

Evaluation of Indirect Tensile Tests for Assessing Stripping of Alabama Asphalt Concrete Mixtures

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Stripping in asphalt concrete has long been recognized as a cause of premature pavement damage. Yet, after many years of research and application, there are few generally accepted conclusions about the severity of the problem, the nature and causes of the process, or methods for evaluating stripping. The evolution of test procedures for assessing stripping potential appears to be progressing toward procedures that measure strength loss of moisture-conditioned mixtures compacted to 6 to 8 percent voids. Indirect tensile tests were performed on asphalt concrete mixes composed of materials common in Alabama. The purpose of these tests was to study the stripping process and to evaluate the test procedure for assessing stripping potential. Results indicate that published moisture-conditioning procedures produce variable strength loss but that either of the two procedures evaluated is acceptable. Results also indicate that asphalt cement content, as well as type of mix, has a significant influence on test results and that generalities concerning stripping potential of aggregate sources, types, and blends are not valid. Finally, test results did not distinctly delineate reported stripping and nonstripping aggregate combinations. Reasons may be that the reported performance of an aggregate combination is not valid for all mix types, or that the test is not a positive indicator of stripping potential. The former is more likely, but incorrect predictions for specific mixes are a definite possibility. Implications are that specific mix designs must be tested and results conservatively interpreted until field performance studies permit further refinements.

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, p. 239). Yet, after many years of research and application, there are few generally accepted conclusions about the severity of the problem, the nature and cause of the process, or methods for evaluating the stripping potential of asphalt-aggregate mixtures. Tunnichiff and Root (2), in the latest of a series of extensive studies of stripping, found no agreement on the severity of the problem, the causes of stripping, or test procedures for predicting stripping.

This lack of consensus is not surprising given the complexity of the process. Stripping was initially considered to be the separation of asphalt coatings from aggregate surfaces (3). This is still considered the dominant failure mode, but some researchers have added that a loss of cohesion in the asphalt cement may also result (4). Compounding the complexity are numerous contributing factors (i.e., coarse and fine aggregate

properties, asphalt cement properties, mix design, construction conditions, environment, and traffic).

The evolution of test procedures for assessing stripping potential appears to be progressing toward procedures that measure strength or modulus loss (loss of adhesion or cohesion, or both) of mixtures (particular aggregate and asphalt proportions) that have been compacted and conditioned (construction, environment, and traffic). This appears to be a logical choice because loss of strength is the most serious consequence of stripping. However, tests that attempt to measure other fundamental properties are still used. Some of these listed by Taylor and Khosla (5) are static immersion, dynamic immersion, chemical immersion, boiling, abrasion, simulated traffic, swell, and stress pedestal.

Evolution of loading has progressed from compression, as standardized in ASTM Method D 1075, to tensile (2, 6-11). Sample preparation has evolved from standard Marshall or Hveem procedures to procedures that compact aged mix to controlled void contents. Conditioning has progressed from simple soaking to vacuum saturation followed by various combinations of freezing, thawing, and soaking.

The objective of the research reported herein was to evaluate indirect tensile tests for assessing the stripping potential of asphalt-aggregate mixtures made from typical Alabama materials. Five aggregate combinations were tested.

LABORATORY TESTS

Tests on compacted mixtures to evaluate moisture damage have historically compared strength or modulus of moisture-conditioned specimens with strength or modulus of unconditioned specimens. This comparison has been made by computing a strength or modulus ratio by dividing the conditioned strength or modulus by the unconditioned strength or modulus.

There have been numerous differences in proposed test procedures. These variations can cause differences in measured strength and modulus values and, therefore, differences in strength or modulus ratios. Consideration of these differences is necessary when evaluating test procedures and selecting limiting criteria.

Variations have been in the following general areas:

1. Sample preparation,
2. Moisture conditioning,
3. Loading conditions, and
4. Interpretation of test results.

Each will be discussed and details used in this study noted.

Sample Preparation

Recommended sample preparation generally follows or permits the Marshall (ASTM D 1559) or some form of kneading (ASTM D 1561) or gyratory shear (ASTM D 3387) procedure. There is no evidence to indicate that strength or modulus ratios might be affected by the method of application of compaction energy. Two parameters that are thought to be important in determining moisture effects are mix aging before compaction and voids content after compaction.

Some test procedures (7, 9, 11) call for aging the uncompacted mix at 140°F for 15 hr before compaction. This aging allows oxidation and hardening of the asphalt cement that, in theory, simulate construction and in-service conditions. There is some agreement that high-viscosity asphalts may be more effective in resisting stripping (2, 4, 5, 12), but the magnitude or significance is not well established. Aging of uncompacted mix was a variable included in this study. Condition 1 specimens were not aged, and Condition 2 specimens were aged for 15 hr at 140°F.

Additional details of the test conditions will be presented subsequently. Condition 1 was recommended by Tunnicliff and Root (2), and Condition 2 is basically a modified version of the accelerated procedure developed by Lottman (7). It is contained in Hazlett (11) as Texas Test Method Tex-531-C.

Air void content will determine the potential intensity of exposure to water. The trend in specifying void content is toward setting specific limits in order to minimize the effect of void content. Lottman (7, 8) recommends no specific limits, but implications are that specification voids should be achieved. Three procedures (2, 9, 11) recommend 6 to 8 percent voids. The Georgia procedure (10) recommends variable voids content depending on mix type, but the range is normally within 5 to 8 percent. All specimens for this study were compacted to void contents of from 6 to 8 percent.

Moisture Conditioning

The following parameters are critical in the moisture-conditioning phase:

1. Initial saturation achieved during vacuum application,
2. Freezing after vacuum saturation, and
3. Soaking.

Vacuum saturation is the first and possibly most important step in moisture conditioning. It determines the extent to which voids are filled with water and, thus, the intensity of exposure of the mix to water. The degree of saturation achieved depends primarily on the magnitude of the vacuum and to a lesser extent on the time of exposure. Three procedures (7, 8, 10) recommend a 26-in. vacuum applied for 30 min. This results in variable degrees of saturation depending on specimen properties. Several vacuum saturation schemes are reported in Kennedy and Anagnos (9) with a recommendation that degree of saturation be limited to from 60 to 80 percent.

Root and Tunnicliff (2) recommend an initial saturation of from 55 to 80 percent and the Texas procedure (11) an initial

saturation of from 60 to 80 percent. Saturation of specimens for this study was maintained within 60 to 80 percent.

There is no consensus about what additional conditioning may be needed after vacuum saturation to promote development of stripping. Freezing, cyclic freezing-thawing, soaking, and freezing plus soaking have been tried. Data from Lottman (7) and Kennedy and Anagnos (9) plotted in Figure 1 indicate that freezing after soaking increases strength loss and that, overall, 18 freeze-thaw cycles are somewhat more severe than freezing plus soaking. However, examination of individual mixes reveals that for many the difference between freeze-soak and cyclic freeze-thaw is small. For nine mixes the freeze-plus-soak conditioning produced the greatest strength loss. The validity of using freezing to simulate the stripping mechanisms has been questioned. It is the opinion of some that the strength reduction caused by freezing may be due to damage that is unrelated to the stripping process.

Data in Figure 2 from Kennedy and Anagnos (9) indicate that soaking, alone or in conjunction with freezing, may have a dominant effect on strength loss. Soaking, whether alone or in conjunction with freezing, should be an integral part of a conditioning procedure. Soaking provides contact time required for stripping mechanisms to develop. For the study reported herein, Condition 1 involved soaking only at 140°F for 24 hr, and Condition 2 involved one 15-hr freeze cycle to 0°F ± 4°F followed by a 24-hr soak at 140°F.

Loading Conditions

The following loading parameters have been varied in studies of strength or stiffness loss:

1. Type of loading,
2. Rate of application, and
3. Specimen temperature.

Indirect tensile (ASTM D 4123) appears to be the loading currently favored for assessing water damage to asphalt concrete. Unconfined compression (ASTM D 1075), Marshall (ASTM D 1559), and Hveem (ASTM D 1560) loadings have been and are being used (2), but they have not received extensive recent research attention. Double punch loading as proposed by Jimenez (6) has received little additional attention. Indirect tensile loading was used in this study.

Rate of loading and specimen temperature are variables that will affect absolute values of tensile strength and modulus but will probably not have a profound effect on strength or modulus ratios. Rates of loading have varied from 0.065 to 2.0 in./min and specimen temperature has varied from 55°F to 77°F. The study by Maupin (13) is often cited to illustrate insensitivity to rate of loading and temperature and to justify the use of a 2.0 in./min loading rate and a 77°F specimen temperature. These practical conditions were used for this study.

Interpretation of Test Results

Specimens were loaded to failure and vertical diametral load and horizontal diametral deformation were recorded. Indirect tensile strength was computed with the relationship

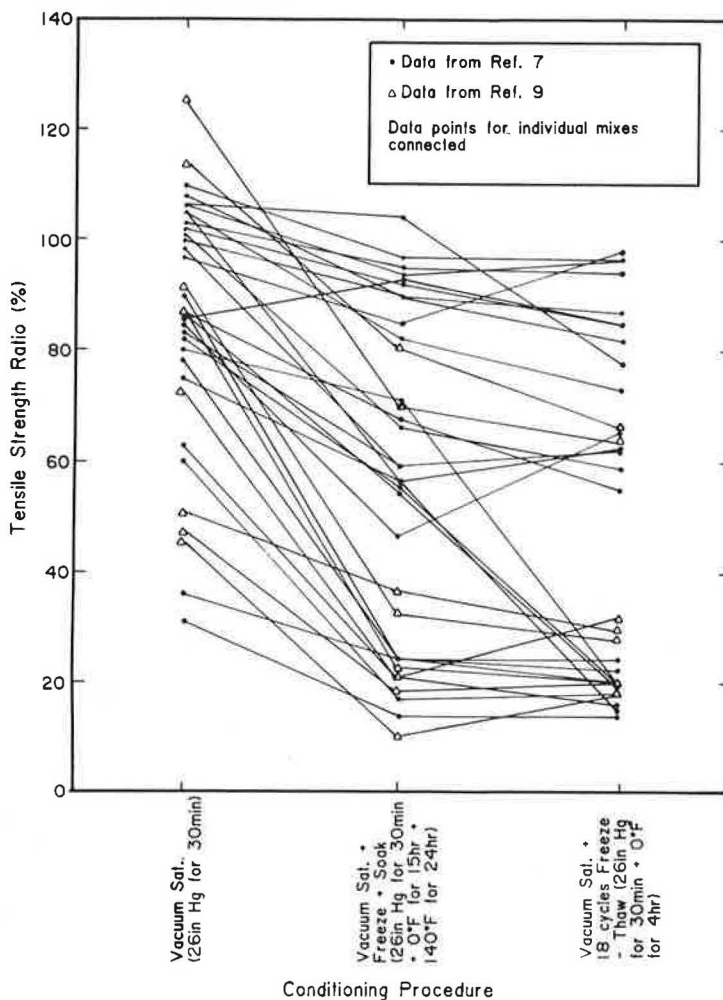


FIGURE 1 Effects of freezing on strength loss.

$$S = 2P_u / \pi t d \tag{1}$$

where

- S = indirect tensile strength,
- P_u = ultimate vertical diametral load,
- t = specimen thickness, and
- d = specimen diameter.

Tensile strength ratio (TSR) was computed by dividing the average strength of a minimum of three conditioned specimens by the average strength of a minimum of three unconditioned control specimens. Specimens were grouped for conditioning and control by sorting so that average void contents of the groups were as close as possible. All individual samples, and thus averages for the groups, have compacted void contents of from 6 to 8 percent.

Tensile modulus values were computed with the relationship

$$E = \frac{0.62}{t} \frac{P}{\Delta} \tag{2}$$

where

- E = tensile modulus,
- P = vertical diametral load, and
- Δ = horizontal diametral deformation at load P .

Tangent modulus values were computed using the initial slope of the load-deformation curve for P/Δ . Secant modulus values were also computed using the ultimate load and corresponding deformation.

MATERIALS

Five aggregate combinations and one asphalt cement were obtained for testing. These were selected to represent typical materials used for asphalt concrete in Alabama. The aggregate combinations were selected to provide a range of field stripping performance from good to poor. The asphalt cement was from the largest producer in Alabama. Three of the aggregate mixes were used in a study of boil and stress pedestal tests (14).

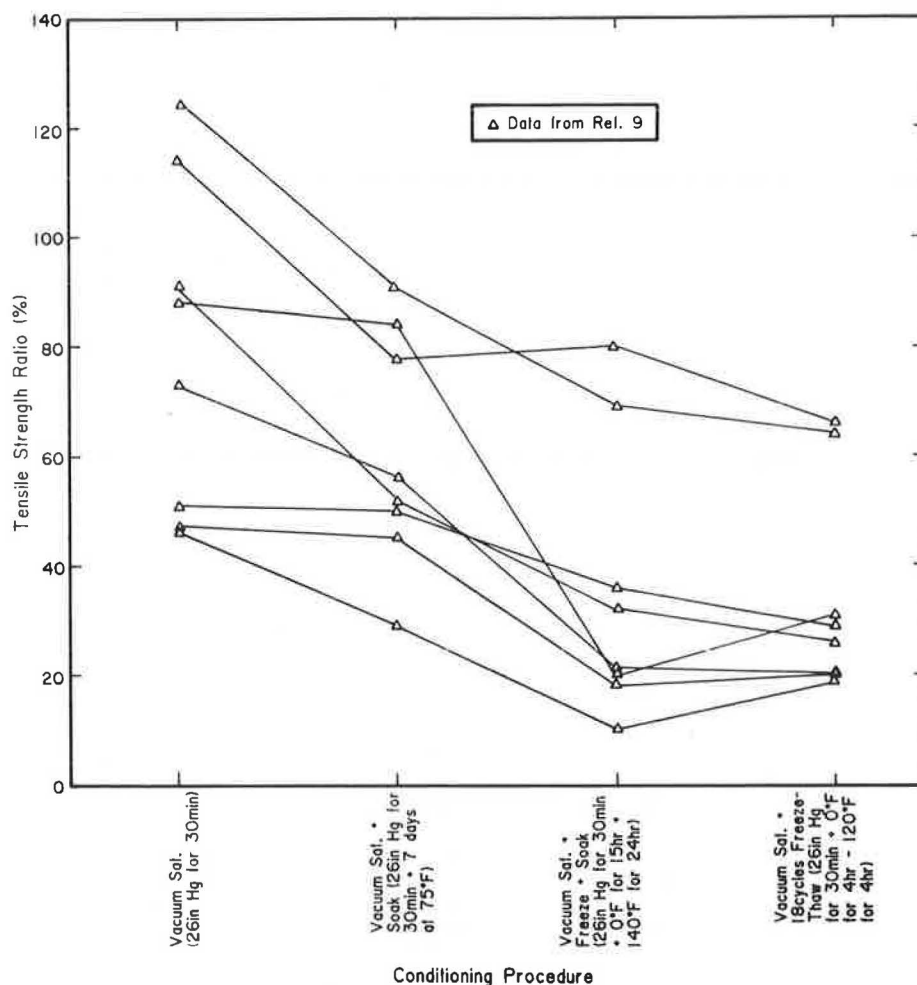


FIGURE 2 Effects of soaking on strength loss.

Asphalt Cement

The asphalt cement used for sample fabrication was grade AC-20, which meets Alabama Highway Department (AHD) specifications, from a source widely used in Alabama. The manufacturers mix crude from various sources, but at the time of sampling the majority of the crude oil was from the Gulf of Mexico.

Aggregate

Five aggregate combinations of three to five individual aggregates each was selected and arbitrarily labeled A-E. Each component of each mix was arbitrarily 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-E were AHD 416 wearing surfaces and D was an AHD 411 wearing surface). Aggregate from the five combinations was also combined to produce mixes meeting base/binder specification (AHD 414 binder layer/AHD 327 bituminous base). Therefore, for each aggregate combination A-E, there will be a surface mix and a base/binder mix. The asphalt cement contents were design asphalt contents for the

specific aggregate combinations. Properties of the mixes are given in Table 1.

The nature of the materials in each mix is distinctly different, but each 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 (C and D) were from different sources than were the gravels and coarse sands. The field performance histories of the aggregate combinations, included in the following descriptions, are a result of a limited survey of highway department personnel. They reflect general opinions regarding mixes from the primary aggregate source rather than specific observations of particular mixes.

Combination A

These are basically limestone mixes, and good performance of similar mixes with few signs of pavement distress attributable to stripping has been reported. Surface Mix A contains 85 percent crushed limestone and 15 percent natural sand and has been used for shoulder paving and leveling. Base/binder Mix A contains 100 percent crushed limestone. The limestone is

TABLE 1 MIX CHARACTERISTICS

	Surface Mix (%)	Base/Binder Mix (%)
Aggregate Combination A		
A1—screenings, dolomitic limestone	65	55
A2—natural coarse sand, quartz	15	—
A3—crushed stone, dolomitic limestone	20	45
Asphalt content ^a	5.5	4.25
Aggregate Combination B		
B1—screenings, limestone	10	10
B2—natural coarse sand, quartz, chert	20	20
B3—crushed gravel, chert	70	10
B4—uncrushed gravel, chert	—	60
Asphalt content ^a	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 ^a	6.25	4.55
Aggregate Combination D		
D1—natural fine sand	15	10
D2—coarse washed sand, quartz	50	20
D3—uncrushed gravel, quartz, chert	35	70
Asphalt content ^a	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 ^a	5.5	4.15

^aAsphalt content based on weight of asphalt cement and aggregate.

dense (specific gravity ≈ 2.8) dolomitic material with an absorption of about 1 percent.

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 percent limestone screenings and 90 percent 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 percent). The surface mix contains crushed gravel and the base/binder mix contains basically uncrushed gravel (10 percent 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 the base/binder mixes contain 15 percent fine sand and 85 percent 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 (0.9 percent).

Combination D

These are siliceous gravel mixes with poor reported stripping performance. The use of antistrip additives has improved performance, but gravel mixes from this region of the state continue to be regarded as particularly susceptible to water damage. The mixes contain 10 and 15 percent fine sand and 90 and 85 percent 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 highly variable cherty material (specific gravity ≈ 2.5) that includes light and porous particles. Absorption is relatively high at about 2.6 percent.

Combination E

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

PREPARATION AND TESTING OF SAMPLES

Samples were produced following the method described in ASTM D 1559 except for the following modification. Aggregate was combined according to the percentages given in Table 1 and sieved on eight sieves to produce portions with particle sizes in the range that passes the 11/2 in. to the No. 200 sieve. Required aggregate for two samples was then combined to meet the job mix formula gradation. The preheated aggregate and asphalt cement were mixed at 300°F for 3 min. The mixture was then placed in two Marshall molds. Thereafter sample preparation continued according to the requirements given in Table 2.

Condition 1

The mixtures in molds were heated for 2 to 3 hr at the compaction temperature (285°F) for temperature stabilization. Compaction was accomplished using a predetermined number of blows in order to achieve 6 to 8 percent air voids. Specimens were cooled to room temperature (3 to 4 hr), and their bulk specific gravity was determined in accordance with ASTM D 2726 (no wax used). The maximum theoretical specific gravity of the mix was determined in accordance with ASTM D 2041, and air voids were calculated in accordance with ASTM D 3203.

TABLE 2 CONDITIONING PROCEDURES

Treatment	Condition 1	Condition 2
Mix aging	No aging	15 hr at 140°F
Curing of compacted specimens	No curing	24 hr at room temperature
Initial saturation	Between 60% and 80%	Between 60% and 80%
Freezing	No freezing	15 hr at 0°F ± 4°F
Soaking	24 hr at 140°F	24 hr at 140°F
Age of specimen at testing	2 days	4 days
Similar procedure	Tunncliff and Root (2)	Modified Texas (11)

Compacted specimens were sorted into two groups (minimum of three specimens) such that both groups had, as nearly as possible, the same average air voids. One group was subjected to accelerated moisture conditioning and the other was used for control. Control specimens were placed in a desiccator and tested at the same time as conditioned specimens.

The conditioning procedure was similar to that described by Tunncliff and Root (2). It was accomplished in two stages, vacuum saturation and soaking. Specimens were submerged in distilled water at room temperature and a partial vacuum was applied for approximately 5 min. The vacuum level needed for saturation was dependent on the type of mix and ranged from 15 to 26 in. of mercury. In all cases the degree of saturation achieved was between 60 and 80 percent. Soaking was achieved by placing the vacuum-saturated specimens in distilled water at 140°F for 24 hr. The final degree of saturation achieved during soaking was highly variable.

Condition 2

This procedure is similar to that described by Hazlett (11). After it was placed in molds, the mix was cooled to room temperature for a minimum of 3 hr. It was then aged at 140°F

for 15 hr, reheated to compaction temperature (285°F) for 2 to 3 hr, and compacted using a predetermined number of blows to produce 6 to 8 percent air voids. The molded specimens were then cured at room temperature for 24 hr. Measurement and computation of specimen properties and sorting and handling of control specimens were the same as for Condition 1.

Specimens were subjected to moisture conditioning in three stages: vacuum saturation, freezing, and soaking. Vacuum saturation was the same as described for Condition 1. Freezing was started immediately after vacuum saturation and lasted for 15 hr at 0.0°F ± 4°F. Each specimen was placed in a plastic bag and this bagged specimen was placed inside another plastic bag. Ten milliliters of distilled water was added to the outer bag to form a moisture barrier and provide sufficient water for saturation. The inside bag was kept open and the outer bag was sealed. The double-bagged specimens were removed from the freezer after 15 hr, taken out of the bags, and placed in a 140°F water bath for 24 hr.

Testing Procedure

After they were soaked, specimens were taken out of the 140°F water bath and placed in another water bath at room tempera-

TABLE 3 INDIRECT TENSILE TESTS RESULTS

Aggregate Combination	Asphalt Content (%)	Moisture Condition 1				Moisture Condition 2				
		Initial Voids (%)	Final Sat. (%)	TSR* (%)	SMR* (%)	Initial Voids (%)	Final Sat. (%)	TSR* (%)	SMR* (%)	
A	Surf.	5.5	6.5	89	87	-	6.2	90	81	58
	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	4.5	6.6	100+	59	30	6.4	100+	82	60
C	Surf.	6.25	7.3	80	109	-	6.9	82	88	72
	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
	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
	B/B	4.15	7.0	88	92	90	6.8	88	75	47

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

ture (77°F) for 2 to 3 hr. Each specimen's final bulk specific gravity and thickness were then determined as described previously.

Immediately after thickness measurement, specimens were loaded in indirect tensile using a Marshall testing machine. Vertical diametral load was applied through 1/2-in.-wide loading strips by controlling vertical deformation at 2 in./min. Horizontal diametral deformation was measured with a device similar to that described by Hudson and Kennedy (15). Vertical diametral load and horizontal diametral deformation were recorded with an X-Y plotter to obtain relationships for tensile strength and modulus calculations.

Calculations

Maximum theoretical mix specific gravity was calculated in accordance with ASTM D 2041. Bulk specific gravity and air voids before and after conditioning were calculated in accordance with ASTM D 2726 and ASTM D 3203, respectively. Degree of saturation, before and after conditioning, was calculated using the relationship

$$S = \frac{B - A}{V(B - C)} \times 100 \tag{3}$$

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, and
- V = voids ratio of specimen.

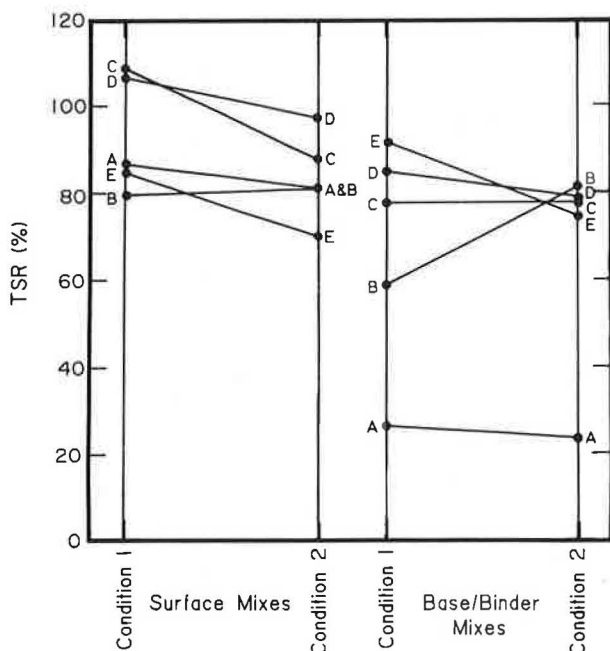


FIGURE 3 Comparison of sample preparation and moisture conditioning.

Tensile strength and secant modulus values were calculated using Equations 1 and 2, respectively. Tensile strength ratio (TSR) and secant modulus ratio (SMR), expressed as percentages, were calculated with the relationships

$$TSR = \frac{\text{Average conditioned indirect tensile strength}}{\text{Average dry indirect tensile strength}} \times 100 \tag{4}$$

and

$$SMR = \frac{\text{Average conditioned secant modulus}}{\text{Average dry secant modulus}} \times 100 \tag{5}$$

TEST RESULTS AND ANALYSIS

A summary of test results is given in Table 3. TSRs and SMRs are tabulated. Ratios of initial tangent modulus were also computed but are not presented because of their high variability as a result of imprecision in the initial portion of the load-deformation curves.

Effects of Sample Preparation and Conditioning Procedures

Numerous variations in sample preparation and conditioning procedures have been studied to try to simulate conditions necessary for stripping. These variations can result in significant differences in test results, as shown in Figures 1 and 2.

For certain applications, such as determining the effectiveness of antistripping agents, absolute values of strength or modulus ratios may not be critical (assuming reasonable approximations of stripping conditions are achieved). However, absolute values are important if the results are to be used for predicting stripping and the need for antistripping additives. They are important because they must be correlated with field stripping performance in order to establish limiting criteria.

Figure 3 shows the differences in TSRs observed for the two sample preparation and moisture conditions. The average difference is about 8 percent, and Condition 2 generally gives lower values. The exception is Combination B for which Condition 2 gives a larger value for the base/binder mix. Condition 2 is more severe primarily because of the freezing, but the effects are somewhat mitigated by the beneficial effects of curing and aging. Differences in SMR-values were similar.

Effects of Sample Properties

Aggregate properties are considered the dominant factor in determining mix stripping. When considering prediction of stripping potential and the associated need for antistripping additives, aggregate constituents are most often considered the controlling influence. However, specimen properties, such as void content and degree of saturation, will also affect strength retention and thereby potentially confound estimates of stripping potential. The effects of these variables are minimized by compacting specimens to standard voids (6 to 8 percent) and moisture conditioning using consistent procedures.

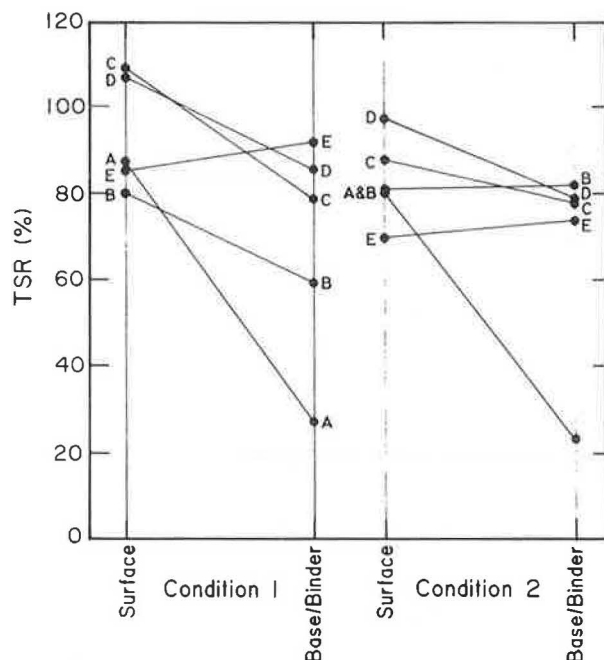


FIGURE 4 Comparison of surface and base/binder mixes.

Additional sample properties that may influence the characterization of a mix as stripping or nonstripping are asphalt cement content and aggregate gradation. They will determine asphalt cement film thickness and void size, which have the potential for influencing strength and modulus retention. Smaller film thickness will make removal from aggregate easier. Larger voids will allow easier access for water. Although void content is controlled (6 to 8 percent), coarser gradations will likely produce fewer but larger voids for a given void content.

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

Film thickness and void size are elusive parameters that defy accurate quantification and thus precise study. They were studied indirectly by examining surface and base/binder mixes of the five aggregate combinations. Figure 4 shows the effect of mix type. In general, base/binder mixes give lower strength retention. This would be the expected response if film thickness were smaller, as indicated by the lower asphalt content. However, base/binder mixes have coarser gradations and should require less asphalt cement for particle coating. Nevertheless, base/binder mixes do appear "leaner." The general trend is also consistent with the postulated influence of void size (i.e., coarser base/binder mixes have larger voids that provide easier access for water).

Notable exceptions to the general trend in Figure 4 are the responses of Combinations A and E. These are limestone aggregate combinations. Combination A base/binder mix has dramatically smaller (60 and 58 percent) TSR-values whereas Combination E base/binder mix has slightly larger (7 and 5 percent) TSR-values. No quantitative reasons can be formulated to explain this divergent behavior, but qualitatively the response is consistent with visual mix richness.

The influence of film thickness was examined by computing particle surface area with procedures suggested by Hudson and Kennedy (16). These values, as well as the ratios of asphalt content to surface area, are given in Table 4. No tendencies were noted when these ratios were plotted versus tensile strength ratios. This is attributed to the influence of other factors such as aggregate properties, and further studies of individual mixes were conducted.

Tests were run on mixes with asphalt cement contents dif-

TABLE 4 TENSILE STRENGTH AND ASPHALT FILM THICKNESS DATA

Aggregate Combination	Asphalt Content (%)	Surface * Area (m ² /kg)	Ratio AC/SA	TSR (%)		
				Condition 1	Condition 2	
A	Surf.	5.5	5.57	0.99	87	81
	B/B	4.25	4.42	0.96	27	24
B	Surf.	7.5	5.41	1.39	80	81
	B/B	4.5	4.79	0.94	59	82
C	Surf.	6.25	5.78	1.08	109	88
	B/B	4.55	4.38	1.04	78	78
D	Surf.	6.25	6.63	0.94	107	98
	B/B	4.9	4.27	1.15	83	79
E	Surf.	5.5	7.14	0.77	85	70
	B/B	4.15	4.98	0.83	92	75

*Computed with procedures from reference 16.

ferent from design asphalt contents. Base/binder Mixes B, D, and E at design asphalt contents appeared "rich," and additional tests were run at lower asphalt contents. Base/binder Mix A appeared lean at 4.25 percent asphalt content, and tests were run with 5.25 percent asphalt content. Surface Mix A at 5.5 percent design asphalt content appeared rich, and tests were run at 4.5 percent asphalt content.

Ratios of asphalt content to aggregate surface area were computed and plotted versus tensile strength ratio (Figure 5). The general trend exhibited is as expected: higher asphalt content-to-surface ratios give higher TSRs. Implications are that film thickness has a definite effect on tensile strength retention. The data cannot be used to infer that asphalt content can be used to control stripping because other mix requirements (stability, flow, voids, cost, etc.) will limit the practical range for asphalt content.

Prediction of Stripping

Current thinking appears to be that aggregate constituent properties are the dominate factor determining the stripping potential of asphalt concrete. However, as noted in the previous sections, asphalt content, aging, voids, and saturation can influence stripping. Some of these factors can be controlled by standardized test procedures. Others are mix specific and emphasize the necessity for testing specific mixes. Therefore, assuming that test conditions reasonably approximate field conditions and that the designation of a mix includes a design asphalt cement content, the indirect tensile test can be evaluated only as a predictor of stripping potential of specific mixes. The following analysis is somewhat weakened by the necessity of relying on the general characterization of an aggregate combination as stripping or nonstripping. The analysis is made

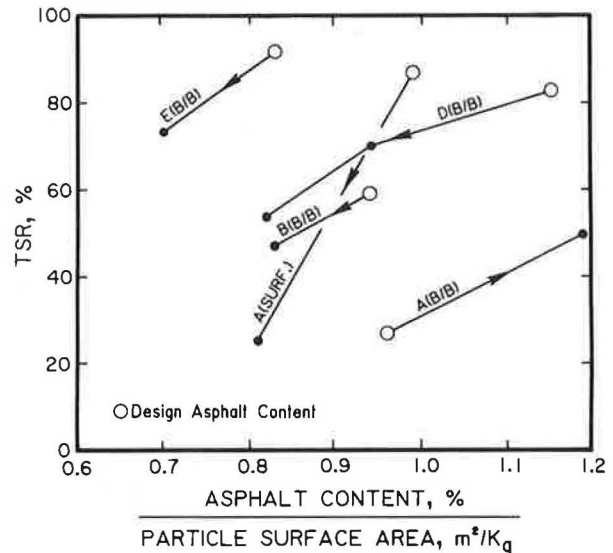


FIGURE 5 Effects of asphalt film thickness on TSR.

with the knowledge that the characterization of the aggregate combination may be invalid for specific mixes.

TSR- and SMR-values from Table 3 are plotted in Figures 6 and 7, respectively. Neither TSR nor SMR differentiates between the two reported stripping combinations (B and D) and the two reported nonstripping combinations (A and E). Results for Combination C, which has variable but generally good reported stripping performance, are also similar.

The dashed horizontal line at TSR = 70 in Figure 6 represents a criterion that has been suggested (9, 11) for separating stripping from nonstripping mixes. Only 3 of 20 data points fall below this criterion, and stripping and nonstripping mixes are basically indistinguishable. A limiting TSR = 80 has also been

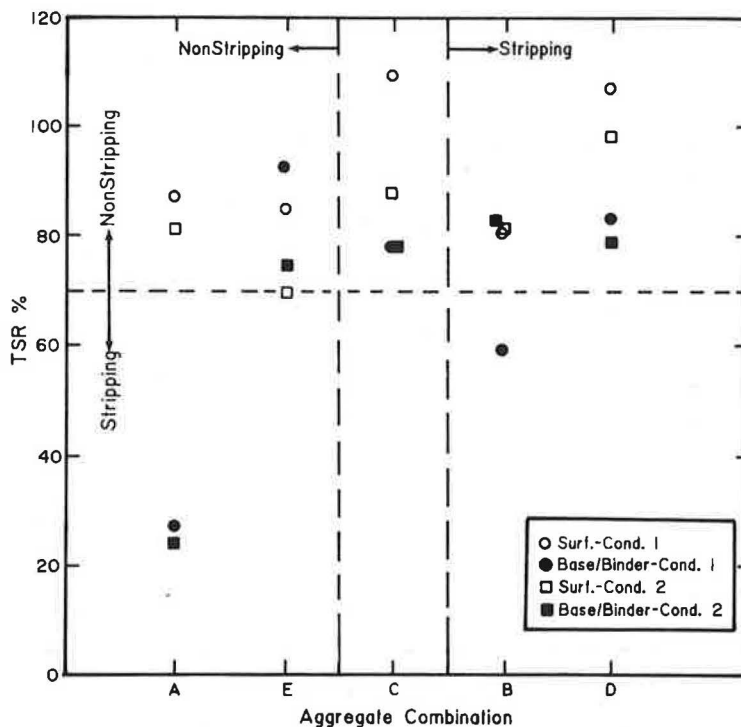


FIGURE 6 Prediction of stripping with TSRs.

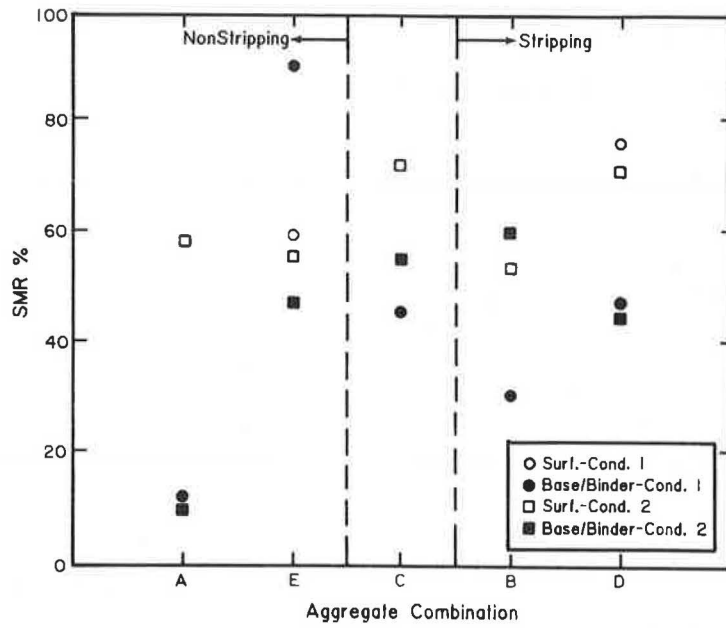


FIGURE 7 Prediction of stripping with SMRs.

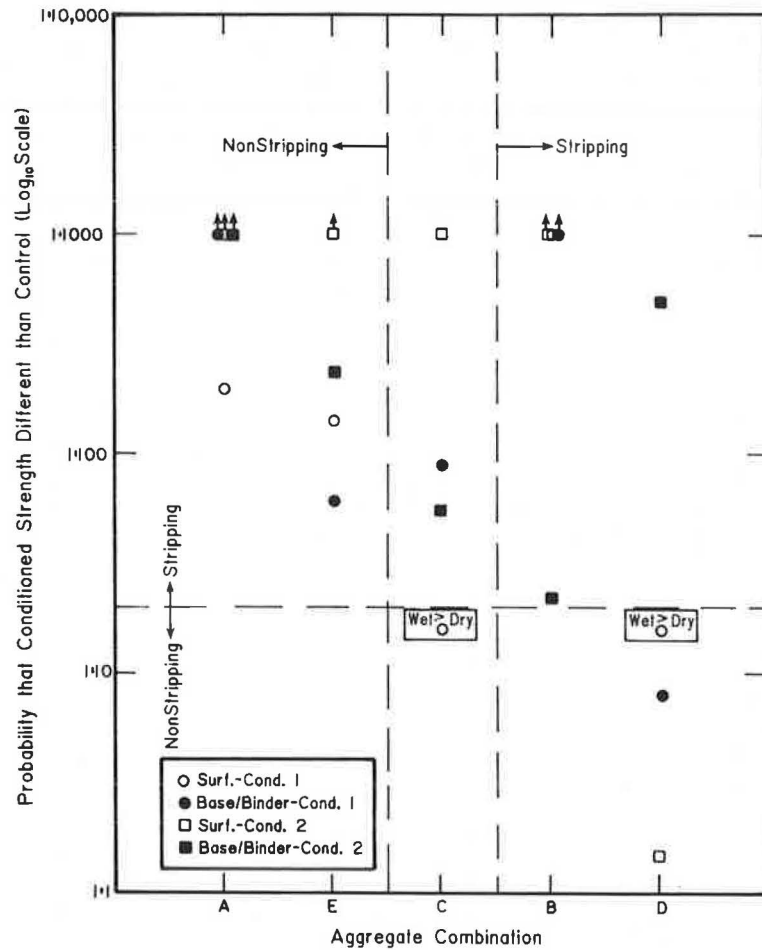


FIGURE 8 Prediction of stripping with probabilistic mean strength comparison.

TABLE 5 TSR-VALUES AND PROBABILISTIC MEAN STRENGTH COMPARISON

Aggregate Combination		Moisture Condition 1		Moisture Condition 2	
		TSR (%)	Prob. Real * Strength Diff.	TSR (%)	Prob. Real * Strength Diff.
A	Surf.	87	1:200	81	> 1:1000
	B/B	27	> 1:1000	24	> 1:1000
B	Surf.	80	1:1000	81	> 1:1000
	B/B	59	> 1:1000	82	1:25
C	Surf.	109	**	88	1:1000
	B/B	78	1:91	78	1:56
D	Surf.	107	**	98	1:2
	B/B	83	1:8	79	1:500
E	Surf.	85	1:143	70	> 1:1000
	B/B	92	1:61	75	1:235

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

** Conditioned strength greater than control strength.

suggested (8, 10). Examination of Figure 6 reveals that four of eight data points for nonstripping mixes and two of eight data points for stripping mixes fall below this criterion. For Combination C the base/binder mixes fall below the TSR = 80 criterion, and the surface mixes are above.

Comparison of Figures 6 and 7 reveals that patterns for SMR are similar to patterns for TSR. SMR-values do not appear to differentiate between stripping and nonstripping mixes.

Tunncliffe and Root (2) have suggested a criterion for predicting stripping that is based on probabilistic comparison of the mean tensile strength of conditioned and control specimens. Their criterion 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" (2, p. 18). The strength data were analyzed using the suggested criterion. The results are tabulated in Table 5 and plotted in Figure 8.

Comparison of TSRs with the probability that the mean strengths are different (Table 5) indicates general correlation but with considerable variability. Figure 8, with the suggested criterion shown as a horizontal line, indicates that 16 of 20 points fall above the line indicating potential strippers. This is contradictory to the predictions in Figure 6 where only 8 of 20 points fell in the stripping category as defined by the TSR = 80 criterion. Application of the probabilistic criterion generally indicates higher stripping potential, and application of the limiting TSR criterion generally indicates lower stripping potential.

For nonstripping mixes (A and E), the probabilistic criterion predicts that all would strip whereas the TSR = 80 criterion predicts that four of eight would strip. For stripping mixes (B

and D), the probabilistic criterion predicts that five of eight would strip whereas the TSR = 80 criterion predicts that three of eight would strip.

CONCLUSIONS

Conclusions drawn from results of the testing program follow.

1. Condition 2 (vacuum saturation, freezing, and soaking) produced lower TSR-values than did Condition 1 (vacuum saturation and soaking), but either appears acceptable in light of uncertainties in modeling the field environment.

2. Base/binder mixes are somewhat more susceptible to stripping than are surface mixes of the same constituents. This may reflect the influence of asphalt cement film thickness (susceptibility to stripping increases with decreased film thickness). Differences in the size and distribution of voids resulting from differences in gradation (coarser gradation producing larger voids) may also be a factor. Larger voids would provide easier access for water.

3. The probabilistic criterion for separating stripping and nonstripping mixes as suggested by Tunncliffe and Root (2) is more severe than a deterministic limiting tensile strength ratio of 70 (9, 11) or 80 (8, 10).

4. The indirect tensile test did not distinctly differentiate reported stripping and nonstripping aggregate combinations. Reasons may be that the reported stripping performance of an aggregate combination is not valid for all mix types or that the test is not a valid indicator of stripping performance. The

former is more likely, but incorrect prediction for specific mixes is a definite possibility. Implications are that specific mix designs must be tested and results conservatively interpreted until field performance studies permit further refinements.

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