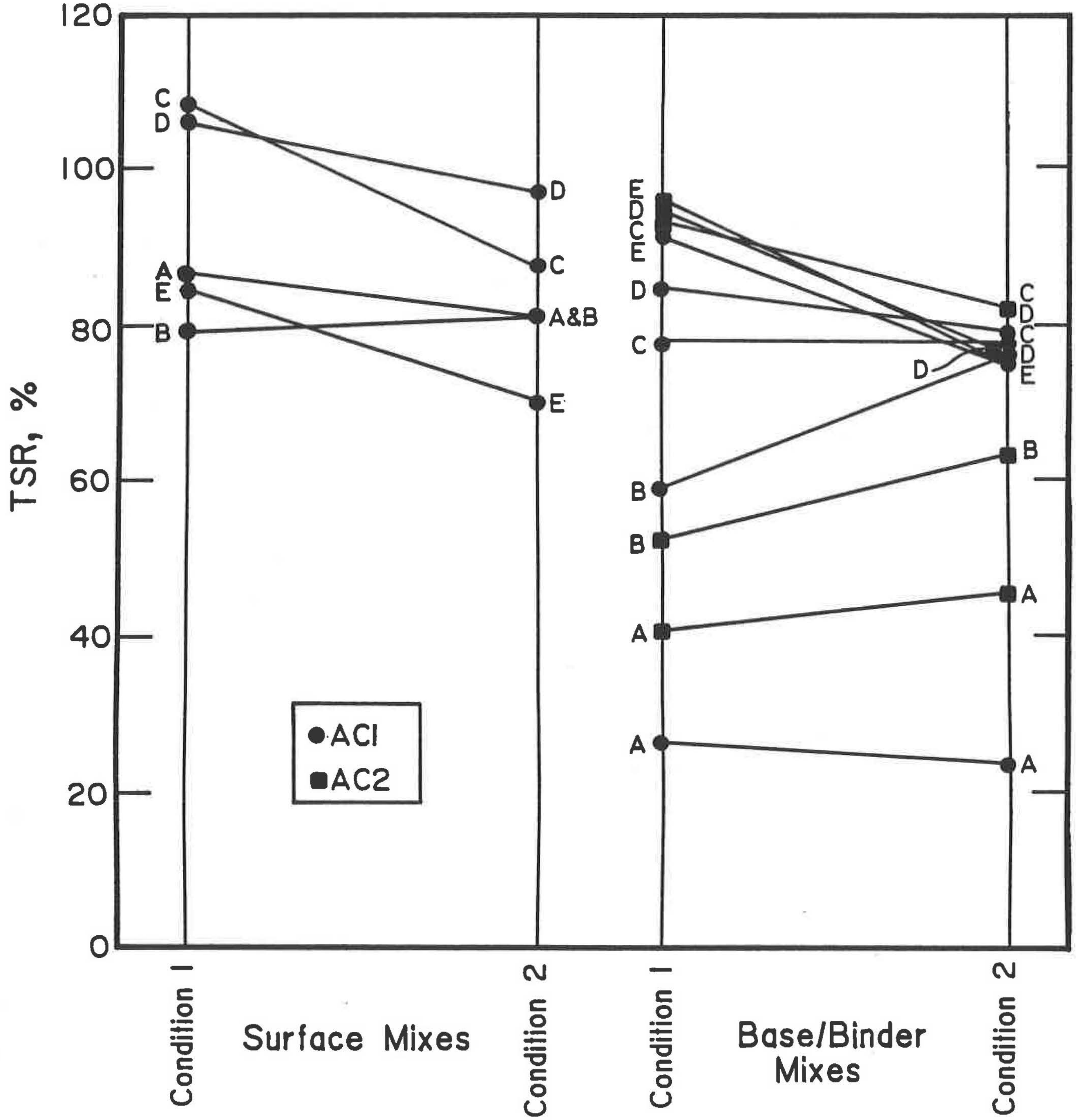

Figure 4. Comparison of Sample Preparation and Moisture Conditioning.

Table 7. Conditioning Procedures

Treatment	Condition 1	Condition 2
Mix aging	No aging	15 hours at 140^0 F
Compacted specimens curing	No curing	24 hours at room temp.
Initial Saturation	Between 60-80%	Between 60-80%
Freezing	No freezing	15 hours at 0 ± 4^0 F
Soaking	24 hours at 140^0 F	24 hours at 140^0 F
Age of specimen at testing	2 days	4 days
Similar procedure	Tunnicliff and Root (Ref. 2)	Modified Texas (Ref. 11)

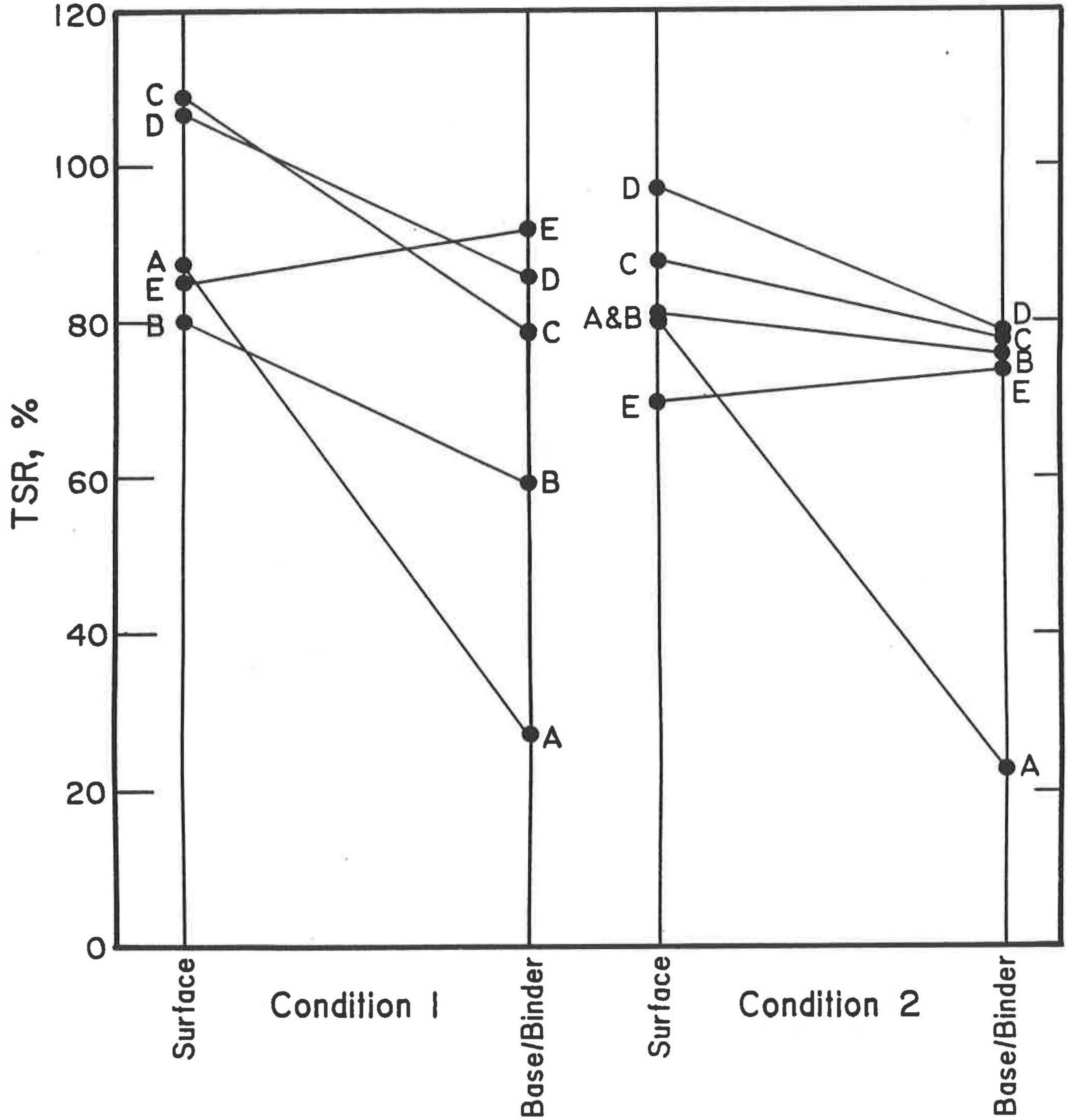

Figure 5. Comparison of Surface and Base/Binder Mixes

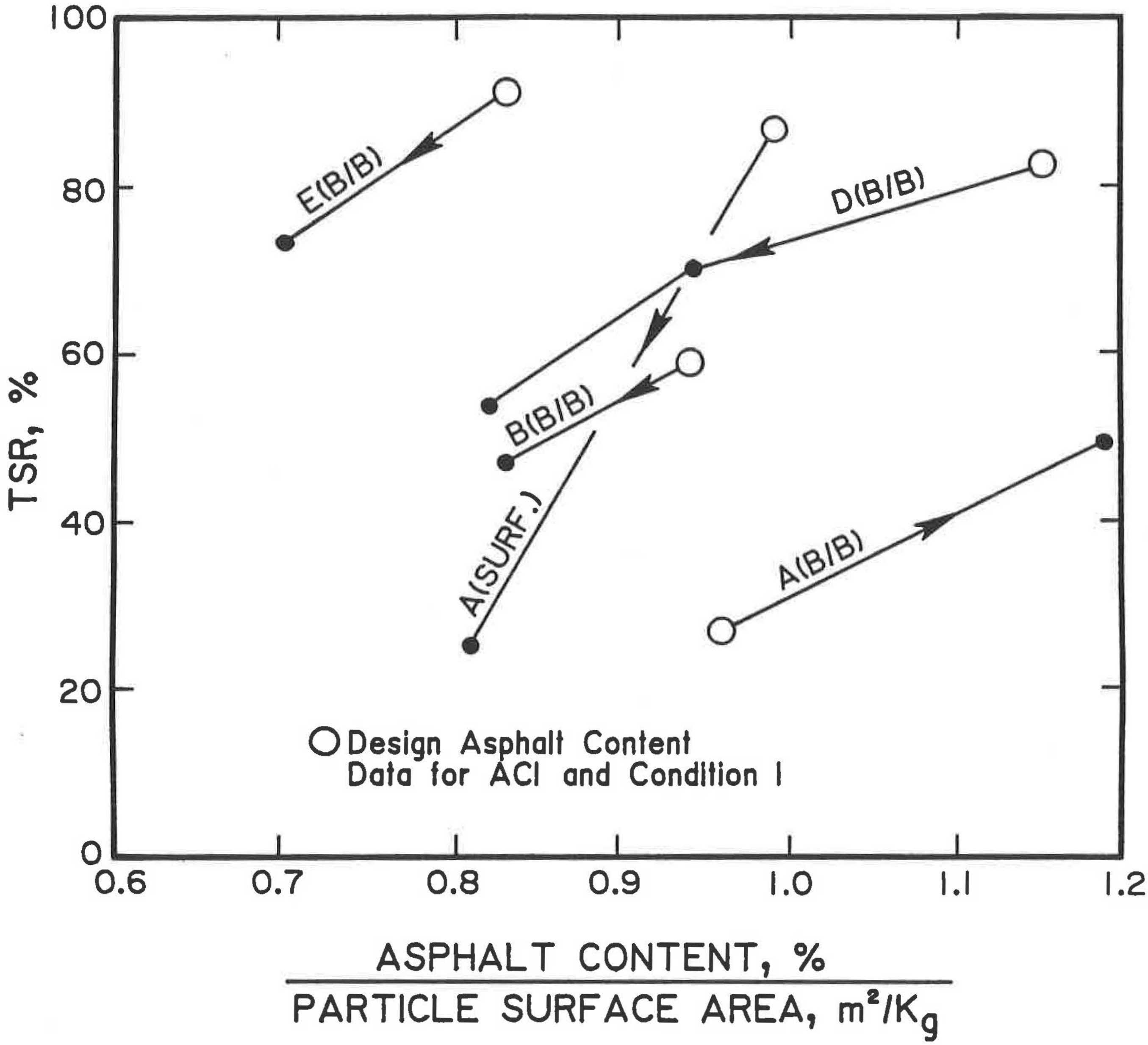

Figure 6. Effects of Asphalt Film Thickness on TSR

and gradation will determine asphalt cement film thickness. The lower asphalt content of base/binder mixes is compensated by coarser gradation but generally base/binder mixes are "leaner" than surface mixes. The effect of asphalt cement film thickness is demonstrated in Figure 6. Tensile strength ratio is plotted versus the ratio of asphalt content to particle surface area (15). Assuming the asphalt cement film thickness is directly proportional to the ratio, the observed decrease in TSR with decreasing ratio is as expected.

Gradation will also affect the nature of the voids in a mix. Although voids content was controlled at 6-8%, coarser gradations will likely produce fewer but larger voids. Larger voids will permit easier access to water and, thus, increase the potential for stripping. This effect is not easy to demonstrate, but evidence to support the contention are the lower TSR values for base/binder mixes. Additional evidence is provided by the fact that the line in Figure 6 for combination A base/binder mix is lower and to the right of the line for the surface mix. For a given TSR, this implies a higher asphalt film thickness is required for the coarser base/binder mix.

The effect of void size on permeability was apparent during vacuum saturation. A trial and error process was used to achieve 60-80% degree of saturation. Less intense partial vacuums and much smaller exposure times were required with base/binder mixes than with surface mixes having the same voids content.

Criteria for separating stripping and nonstripping mixes or for predicting the need for antistripping agents has been limiting TSR's. Minimum values of 70% (5 and 13) or 80% (12 and 14) have been suggested.

Data for mixes without antistrip agents are plotted in Figure 7 with the 80% criteria and reported performance. The following observations can be made from Figure 7:

1. There is not a strong correlation with reported performance.
2. None of the surface mixes were classified as strippers with 70% criteria and only one was classified as a stripper with 80% criteria.
3. For nonstripping base/binder mixes (A & E), the 70% criteria correctly categorized 4 mixes for E but the 80% criteria correctly categorized only 2 mixes; both for E.
4. For stripping base/binder mixes (B & D), the 70% criteria correctly categorized 3 mixes, but the 80% criteria correctly categorized 6 mixes.
5. The moisture conditioning procedure had no significant effect on mix classification with 70% criteria, but with 80% criteria, condition 2 resulted in an additional 7 mixes falling in the stripping category. Unfortunately 3 of these are for combination E, a supposedly nonstripping mix.
6. With the exception of combination A and B base/binder mixes, the predictions, in general, were unconservative.

Lottman (11) has suggested that a modulus ratio may be a better predictor of stripping than a tensile strength ratio. Secant modulus values were measured at failure stresses and secant modulus ratios (SMR) computed. Analysis of the SMR's showed trends similar to the TSR's with no improvements in correlation with reported performance.

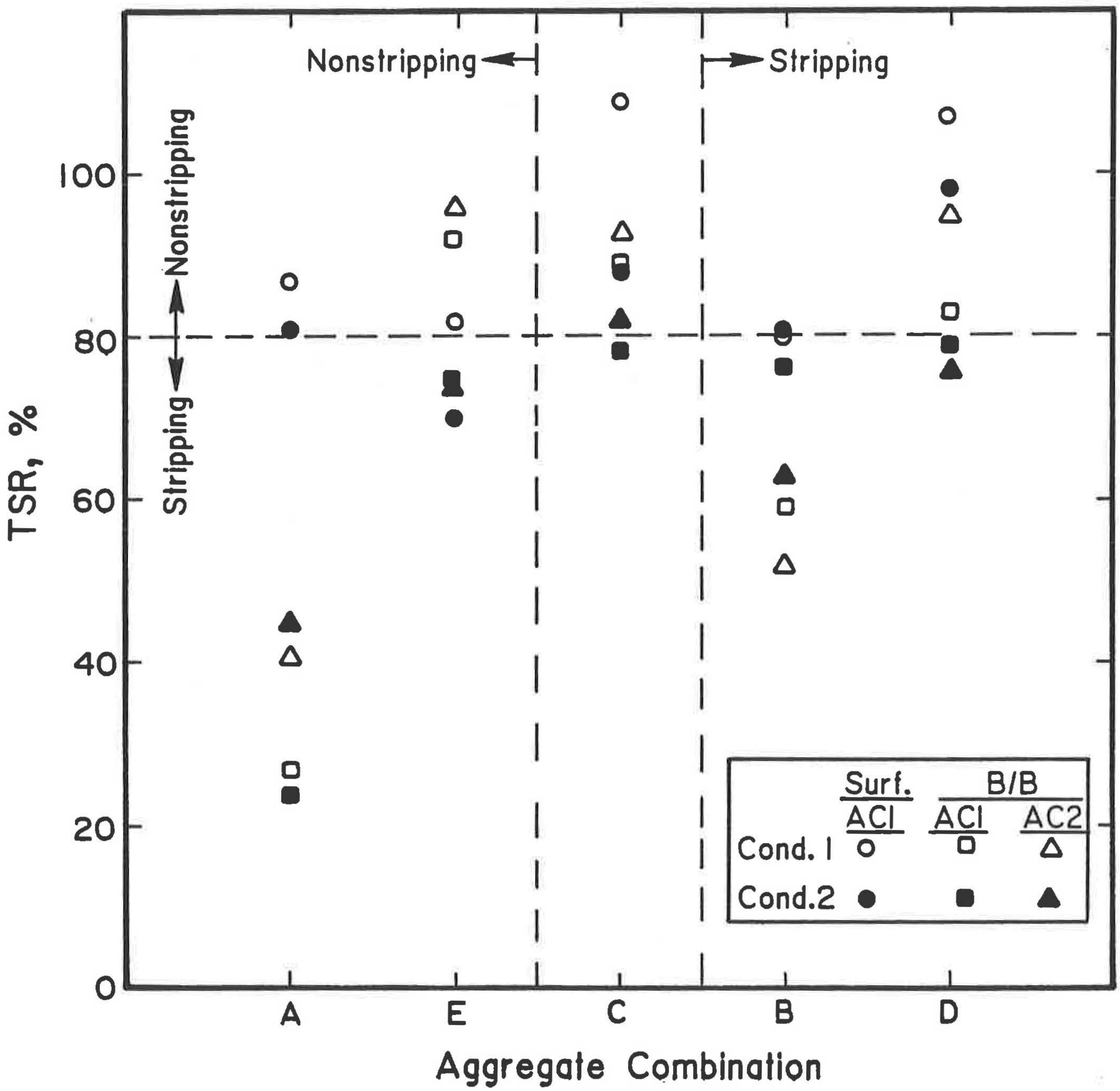

Figure 7. Prediction of Stripping with TSR's

Tunnicliff and Root (2) have suggested criteria for predicting stripping that is based on probabilistic comparison of the mean tensile strength of conditioned and control specimens. Their criteria is, "...a probability of 20:1 or more that the difference between wet and dry specimens is real was used to indicate that an additive should be considered." The strength data was analyzed using the suggested criteria. The results are tabulated in Table 8 and plotted in Figure 8. The probability criteria is shown on Figure 8 as the horizontal line at a probability of 20:1.

Comparison of the predictions with the deterministic criteria in Figure 7 with the probabilistic criteria in Figure 8 reveals contradictory predictions. In Figure 7, only 7 of the 30 points fall below 70% criteria indicating stripping mixes, whereas, 21 of the 30 points fall above the 20:1 criteria in Figure 8 indicating stripping mixes. Comparison of the criteria for individual aggregate combinations is shown below:

Aggregate Combination	Reported Performance	No. Predicted Strippers	
		Deterministic	Probabilistic
A	Non Stripper	4	6
B	Stripper	3	6
C	Variable	0	3
D	Stripper	0	1
E	Non Stripper	0	5

These comparisons indicate that the probabilistic criteria is much more conservative than the deterministic criteria.

Tests were run on base/binder mixes with antistrip additives for combinations A & B. Results are summarized in Table 9 and the effects of

Table 8. TSR and Probabilistic Mean Strength Comparison - No Additives

Aggregate Combination		Asphalt Cement 1				Asphalt Cement 2			
		Moisture Condition 1		Moisure Condition 2		Moisture Condition 1		Moisture Condition 2	
		TSR (%)	Prob. Real * Strength Diff.	TSR (%)	Prob. Real * Strength Diff.	TSR (%)	Prob. Real * Strength Diff.	TSR (%)	Prob. Real * Strength Diff.
A	Surf.	87	200:1	81	>1000:1	--	--	--	--
	B/B	27	>1000:1	24	>1000:1	41	>1000:1	45	>1000:1
B	Surf.	80	1000:1	81	>1000:1	--	--	--	--
	B/B	59	1000:1	76	22:1	52	600:1	63	110:1
C	Surf.	109	**	88	1000:1	--	--	--	--
	B/B	78	91:1	78	56:1	93	5:1	82	13:1
D	Surf.	107	**	98	1.5:1	--	--	--	--
	B/B	83	8:1	79	500:1	95	2:1	76	8:1
E	Surf.	85	143:1	70	>1000:1	--	--	--	--
	B/B	92	61:1	75	235:1	96	3:1	74	670:1

* Two tail "t" test to compare mean tensile strength.

** Conditioned strength greater than control strength.

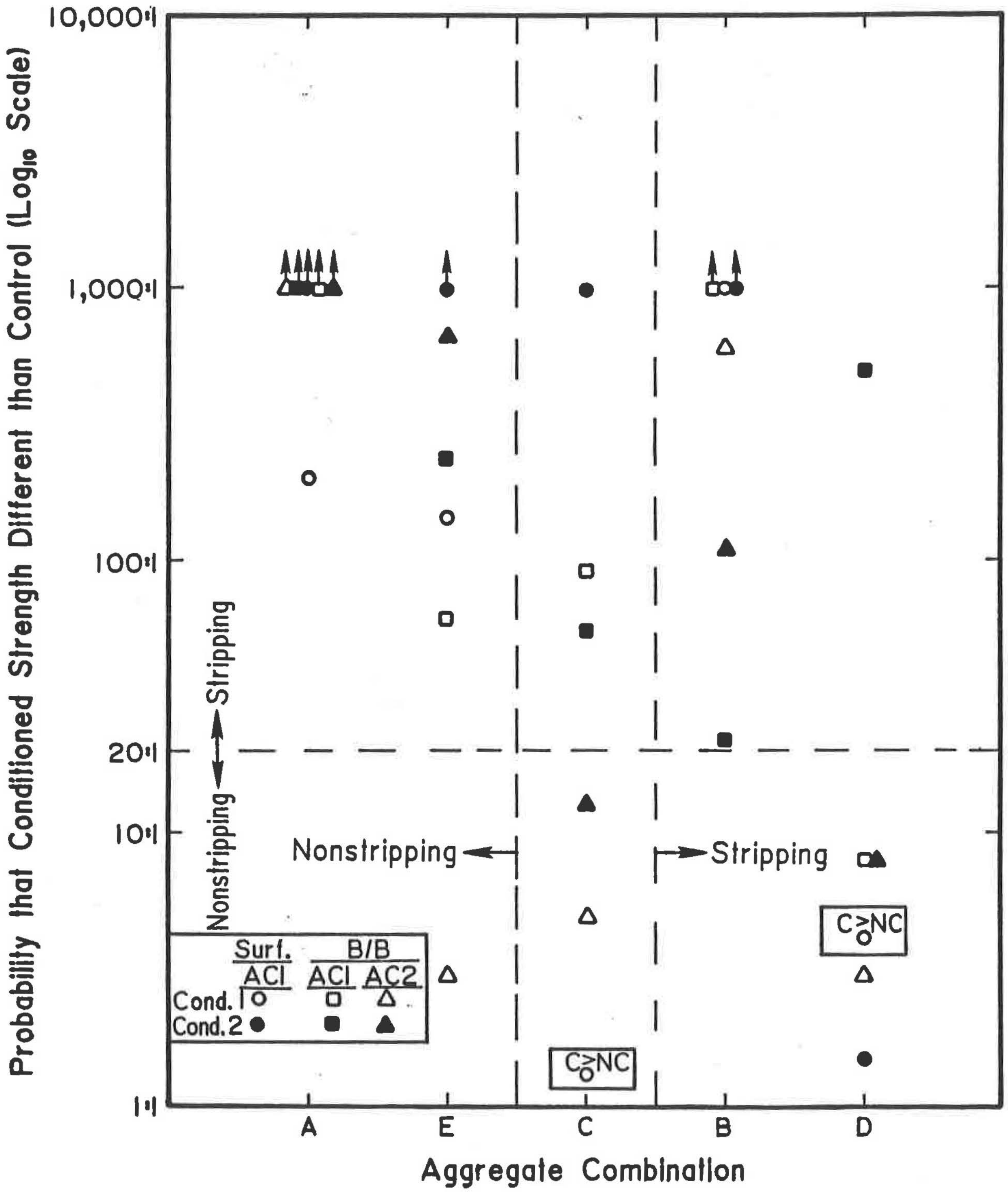

Figure 8. Prediction of Stripping with Probabilistic Mean Strength Comparison.

the various agents demonstrated in Figure 9. TSR values with and without antistrip agents are shown. None of the agents increased the TSR's for combination A mixes above a 70% criteria. TSR's for all but one combination B mix were increased above 70%. However, only the agent BA increased TSR's above an 80% criteria. This is consistent with boil test results where only the agent BA increased coating retention for combination B mixes above a 90% coating retention criteria. The variability in response illustrates the necessity for testing particular combinations of aggregate and asphalt cement in order to assess the effectiveness and dosage rate for antistrip agents.

Tunnicliff and Root (2) have recommended a two step procedure to determine antistrip effectiveness. First conditioned and unconditioned strength of a treated mix are compared. A probability of greater than 20:1 that the strengths are different is the first indicator that the antistrip agent is effective. The second step compares tensile strength ratios for untreated and treated mixes. A probability of 100:1 or more that the tensile strength ratios are different is the second indicator that the antistrip agent is effective enough.

Probabilities for combination A and B base/binder mixes are tabulated in Table 9. For combination A with AC1, the probability that conditioned strength is different from unconditioned strength is greater than 20:1 for all agents indicating potential stripping even if antistrip agents are used. This is consistent with the deterministic approach, Figure 9, where all TSR's are below 70%. The second comparison between treated and untreated TSR's indicates that all antistrip agents were effective since probabilities that TSR's are different are all above 100:1. This is also

Table 9. Indirect Tensile Test Results - With Additives

Aggregate Combination	Additive	Asphalt Content(%)	Asphalt Cement 1					Asphalt Cement 2				
			Initial Voids(%)	Final Sat.(%)	TSR (%)	Prob. Cond. St. Diff. from Uncond.*	Prob. Treated TSR Diff. from Untreated*	Initial Voids(%)	Final Sat.(%)	TSR (%)	Prob. Cond. St. Diff. from Uncond.*	Prob. Treated TSR Diff. from Untreated*
A-Base/Binder	None	4.25	7.4	94	27	>1000:1	--	6.7	100+	41	>1000:1	--
	HL_a	4.25	7.3	100+	56	100:1	>1000:1	7.2	100+	68	>1000:1	185:1
	BA_b	4.25	7.2	100+	58	200:1	600:1	7.4	100+	59	330:1	40:1
	KB_b	4.25	6.0	100	61	70:1	400:1	6.9	100+	44	150:1	1.4:1
	KB_c	4.25	6.0	100	58	70:1	130:1	6.7	100	41	>1000:1	--
B-Base/Binder	None	4.5	6.6	100+	59	>1000:1	--	7.7	100+	52	600:1	--
	HL_a	4.5	6.7	100+	72	27:1	7:1	6.4	100+	67	>1000:1	700:1
	BA_b	4.5	6.7	100+	89	3:1	500:1	6.3	100+	82	22:1	600:1
	KB_b	4.5	7.1	100+	73	660:1	40:1	7.3	100+	71	>1000:1	170:1
	KB_c	4.5	6.6	100+_	80	>1000:1	410:1	6.8	100	78	>1000:1	1000:1

a - 1% Hydrated Lime (Based on Aggregate Weight)
b - 0.5% Antistrip Agent (Based on Asphalt Weight)
c - 1.0% Antistrip Agent (Based on Asphalt Weight)
* - Computed for average of minimum of 3 unconditioned and 3 conditioned specimens

All test with moisture condition 1.

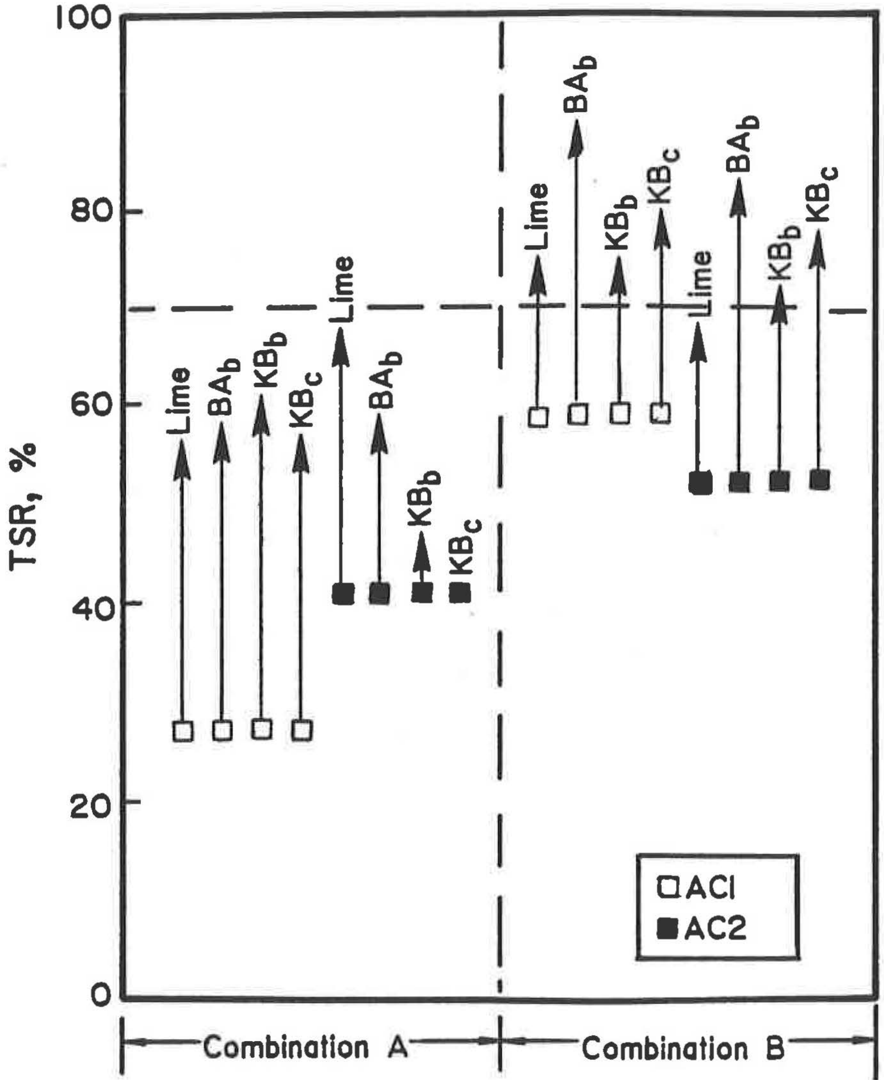

Figure 9. Effects of Antistrip Agents on TSR

consistent with the deterministic approach where TSR's were increased by about 30% (see Figure 9). Implications are that increased dosage rates may have achieved acceptable results.

For combination A with AC2, the first step comparison indicates that none of the agents were effective in preventing stripping (probabilities of strength differences greater than 20:1). This is consistent with Figure 9 where all TSR's are less than 70%. The second comparison indicates that only lime was effective, i.e., probability that TSR's are different is greater than 100:1. This is consistent with Figure 9 where the arrow for lime is the longest indicating that it is the most effective.

Similar comparisons for combination B reveals that agent BA is the most effective. It meets an 80% TSR criteria for both asphalt cements and meets both probabilistic criteria for AC1. It is very close for AC2. The probability that conditioned strength is different from unconditioned strength is 22:1 and criteria is 20:1. The probability that treated and untreated TSR's are different is 600:1 meeting the 100:1 criteria for the second comparison.

None of the other agents meet both the probabilistic criteria or the 80% criteria. The KB agent and lime for AC1 do, however, meet a 70% TSR criteria.

Comparison of Boil and Indirect Tensile Tests

Test results for individual aggregate combinations can be compared by examining Figures 2 and 7. The results can be compared for consistency between tests and accuracy of the tests in predicting reported performance.

For combination A, the relative ranking of surface and base/binder mixes is the same for both tests. The boil test predicts both type mixes as strippers, contrary to reported performance, but the tensile test predicts only the base/binder mixes as strippers (70 or 80% TSR criteria).

For combination E, both tests predict both type mixes as nonstrippers when 70% TSR criteria is used. This is consistent with reported performance. However, when 80% TSR criteria is used the tensile test with moisture condition 1 predicts stripping.

For combination C, the boil test generally predicts stripping and the tensile test generally predicts nonstripping (70 or 80% TSR criteria).

For combination B, the boil test predicts stripping for both type mixes which is consistent with reported performance. The boil test with 70% TSR criteria predicts variable performance, but with 80% TSR criteria predictions are consistent with boil test predictions (surface mixes at 80% TSR).

For combination D, both tests predict no stripping which is contrary to reported performance.

An overall comparison of the test procedures can be made by examining the test data summarized in Table 10 and plotted in Figure 10. A 90% coating retention criteria and 80% TSR criteria are shown on Figure 10. The trend exhibited by the data points instill a certain confidence that both tests are measuring, at least partially, similar processes. The linear regression relationship shown confirms this trend but the $r^2 = 0.62$ indicates that there is considerable unassociated variation. Figure 10 is not recommended for estimating TSR from coating retention or vice versa.

Table 10. Summary of Boil and Indirect Tensile Tests Data

Aggregate Combination	Type Mix \ Anti-Strip Agent	AC 1														
		Boiling Test % AC Retained					Indirect Tension Test Tensile Strength Ratio (%)									
							Condition 1					Condition 2				
		None	HL	BA	KB_a	KB_b	None	HL	BA	KB_a	KB_b	None	HL	BA	KB_a	KB_b
A	Surface	70	80	95	95	-	87	-	-	-	-	82	-	-	-	-
	Base	25	50	60	60	-	27	56	58	61	58	24	-	-	-	-
B	Surface	55	70	90	60	85	80	-	-	-	-	81	-	-	-	-
	Base	25	65	95	70	80	59	72	97	73	83	76	-	-	-	-
C	Surface	95	80	95	95	-	109	-	-	-	-	88	-	-	-	-
	Base	80	-	-	-	-	78	-	-	-	-	78	-	-	-	-
D	Surface	95	85	95	95	95	107	-	-	-	-	98	-	-	-	-
	Base	90	-	-	-	-	82	-	-	-	-	79	-	-	-	-
E	Surface	95	-	-	-	-	85	-	-	-	-	70	-	-	-	-
	Base	90	-	-	-	-	92	-	-	-	-	75	-	-	-	-

Aggregate Combination	Type Mix \ Anti-Strip Agent	AC 2														
		Boiling Test % AC Retained					Indirect Tension Test Tensile Strength Ratio (%)									
							Condition 1					Condition 2				
		None	HL	BA	KB_a	KB_b	None	HL	BA	KB_a	KB_b	None	HL	BA	KB_a	KB_b
A	Surface	70	90	85	80	-	-	-	-	-	-	-	-	-	-	-
	Base	35	50	60	50	55	41	68	59	44	41	45	-	-	-	-
B	Surface	60	75	90	50	80	-	-	-	-	-	-	-	-	-	-
	Base	35	55	90	75	80	52	67	82	71	78	63	-	-	-	-
C	Surface	75	75	95	95	-	-	-	-	-	-	-	-	-	-	-
	Base	85	-	-	-	-	93	-	-	-	-	82	-	-	-	-
D	Surface	95	85	95	95	95	-	-	-	-	-	-	-	-	-	-
	Base	95	-	-	-	-	95	-	-	-	-	76	-	-	-	-
E	Surface	90	95	100	100	-	-	-	-	-	-	-	-	-	-	-
	Base	90	-	-	-	-	96	-	-	-	-	74	-	-	-	-

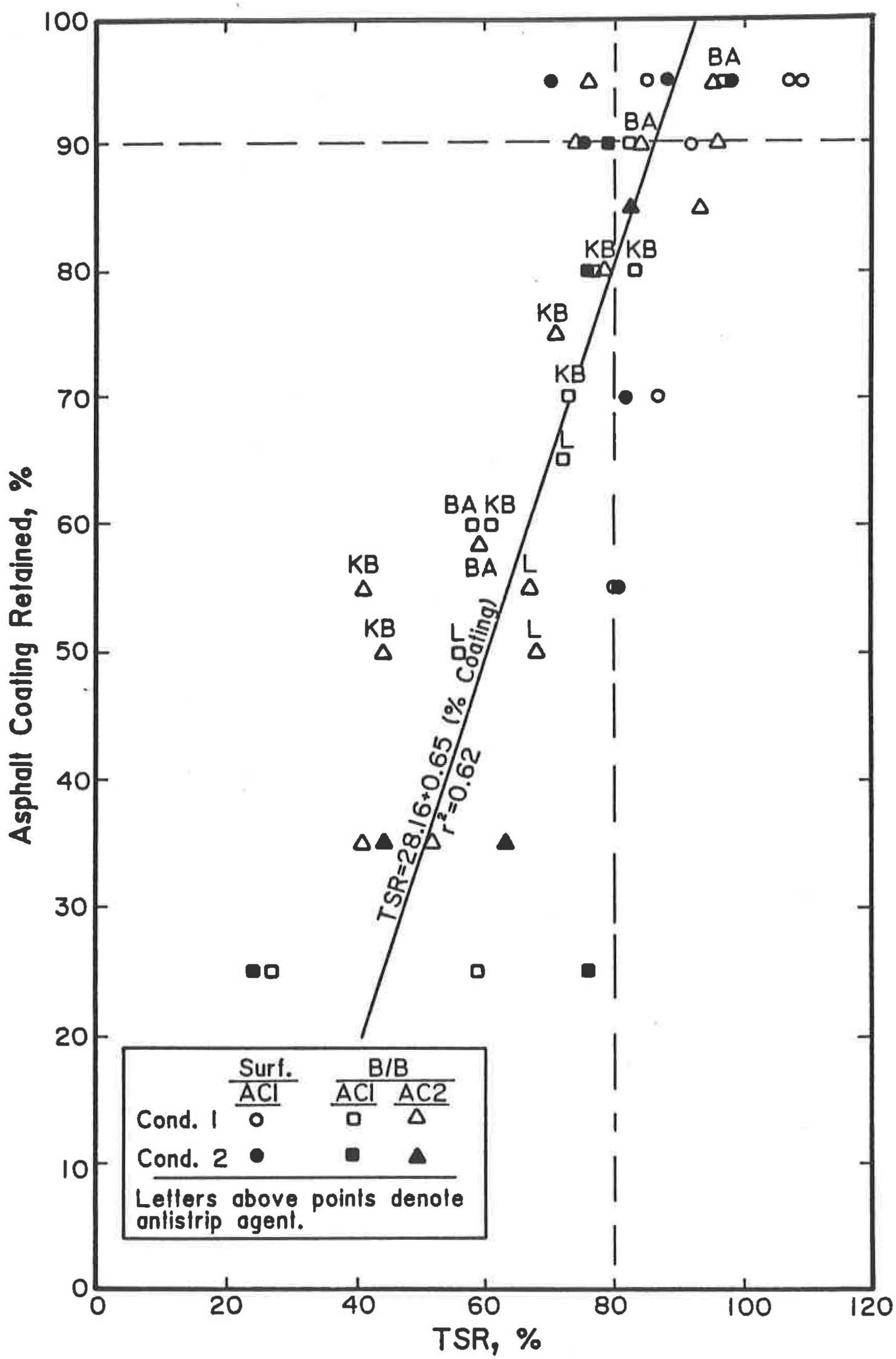

Figure 10. Comparison of Boil and Indirect Tensile Tests

If data points on the criteria lines are assumed to indicate a match between tests, then only 8 data points fall within the upper left and lower right zones where the tests predict different stripping potential. This means that 37 or 82% of the test predicted the same stripping potential. This does not mean that such a high percentage of predictions matched reported performance since there were numerous cases where both tests predicted performance different than reported.

CONCLUSIONS AND RECOMMENDATIONS

Because of the complexity of the test and lack of strong correlation with reported performance the stress pedestal test is not recommended for determining stripping potential or antistrip agent effectiveness. The boil and tensile strength test, in combination, are recommended as a viable, although imperfect, system. Both procedures test the entire mix at design asphalt contents. Aging can be simulated and the indirect tensile tests provides limited simulation of construction and environmental conditions. The lack of strong correlations with reported field performance detracts from both tests. However, the subjective nature of the reported performance and the relatively strong correlation between tests strengthens their choice. Additional tests with field mixes and long term systematic performance evaluation will be necessary to verify application of the test procedures and proposed criteria.

The indirect tensile tests measures loss of strength, the basic result of stripping, and offers a definitive laboratory tests for assessing stripping potential and evaluating antistrip agent effectiveness. The boil test correlate relatively well with the tensile tests and reported performance, and offers a simple field tests for quality control.

Each proposed mix; aggregate, asphalt cement and antistripping agent, must be tested. A change in any ingredient can affect test results and requires retesting.

The simple deterministic criteria is recommended for analyzing test results. A minimum 90% asphalt coating retention and 80% TSR is recommended for separating stripping from nonstripping mixes. Situations may arise when the two tests produce conflicting results. In these cases necessary steps should be taken to insure that the TSR criteria is met. As outlined below this may mean acceptance of coating retentions less than 90% for field quality control.

Utilization of boil and indirect tensile tests within normal mix design operations is recommended. Details of test procedures are contained in the Applendix. In addition to aggregate, proposed asphalt cement and antistripping additives should be submitted for evaluation. Antistripping additives should be accepted only after meeting established criteria with the proposed aggregate and asphalt combination. After selection of mix proportions, boil and tensile test should be conducted on mixes without antistrip additives and a decision made regarding the need for antistripping additives. If retained tensile strength is less than 80%, the test should be repeated with proposed antistripping agents to determine dosage rates to achieve a minimum 80% strength retention. For limestone mixes with a known history of acceptable performance, the 80% strength retention criteria may be waived.

A minimum retained coating criteria of 90% is recommended for the boil test. However, a lower retained coating may be accepted provided tensile strength retention is equal to or greater than 80%. Boil test specimens to be used for field evaluation are recommended in all cases, but where a coating retention criteria less than 90% is accepted, they should be mandatory. These specimens should be used for comparison with field specimens to insure compliance during construction.

Because of the difficulties inherent in quantifying retained coating for complete mixes, initially the boil test with one size standard aggregate, as well as the complete mix, should be conducted when anti-stripping additives are used. The purpose of these tests will be to detect antistripping additives and to monitor their effectiveness. A minimum coating retention value and specimens for field comparison should be developed and used to detect and quantify antistripping additives. The use of the complete mix and the one size standard aggregate with the boil test should be evaluated and the most effective selected for antistrip additive control.

During production, a boil test should be run for every 1000 tons of mix produced. The percent retained coating should be determined and field specimens compared with the provided laboratory specimens. A coating retention value less than 10% of the acceptable value and/or distinct visual differences with the laboratory specimen should be cause for retesting. Confirmation of noncompliance after retest of the mix being produced should result in a complete laboratory re-evaluation (tensile and boil tests) with materials being used.

When antistripping additives are used, they should be evaluated under conditions approximating field conditions. When additives are added with on-line blending equipment at the mixing plant no aging will be required, and testing may begin immediately after blending with asphalt cement. When additives are added at the refinery the asphalt cement with additive should be aged 96 hrs. at 325^{0}F in a closed container prior to testing.

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APPENDIX

TEST PROCEDURES

EFFECT OF WATER ON LOOSE
ASPHALT CONCRETE MIXTURES
(BOILING TEST)

1. SCOPE

This test method covers a procedure to determine the percentage of asphalt coating retained on aggregate in order to evaluate the susceptibility of a paving mix to stripping. It is also used to evaluate the effectiveness of anti-stripping additives.

2. APPARATUS

1 - Stainless steel bowl 8 inches in diameter and 3 inches in depth
2 - Oven capable of attaining a temperature of 350 ^{0}F
3 - Balance with capacity of 2000 grams, sensitive to 0.1 gram
4 - Small spatula with a 4 in blade
5 - Hot plate
6 - 2000-ml Pyrex glass beaker
7 - Glass rod 1/4 inch thick and 10 inches long
8 - Thermometers for general use to measure temperatures between 50-500 ^{0}F sensitive to 1 ^{0}F
9 - Tongs
10 - Six-ounce ointment cans
11 - Asbestos gloves
12 - Distilled or deionized water
13 - Stop watch

3. TEST PROCEDURE

3-1 Mix Preparation

3-1-1 Heat about 100 grams of asphalt at 325 ± 5 ^{0}F for 24-26 hours. If liquid anti-strip agents are to be evaluated and have not been preblended they must be added to the asphalt. Preheat the asphalt to 275 ^{0}F, add the required amount of anti-strip agent, and immediately mix for 2 minutes. If hydrated lime is to be used, it must be added to aggregate, mixed dry, sprayed with water (3-5% of aggregate weight), remixed and dried at 210 ^{0}F for 24 hours.

3-1-2 Heat 300 grams of aggregate in the stainless steel bowl for 1 1/2 hours at 325 ± 5 ^{0}F.

3-1-3 Add the required amount of asphalt cement to the aggregate in the bowl and mix for 3 minutes while the bowl is on the hot plate at moderate heat. Reduce the heat and complete mixing until complete aggregate coating is achieved.

3-1-4 Allow mix to cool to room temperature.

3-2 Performing Boiling Test

3-2-1 Fill 1000 ml. of distilled water in a beaker, and heat to boil on a hot plate.

3-2-2 Reduce the heat so that boiling is minimum.

3-2-3 Add the mix to the boiling water, this will bring the water to below the boiling point.

3-2-4 Increase heat so that the boiling restarts within 2-3 minutes.

3-2-5 Maintain the water at medium boil for 10 minutes.

3-2-6 Stir the mix with the glass rod at 3 minute intervals.

3-2-7 Remove the beaker from the hot plate and allow mix to cool to room temperature.

3-2-8 Decant the water from the beaker and empty the mix into a white paper towel.

3-2-9 During and after boiling, skim stripped asphalt from the surface of the water by using a paper towel to prevent recoating.

3-3 Evaluation of Coating Retained

Visually estimate the degree of stripping present in the mixture. A panel of at least 3 members should estimate the percent asphalt coating retained and the average should be used. The mix should be examined only after it has been allowed to dry. A rating board should be progressively established to aid rating. For field control, specimens will be compared to laboratory specimens to detect changes and to evaluate for compliance.

4 REPORTING TEST RESULTS

Estimated percent asphalt coating retained is reported to the nearest 5 percent. For field control, differences with laboratory control specimens should be reported.

METHOD OF TEST FOR EVALUATING THE MOISTURE SUSCEPTIBILITY OF ASPHALT CONCRETE MIXTURES BY DIAMETRAL TENSILE SPLITTING

1. SCOPE

This test method covers a procedure to determine the effect of water on compacted asphalt concrete mixtures. It compares the diametral tensile strength of moisture conditioned specimen with that of unconditioned specimens. The test method may also be used to evaluate the effect of anti-strip additives on asphalt concrete.

2. APPARATUS

The apparatus outlined in ASTM D 1559 are needed along with the following:

2-1 Vacuum pump capable of producing a pressure drop of 26 inches of mercury

2-2 Pyrex or equivalent vacuum jars six inches in diameter and six inches high with smooth fired edges, flat rubber gaskets, stiff round metal plates greater than the jar diameter with vacuum hose receptacles, vacuum hose, and five inch diameter screen-type spacers of 1/2 inch height.

2-3 Stainless steel loading strips 1 inch wide and 2 1/2 inch long as shown in ASTM D 4123.

2-4 Calipers for measuring specimen height to the nearest .05 inch.

2-5 Distilled or deionized water.

3. TEST PROCEDURE

3-1 Mix preparation.

3-1-1 If liquid anti-strip agents are to be evaluated and have not been preblended they must be added to the asphalt. Preheat the asphalt to 275^{0}F, add the required amount of anti-strip agent, and immediately mix for 2 minutes. If hydrated lime is to be used, it must be added to the aggregate, mixed dry, sprayed with water (3-5% of aggregate weight), remixed and dried at 210^{0}F for 24 hours.

3-1-2 Six specimens are mixed and prepared as described in ASTM D 1559 using the design aggregate and asphalt cement. Place the loose mix in the Marshall molds after mixing.

3-1-3 Cover the molds and stabilize the mixture at the required compaction temperature by placing in an oven for 2-3 hours.

3-2 Molding

3-2-1 Compact specimens using the Marshall hammer. Adjust the number of blows so that the compacted specimen will contain 7 ±1% air voids. This will require trial and error to determine the required number of blows.

3-2-1 Cool specimens in the molds to room temperature as rapidly as possible and extract from the molds.

3-3 Density Determination

3-3-1 Determine the maximum theoretical specific gravity of the mix in accordance with ASTM D 2041.

3-3-2 Determine the bulk specific gravity of the six specimens in accordance with ASTM D 2726.

3-3-3 Calculate percent air voids of the six specimens in accordance with ASTM D 3203.

3-3-4 Sort the six specimens into two groups so that the average percent air voids of the two groups are approximately equal.

3-3-5 Place one of the groups (control) in a disiccater and store until testing.

3-4 Moisture Conditioning

3-4-1 Place specimens of the group to be conditioned in Pyrex jars and add distilled water to submerge the specimen (1 inch above specimen).

3-4-2 Apply initial vacuum level to the specimens in the jars for 5 minutes. Determine the degree of saturation. If the level of saturation is too low, increase the level of vacuum until a degree of saturation between 60-80% is achieved. Saturation in excess of 80% requires molding new specimens.

3-4-3 Calculate degree of saturation using the relationship:

$$S = \frac{(B-A)}{V\ (B - C)} \times 100$$

where

S = degree of saturation, %
A = dry weight of specimen in air
B = weight of surface-dry specimen after saturation
C = weight of saturated specimen in water
V = percent air voids expressed as a decimal

3-4-4 After vacuum saturation to the desired level is achieved, place specimens in a water bath for 24 hours at 140 ^{0}F.

3-5 Indirect Tensile Testing

3-5-1 Remove moisture conditioned specimens from the water bath and place them in another water bath at room temperature 72-77 ^{0}F for 1 hour.

3-5-2 For soaked specimens, determine the bulk specific gravity, percent air voids and the final degree of saturation as before.

3-5-3 Determine the specimen height and diameter for the control and conditioned specimens.

3-5-4 Test all specimens by indirect tensile loading to failure using the Marshall machine at a rate of loading of 2 inches per minute. Condtioned specimens should be tested immediately after bulk specific gravity and height determination to prevent drying.

4. CALCULATIONS

4-1 Calcuate the indirect tensile strength of the specimens using the relationship:

$$S_t = \frac{2\,P_u}{\pi t d}$$

where

S_t = indirect tensile strength,
P_u = maximum diametral load,
t = specimen thickness, and
d = specimen diameter

4-2 Calcuate the tensile strength ratio (TSR) using the relationship:

$$TSR = \frac{\text{Average conditioned indirect tensile strength}}{\text{Average unconditioned indirect tensile strength}} \times 100$$

5. REPORTING TEST RESULTS

Report the initial air voids content, initial degree of saturation (after vacuum application), final degree of saturation (after soaking) and indirect tensile strength of all specimens. Report the tensile strength ratio (TSR) as a percentage.