Water Sensitivity Test Methods for Asphalt Concrete Mixtures: A Laboratory Comparison

JOHN S. COPLANTZ AND DAVID E. NEWCOMB

This study provides a comparison of four asphalt concrete water sensitivity (stripping) test methods by ranking the relative resistance to water-induced damage of a variety of field-prepared mixtures obtained during construction. Each test method evaluates water sensitivity by determining resilient modulus or indirect tensile strength, or both, of a compacted specimen before and after moisture conditioning. Conditioning of the samples is performed by vacuum saturation to predetermined levels and, in some cases, freeze-thaw cycles. One test method consists of vacuum saturation only. Another adds a single freeze-thaw cycle to vacuum saturation. The third method is a repeat of the second method, but at a lower saturation level. Finally, the fourth test method is an extension of the third, involving additional freeze-thaw cycles. Test results indicated that stripping damage did not occur in specimens subjected to vacuum saturation only. Freeze-thaw cycles caused damage to the specimens. Higher saturation levels resulted in increased damage to the specimens, as expected, but the rank of relative water sensitivity of the mixtures was found to be nearly the same. Laboratory performance after seven freeze-thaw cycles varied with aggregate and asphalt characteristics and could not be predicted using performance data from one freeze-thaw cycle only.

Many flexible pavements have suffered from an increased rate of damage to the asphalt concrete layer due to the effects of water. The damage is the result of a lack of cohesion within the mixture caused by a loss of bond strength between asphalt cement and aggregate. This moisture damage mechanism is sometimes referred to as stripping.

Many different laboratory test methods are used by state highway agencies to quantify the water sensitivity of a mixture and to estimate improvements in field performance of water sensitive mixtures that may be realized by the use of antistripping additives. Experts agree that the best test method to use is one in which the laboratory moisture damage mechanism closely simulates that which occurs in the field. They also state that the method used to measure the effects of moisture damage should be some type of fatigue, resilient modulus, or tensile test (*1–5*). In addition, the test should be run on the actual aggregate and asphalt cement to be used in the roadway and should be severe yet sensitive enough that the effect of the amount and kind of antistripping additive can be identified (*4, 5*).

Four water sensitivity test methods currently in use were evaluated by testing a variety of asphalt mixtures. Each test method involved submersion and vacuum saturation of a compacted bituminous specimen in water. Three of the four test methods incorporated freeze-thaw cycling after saturation. Resilient modulus and indirect tensile strength were obtained before and after vacuum saturation or freeze-thaw conditioning, or both. The study was intended to evaluate the test methods, not the properties of the mixtures. The test methods are quite similar in nature: they differ in time and amount of exposure to saturation and to freeze-thaw cycling. Past experience indicates that test methods that involve exposure to saturation only are not severe enough to predict stripping characteristics. Test methods incorporating exposure to saturation and freeze-thaw cycling have received much more acceptance from researchers as indicators of stripping potential. However, the amount of time required to perform these more extensive tests is generally unpopular with most highway agencies. This study was undertaken to determine whether the freeze-thaw cycle can be eliminated and whether the standard vacuum saturation plus one freeze-thaw cycle test can predict multiple freeze-thaw behavior.

PROJECTS EVALUATED

Dense-graded, field-prepared mixtures were obtained from various locations throughout northern Nevada. The mixtures were sampled from construction operations during the summer of 1986. All mixtures were of Type 2 specification and were in accordance with the Nevada Department of Transportation (NDOT) standard specifications (*6*). A list of these requirements is given in Table 1. Table 2 is a listing of all of the projects that were evaluated for the study. Project locations, traffic data, and general climatic data are also given. Many of the projects were overlays of existing sections. These projects were chosen from a larger data base that will be used for field evaluation studies. Each mixture selected for this study was known to be water sensitive. Projects were selected to provide an overall range of material types as well as environmental conditions.

MATERIALS

The materials used in the mixtures evaluated in this study are given in Table 3.

J. S. Coplantz, Texas Research and Development Foundation, 2602 Dellana Lane, Austin, Tex. 78746. D. E. Newcomb, Center for Construction Materials, Department of Civil Engineering, University of Nevada-Reno, Reno, Nev. 89557.

TABLE 1 STANDARD SPECIFICATIONS FOR TYPE 2 AGGREGATES AND DENSE–GRADED ASPHALT CONCRETE MIXTURES

Sieve Size	Percentage Passing by Weight
1 in.	100
3/4 in.	90–100
1/2 in.	
3/8 in.	63–85
No. 4	45–63
No. 10	30–44
No. 16	
No. 40	16–24
No. 200	3–9

NOTE: Liquid limit = 35 percent max; plasticity index = 6 percent max; fractured faces = 50 percent min; and Los Angles abrasion = 45 percent max. For asphalt concrete, stability = 35 min and air voids = 3 to 6 percent.

TABLE 2 PROJECTS EVALUATED FOR STUDY

Mixture	Location	Air Freeze-Thaw Cycles	Climate
A	US-50, Churchill Co.	154	Moderate
B	5th Street, Carson City	176	Moderate
C	US-395 business, Washoe Co.	154	Moderate
D	US-395 business, Washoe Co.	154	Moderate
E	IR-580, Washoe Co.	154	Moderate
F	IR-80, Elko Co.	165	Severe
G	IR-80, Elko Co.	230	Severe
H	US-95, Clark Co.	69	Mild to moderate

TABLE 3 MATERIALS USED IN MIXTURES

Mixture	Asphalt Type	Asphalt Content (%)	Lime Content (%)
A	AR-4000	6.5	1.5
B	AR-4000	6.5	1.5
C	AR-4000	7.0	1.5
D	AR-4000	7.0	1.5
E	AR-4000	6.0	1.5
F	AC-10	6.5	1.5
G	AR-8000	6.5	1.5
H	AR-8000	–	No lime

NOTE: Dash indicates data not available.

Asphalts

Projects A through D used AR-4000 asphalt cement as the binder. Project E was constructed using an AC-10, and Projects F and G were constructed with AR-8000 as the binder.

Aggregates

A large majority of the aggregate sources throughout the state of Nevada show a tendency to be water sensitive. To combat the damaging effects of water, all mixtures except Mix H contained hydrated lime as an antistripping material. For mixtures containing lime, aggregates on the cold feed belt were sprayed with water to prewet the surface. The lime was then added in powdered form. Mixing of the lime and aggregate was accomplished either by a series of riffles between the cold feed belts or by pugmill. The lime-aggregate mixture was then carried to the drum mixer by an additional cold feed belt.

SAMPLE PREPARATION

Dense-graded asphalt concrete mixtures were evaluated for the study. The mixtures were sampled in the field in a loose state from behind the laydown machine. The samples were placed in plastic concrete cylinder molds and transported to the laboratory. On arrival, the mixtures were split into representative sample sizes suitable for testing. The samples were then reheated to a compaction temperature of 230°F and compacted into standard specimens 4 in. in diameter by 2.5 in. high by the Hveem method. The compactive effort was adjusted to provide air void levels in the 7 to 9 percent range. This was done to ensure that the laboratory-compacted specimens would closely resemble expected field conditions with respect to air void levels. After compaction, the samples were allowed to cool overnight to 77°F. Testing of the samples began approximately 24 hr after compaction.

TEST METHODS

Conventional quality control tests were performed by NDOT. The tests were performed in accordance with standardized AASHTO (*7*) and NDOT (*8*) procedures. These data are not reported in this paper; however, all mixtures conformed to specifications. Resilient modulus, indirect tensile strength, air void and saturation measurement, and water sensitivity tests were performed by the University of Nevada-Reno Construction Materials Laboratory. These test methods are briefly discussed.

Resilient Modulus

The resilient modulus (Mr) of the test specimens was determined at 77°F in accordance with ASTM D 4123 (*9*). Control samples were tested in the dry condition, and samples subject to vacuum saturation or freeze-thaw conditioning, or both, were tested under saturated-surface-dry (SSD) conditions.

Indirect Tensile Strength

Indirect tensile strength, or split tension test (St), results were obtained at 77°F by using the loading procedure described by Lottman (*10*). However, a 2.0-in./min deformation rate was used until sample failure occurred. Control samples were also tested in the dry condition, and samples subjected to vacuum saturation or freeze-thaw cycling, or both, were tested under SSD conditions.

Water Sensitivity Tests

Four different methods of testing water sensitivity were evaluated. Each test method required specimens to be compacted to an air void level near that of field conditions (7 to 9 percent). Each method called for vacuum saturation of the samples with water. Three of the four test methods used freeze-thaw cycles to further condition the specimens. Measurements of resilient modulus and indirect tensile strength were determined for conditioned and unconditioned specimens. Measurements on conditioned specimens were taken at SSD conditions and compared with the test results of the unconditioned samples. The first three test methods are essentially slightly modified versions of those used by Lottman (*10*). The last method is a modification of that used by Scherocman et al. (*5*). Detailed descriptions of each test method follow. The testing sequence is shown in Figure 1.

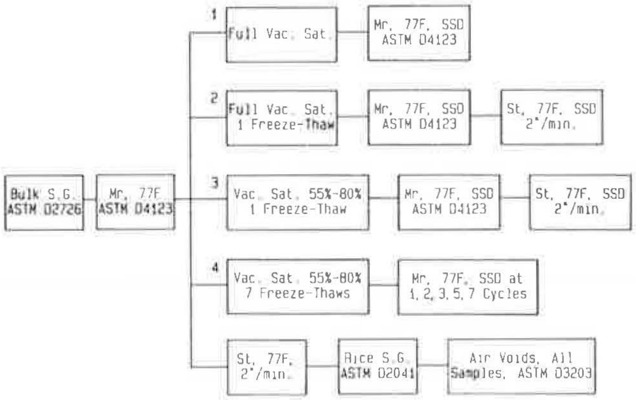

FIGURE 1 Testing sequence used in study.

1. Test Method 1 consisted of vacuum saturation at a level of 24 in. of Hg for 30 min. Saturation levels were not determined, but, on the basis of previous experiments, they were estimated to be near 100 percent. Resilient modulus measurements were taken before and after conditioning.
2. Test Method 2 consisted of vacuum saturation to the same level and duration used in Method 1. The samples were wrapped in plastic and frozen at −20°F for 15 hr. The frozen specimens were unwrapped and submerged in 140°F water for 24 hr, then submerged in 77°F water for approximately 2 hr. Resilient modulus and indirect tensile strength measurements were taken before and after conditioning.
3. Test Method 3 used a vacuum level and duration corresponding to a saturation level of from 55 to 80 percent. The saturation level was determined by the procedure described by Tunnicliff and Root (*4*). It was found that a vacuum level of 14 in. of Hg for 5 min followed by 30 min under atmospheric conditions produced saturation levels within this range. The samples were then subjected to the freeze-thaw cycle used in Test Method 2. Resilient modulus and indirect tensile strength measurements were taken before and after conditioning.
4. Test Method 4 used the same vacuum level and duration as Test Method 3 to provide saturation levels between 55 and 80 percent. The samples were then run through a series of multiple freeze-thaw cycles, each of which was the same as that used in Test Method 2. Resilient modulus measurements were obtained after one, two, three, five, and seven cycles and compared with the test results of the unconditioned samples.

TEST RESULTS

Measurements of resilient modulus, indirect tensile strength, and air voids were recorded for each mixture before conditioning. Results are given in Table 4. Values of resilient modulus ranged from 228 to 999 ksi. Indirect tensile strength test values ranged from 82 to 238 psi. As expected, mixtures prepared with AR-8000 asphalt cement have higher stiffness values. Note that air void levels were held between 6.8 and 9.1 percent to simulate the range of air void levels expected in the field.

TABLE 4 AVERAGE TEST RESULTS BEFORE CONDITIONING AND SATURATION LEVEL FOR TEST METHOD 3 AFTER SATURATION BY VACUUM

Mixture	Resilient Modulus (ksi)	Indirect Tensile Strength (psi)	Air Voids (%)	Percentage Saturation (Method 3)
A	419	147	8.2	71
B	519	135	7.3	93
C	505	129	7.7	76
D	406	–	9.1	74
E	404	94	7.5	78
F	269	82	9.0	75
G	999	238	7.0	88
H	228	–	6.8	70

NOTE: Dashes indicate no data available.

Resilient modulus and indirect tensile strength measurements taken after Test Methods 1–3 are shown in Figure 2. Results from Test Method 1 actually show higher resilient moduli than those obtained from unconditioned specimens. Lower resilient modulus and indirect tensile strength values were observed for Test Method 2 than for Test Method 3. Measurements of resilient modulus for Test Method 4 are given in Table 5 and shown in Figure 3. In general, for all mixtures, the resilient modulus decreases with an increasing number of freeze-thaw cycles.

Retained resilient modulus and indirect tensile strength ratios after Test Methods 1–3 are shown in Figure 4. Each ratio was calculated by dividing the conditioned value by the original value and multiplying by 100 percent. Test Method 1 ratios were the greatest of the three. Ratios for Test Method 2 were lower than for Test Method 3. Resilient modulus ratios for Test Method 4 are given in Table 6 and shown in Figure 5. The ratios tend to decrease as the number of freeze-thaw cycles increases. This type of behavior is to be expected

TABLE 5 RESILIENT MODULUS BEFORE AND AFTER VACUUM SATURATION AND MULTIPLE FREEZE-THAW CYCLE CONDITIONING

	Resilient Modulus at 77°F (ksi)					
Mixture	Original	1 Cycle	2 Cycles	3 Cycles	5 Cycles	7 Cycles
A	489	324	273	189	120	68
B	572	318	230	166	112	72
C	506	277	146	107	50	28
D	427	305	281	211	151	86
E	440	209	201	190	173	117
F	265	123	89	63	47	30
G	950	477	490	475	448	394
H	271	112	55	33	16	9

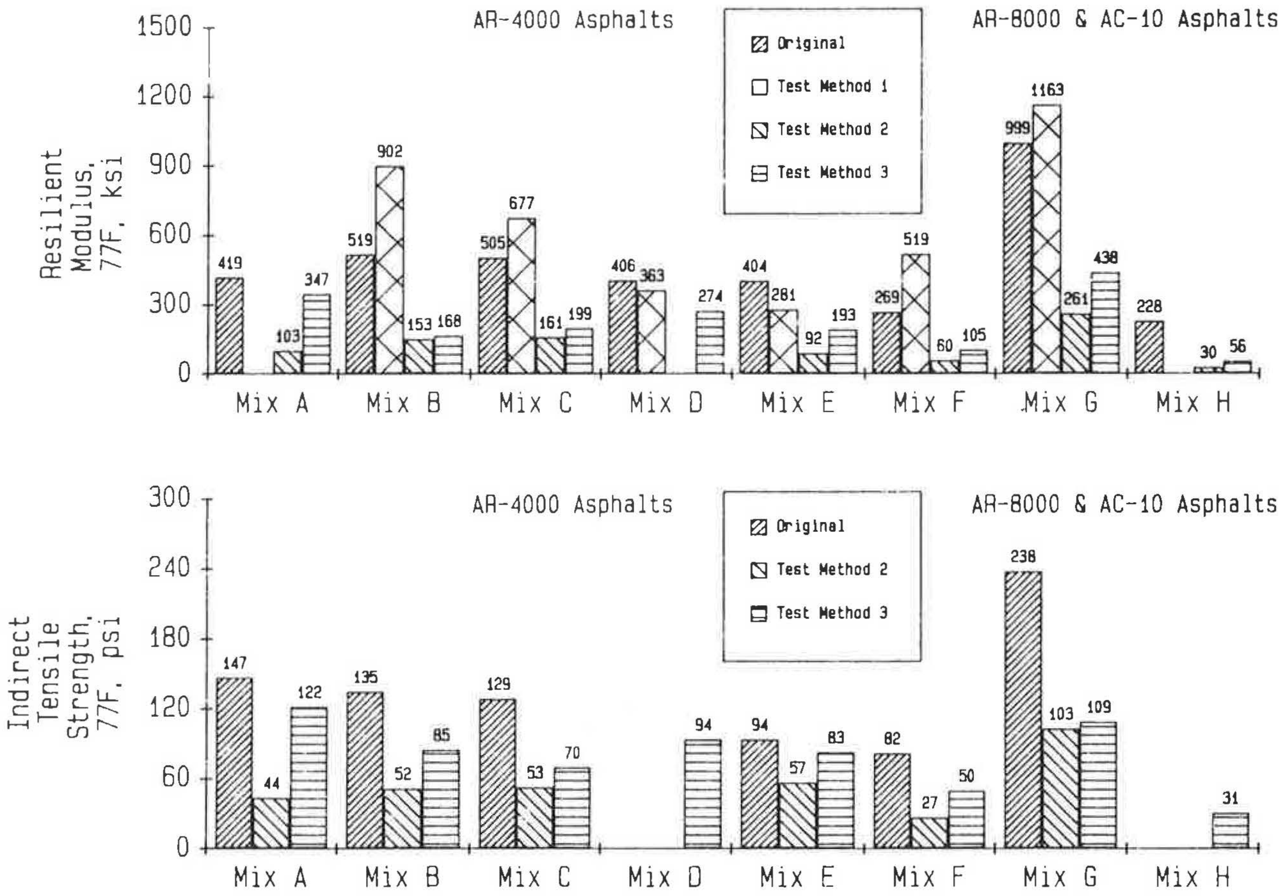

FIGURE 2 Resilient modulus and indirect tensile strength before and after vacuum saturation and freeze-thaw conditioning.

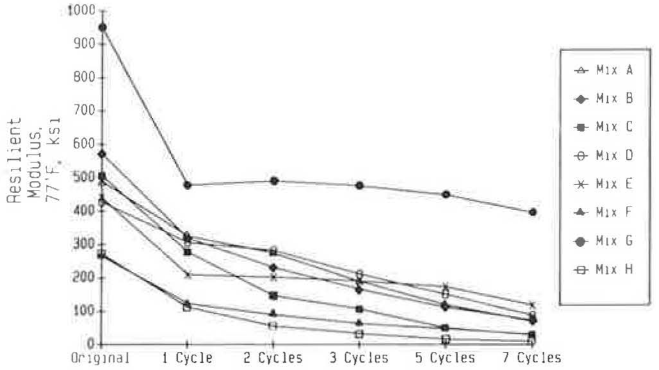

FIGURE 3 Resilient modulus versus freeze-thaw cycles.

when mixtures are repeatedly subjected to severe freeze-thaw cycles.

DISCUSSION OF TEST RESULTS

Recalling that the intent of this paper is to provide a comparison of test methods and not mixture properties, it can be seen from Figure 2 that, in terms of damage to the specimens, Test Method 1 proved to be the least severe. This method consisted of vacuum saturation only; no freeze-thaw cycles were used. A majority of the test results indicated that increases in resilient modulus took place after vacuum saturation. This type of behavior is not uncommon (*10*). Difficulty in controlling the temperature of the vacuum saturation bath may also have led to an increase in measured strength. Nevertheless, these results indicate that vacuum saturation without freeze-thaw cycling may not be severe enough to damage the mixtures. The performance of these materials after a freeze-thaw cycle indicates that they are water sensitive. However, vacuum saturation alone did not appear to initiate a stripping mechanism.

Data from Test Methods 2 through 4, each involving the use of freeze-thaw cycles, indicated that a substantial amount of damage occurred to each mixture. This would tend to favor the use of freeze-thaw cycles in a water sensitivity test method for wet-freeze regions. Comparisons of resilient modulus and indirect tensile strength values after freeze-thaw conditioning (Figure 2) indicate that the severity of damage is greater for Test Method 2 than for Test Method 3. This trend is shown for all mixes tested regardless of material type. Recall that saturation levels for Test Method 2 were near 100 percent whereas levels for Test Method 3 were held between 60 and 85 percent (Table 4).

A plot of retained resilient modulus ratios comparing Test Methods 2 and 3 is shown in Figure 6. Likewise, Figure 6 shows a plot of retained indirect tensile strength ratios for the two test methods. The data for the resilient modulus ratios indicate that there may be a relationship between ratios for the

TABLE 6 RATIOS OF RETAINED RESILIENT MODULUS AFTER VACUUM SATURATION AND MULTIPLE FREEZE-THAW CYCLE CONDITIONING

Mixture	Saturation (%)	Air Voids (%)	Resilient Modulus Ratios (%) After 1 Cycle	2 Cycles	3 Cycles	5 Cycles	7 Cycles
A	77	8.0	66	56	39	25	14
B	85	6.8	56	40	29	20	13
C	75	7.6	55	29	21	10	5
D	77	8.5	71	66	49	35	20
E	81	8.0	47	46	43	39	27
F	65	8.9	46	34	24	18	11
G	82	7.3	50	52	50	47	41
H	72	7.2	41	20	12	6	3

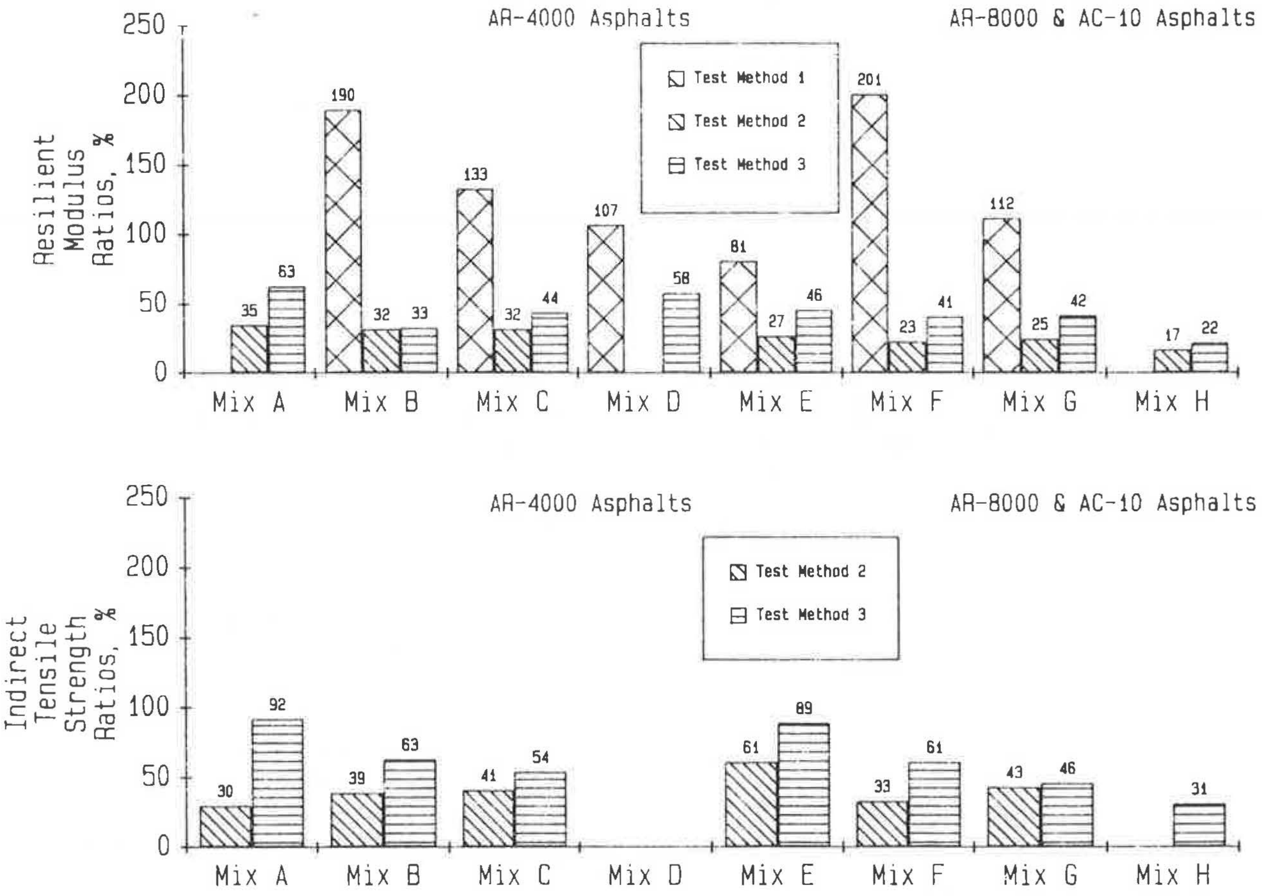

FIGURE 4 Retained resilient modulus ratios and indirect tensile strength ratios before and after vacuum saturation and freeze-thaw conditioning.

two test methods. The indirect tensile strength ratios are much more scattered. Some of the data scatter may be due to the range of saturation levels used for Test Method 3. The indirect tension ratios were calculated using two subsets of samples, one for original values and one for conditioned values. The resilient modulus ratios were calculated from the same subset of samples. The inherent variation in properties between the two indirect tension subsets could also explain the wider data scatter. Because of the small data base available, a regression analysis to determine the relationship (if any) between the two test methods was not performed.

Test Method 4 was a repeat of Test Method 3 with the addition of more freeze-thaw cycles. As expected, additional freeze-thaw cycles resulted in lower resilient moduli (Table 5 and Figure 3) and also lower retained resilient moduli (Table 6 and Figure 5). The relationship between resilient modulus or retained resilient modulus and the number of freeze-thaw cycles is not a constant. Generally, as the number of freeze-thaw cycles increases, the resilient modulus of the mixture decreases. Each mixture has its own unique curve, indicating that behavior through multiple freeze-thaw cycles is a characteristic of mixture composition. These concepts are shown in Figure 3.

As the data in Table 7 indicate, the sensitivity of each mixture to water-induced damage was given a relative ranking based on the retained resilient modulus ratios from each test

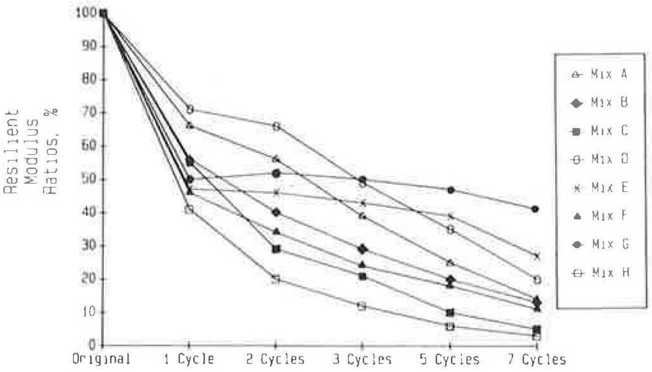

FIGURE 5 Retained resilient modulus ratios versus freeze-thaw cycles.

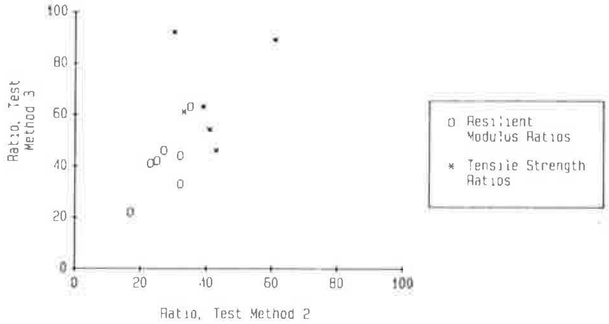

FIGURE 6 Plot of retained resilient modulus ratios and tensile strength ratios—Test Method 3 versus Test Method 2.

TABLE 7 RELATIVE RANK OF SENSITIVITY TO WATER DAMAGE FOR EACH MIXTURE

Method 1	Method 2	Method 3	Method 4 After 3 Cycles	Method 4 After 7 Cycles
Mix F	Mix A	Mix A	Mix G	Mix G
Mix B	Mix B	Mix D	Mix D	Mix E
Mix C	Mix C	Mix E	Mix E	Mix D
Mix G	Mix E	Mix C	Mix A	Mix A
Mix D	Mix G	Mix G	Mix B	Mix B
Mix E	Mix F	Mix F	Mix F	Mix F
Not tested	Mix H	Mix B	Mix C	Mix C
Mix A	Not tested	Mix H	Mix H	Mix H
Mix H	Mix D			

NOTE: Mixtures are ranked highest to lowest in water-induced damage based on retained resilient modulus values.

method. It can be seen that Test Method 1 clearly does not provide an adequate indication of performance when freeze-thaw cycles occur. The differences in sensitivity ranking between Test Method 1 and Test Methods 2 and 3 are considerable. For Test Method 1, Mix F ranked highest in resistance to water-induced damage. After freeze-thaw cycles were added, its resistance to water damage decreased to sixth highest. Likewise, Mix E was ranked sixth highest in resistance to water-induced damage by Test Method 1. After seven freeze-thaw cycles, its resistance to water damage was ranked as second highest, a jump of four positions. Damage rankings for Test Methods 2 and 3 are in considerable agreement with the exception of Mix B. Additional freeze-thaw cycles, however, affected the outcome somewhat. Comparing results of Test Method 3 with those after three and seven cycles of Test Method 4 indicates that Mix B and Mix G increase in relative resistance to water-induced damage, and Mix A and Mix C experience decreased resistance. It appears that the additional cycles may be needed to accurately determine long-term performance of these mixes in high freeze-thaw regions.

CONCLUSIONS

For the materials and mixtures involved in this study, the conclusions stated herein are applicable. Generating accurate and useful water sensitivity test data requires time. Results indicate that mixtures subjected only to vacuum saturation may not show evidence of stripping potential, but the same mixtures may readily strip with the addition of one or more freeze-thaw cycles. A freeze-thaw cycle adds 40 hr to the duration of the test but is required to accurately determine a given mixture's sensitivity to water. This level appears to be adequate for most work involving acceptance of material sources. Higher saturation levels will generally increase the amount of stripping that occurs in any given mixture. A controlled level of saturation may provide better control on the amount of water entering the permeable voids of the sample and reduce the chances of possible swelling of the sample as the result of oversaturation. Swelling of this type may affect the internal void structure of the sample and allow damage to occur that might not occur under field conditions.

The amount of damage to a mixture caused by stripping varies with the number of freeze-thaw cycles. In general, the amount of water-induced damage increases with additional freeze-thaw cycles. Because the change in water sensitivity of a mixture between one freeze-thaw cycle and seven freeze-thaw cycles is a characteristic of the mixture, retained resilient modulus ratios for seven freeze-thaw cycles cannot be accurately predicted from a test method that uses only one freeze-thaw cycle.

When the feasibility of using a material is being investigated, one freeze-thaw cycle should be sufficient in most cases. This test can determine if there are problems with the material that could cause stripping-related distress early in pavement life. To determine the long-term effect of stripping on field performance, multiple freeze-thaw cycles may need to be used. Multiple cycles may indicate that additional stripping can occur after only one freeze-thaw cycle. The true stripping potential of a mixture may be masked somewhat by test methods that use only one cycle.

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