Laboratory Evaluation of Moisture Damage to Bituminous Paving Mixtures by Long-Term Hot Immersion

ILAN ISHAI AND SIMON NESICHI

This paper deals with the development of a moisture damage (MD) sensitivity test for bituminous paving mixtures under hot and humid climatic conditions. The concept and test are based on characterizing the moisture damage sensitivity by long-term durability curves that express the variation of retained strength with hot immersion (60°C) time as long as 14 days. The original version of the test was modified by characterizing MD sensitivity using the retained strength value at 6 days of hot water immersion. Both versions of the test have been proven to be superior to the traditional 1-day Marshall immersion test in detecting sensitive mixtures. The modified version is a practical substitute for its former version that was based on longer immersion periods (up to 14 days) and a greater number of sample sets (five versus three needed by the current procedure). The development of the test was supported by laboratory and initial field experience, as well as by theoretical considerations of the behavior of mixtures during long immersion periods. Suggestions for needed further research are outlined at the end of the paper.

The damaging effects of moisture on the physical properties and mechanical behavior of bituminous paving mixtures have been known for many years (*1*). To overcome the problem, many laboratory tests were developed, all attempting to evaluate mixtures' sensitivity to moisture damage (MD). The most popular and practical of these tests appear to be the immersion-mechanical tests, which measure changes in mechanical behavior of compacted samples caused by exposure to moisture (*2*). Typically, the results of these tests are reported in terms of percentage retained strength. Various tests of this type have been developed (*3–8*).

For many years, the Marshall immersion test (*4*, pp. 29–30) was the only MD sensitivity test in use in Israel. Indeed, this test is still included in various national specifications with quality criteria of 60 to 75 percent retained stability values for roads and highway pavements and 75 percent for airfield pavements.

Recently, doubts about the test's ability to detect sensitive mixtures have arisen. In some cases, bituminous mixtures with hydrophilic aggregate, which complied with the specification's criteria, stripped in the field shortly after placement (*9*). Doubts about the quality of the test were also raised by other writers (*10*) and in personal communications. Therefore a research project, one of the aims of which was to develop a better test, was conducted at the Transportation Research Institute of the Technion, Haifa (*11*). The purpose of this paper is to describe this research and its main findings with respect to the laboratory evaluation of moisture damage to bituminous paving mixtures.

I. Ishai, Civil Engineering and Transportation and Geodesy Departments, Technion-Israel Institute of Technology, Haifa 32 000, Israel. S. Neisichi, Public Works Department, Israel Ministry of Construction and Housing, Government City, Sheik Jarach, Jerusalem, Israel.

DEVELOPMENT OF TEST

Basic Requirements

The basic requirements for developing a laboratory MD sensitivity test can be summarized as follows (*11, 12*):

1. It must be fairly rapid and simple,
2. Its reproducibility must be fairly high,
3. It must bring out differences sought in a distinctive manner,
4. It should have a sound analytical basis,
5. The needed testing time and equipment should enable commercial laboratories to include the test as a part of routine procedures for design of job-mix formulas,
6. The exposure to moisture should cause damage similar in amount and type to that occurring in the field, and
7. Acceptance and rejection criteria should be based on correlation with field experience.

An effort was made to develop and adopt an MD test that, for local conditions, had been proven to be superior to the Marshall immersion test. This test is the Durability Index (DI) Test, which had originally been developed for research purposes (*13*) but was proven to be successful in field use as well (*9*).

Original Version of Durability Index

Because the original version of the DI test has already been described in detail (*9, 13*), only a short review of its main features is given here. The test is based on subjecting five identical sets of Marshall specimens to hot water immersion (at 60°C) for up to 14 days. Each set is tested after a different immersion period (0, 1, 4, 7, and 14 days), and the retained strength values versus immersion time graphically describe a durability curve (Figure 1). The strength parameter usually used is the Marshall stability value; however, other strength parameters, such as resilient modulus (*13*), have also been used.

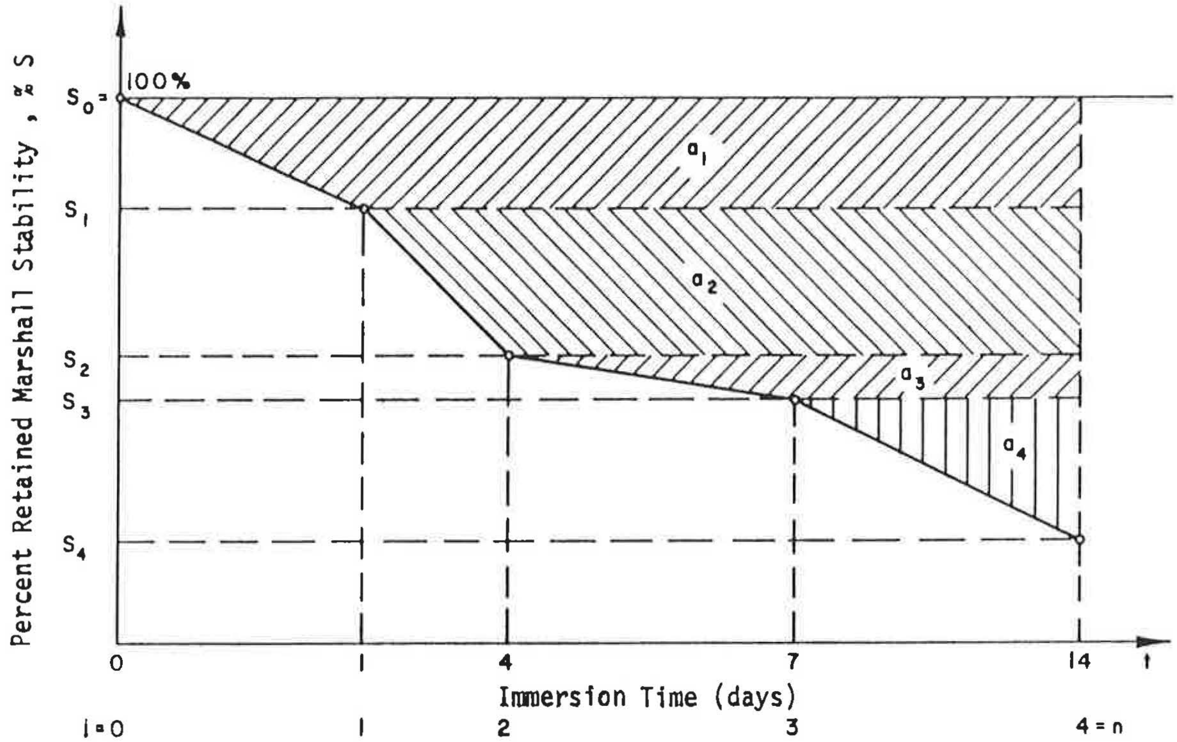

FIGURE 1 Schematic description of durability curves with parameters that define durability indices (*13*).

The MD sensitivity of the mixture tested is reported in terms of **Durability Index (DI) or Equivalent Retained Strength** (ERS). The DI is defined as the average strength loss area enclosed between the durability curve and the line s_0 = 100 percent. Based on Figure 1, DI is expressed as

$$DI = (1/t_n) \sum_{i=1}^{n} a_i = (1/2t_n) \sum_{i=0}^{n-1} (s_i - s_{i+1}) \times [2t_n - (t_i + t_{i+1})] \quad (1)$$

where

s_{i+1} = percent retained strength at time t_{i+1},
s_i = percent retained strength at time t_i, and
t_i, t_{i+1} = immersion periods (from beginning of test).

It should be noted that the area increments (a_i) are defined and partitioned horizontally because they express the relative contribution of the immersion period increments to the total loss in strength. In this respect, the relative weight of the early time increments is much higher than that of later ones.

The DI expresses an equivalent 1-day strength loss. Positive values of DI indicate strength loss, negative ones strength gain. By definition, DI < 100. Consequently, it is possible to express the percentage 1-day ERS as

$$ERS = (100 - DI) \quad (2)$$

It should be noted that although only five immersion periods are used to describe a 14-day period, later studies (*11*) revealed that no changes in ERS values resulted when more incremental testing periods (up to almost daily strength tests) were added (Figure 2). Experience (*9, 13*) has proven that the test complies fairly well with Requirements 2, 3, and 4 mentioned previously. No field data yet exist to verify its compliance with Requirements 6 and 7, although hot immersion appears to be more logical for Israeli conditions than, say, freeze-thaw cycles given the hot and humid climate. Experience has proven the applicability of the Marshall test for reliable detection of MD sensitivity. This test was also adopted because the method and testing equipment are commonly used locally in bituminous paving technology. However, the long immersion period and the comparatively large number of samples involved are not compatible with Requirements 1 and 5. Therefore a research effort was undertaken to improve these limitations.

Development of Modified Version of DI

Review of numerous durability curves based on retained Marshall stability values derived under the DI testing procedure reveals an interesting phenomenon between 4 and 7 days of immersion. When the values of retained strength versus bitumen content are plotted, it turns out that the curve representing the equivalent strength loss (DI) is usually located in the zone confined by the curves representing 4 and 7 days of immersion. This brought up the idea that the whole durability curve may be replaced by the 5- or 6-day retained strength value (Figure 3).

The first attempt to verify this assumption was made by subjecting three mixtures to moisture immersion periods as required in the original version, with an additional test after 5 days of immersion. The mixtures were composed of identical basalt aggregate (Table 1) and 60- to 70-pen bitumen. However, the variations in filler type and percentage of

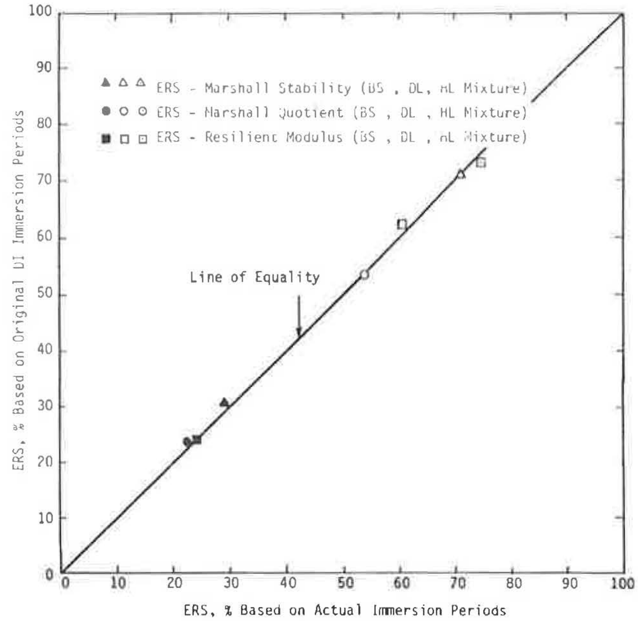

FIGURE 2 Equivalent retained strength values for different immersion periods versus values based on original DI procedure (*11*).

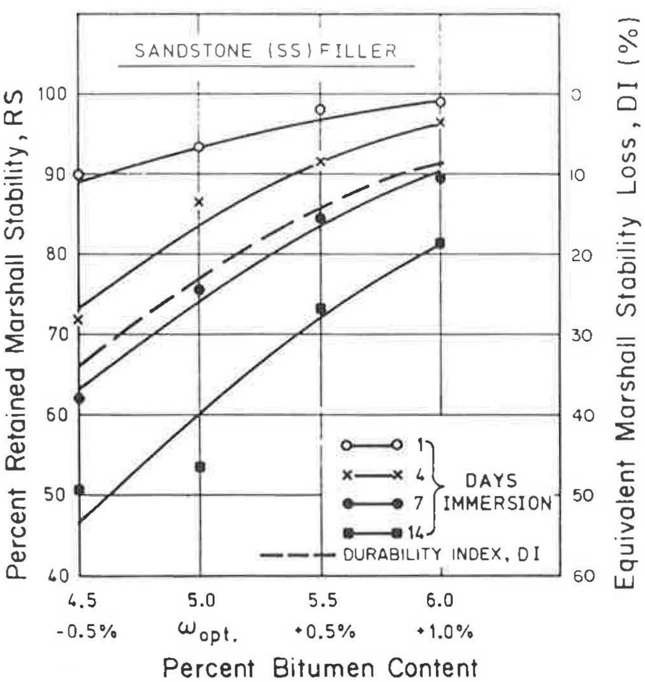

FIGURE 3 Effect of bitumen content on durability potential for different periods of immersion: dolomite aggregate, sandstone filler (*13*).

permeable voids in the mixture (Table 2) provided the needed variability in MD resistance. Retained strength values as required by the original DI test version, as well as after 5 days of immersion, were calculated for three mechanical parameters (Marshall stability, Marshall quotient, and resilient modulus) and are shown in Figure 4. Because all of the values in Figure 4 fell to the right of the line of equality, it became obvious that a 5-day immersion period was not enough; therefore the 6-day value was tried. At first, theoretical 6-day retained strength

TABLE 1 PROPERTIES OF BASALT AGGREGATE USED IN RESEARCH

Property	Value
Specific gravity	
Bulk	
+No. 4	2.72
−No. 4	2.65
Apparent	
+No. 4	3.0
−No. 4	2.86
Water absorption (%)	
+No. 4	3.75
−No. 4	4.0
Sand equivalent (%)	63.5
Los Angeles abrasion, 3/8 in.–1/2 in. (%)	25
Bitumen absorption (%)	1.5
Gradation: percentage passing sieve	
1/2 in.	100
3/8 in.	82
No. 4	60
No. 10	42
No. 40	23
No. 80	15
No. 200	6.5

values, computed from durability curves derived in various studies (*9, 11, 13*) by assuming a linear drop in retained strength between 4- or 5-day and 7-day immersion periods, were compared with original DI test values. This time, agreement was excellent with a coefficient of variation of 0.99 (*11*) for the 36 mixtures studied, as shown in Figure 5.

Given this high degree of correlation, it was decided to form a data bank of various types of mixtures, for which durability testing based on the original version of the DI test, as well as the modified, shortened 6-day immersion test procedures, would be conducted. The experience gained with various types of mixtures (conventional hot mixtures, recycled hot mixtures,

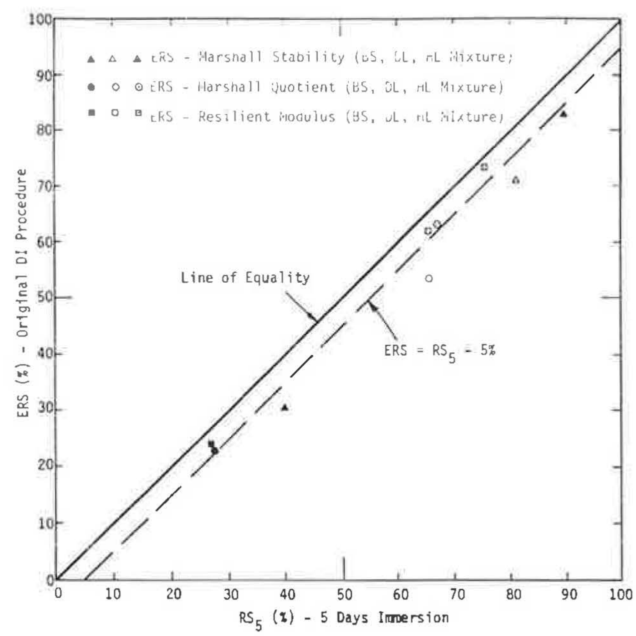

FIGURE 4 Equivalent retained strength values based on original DI procedure versus retained strength values after 5 days of immersion.

TABLE 2 PROPERTIES OF MIXTURES USED (*11*)

Filler Desig-nation	Filler Type	ω_{opt}[a] (%)	ω_{act}[a] (%)	Mixture Density (kg/m^3)	Marshall Stability (lb)	Resilient Modulus at 25°C (kg/m^2)	Tensile Strength (psi)	Flow (1/100 in.)	Marshall Quotient (lb/in. × 10^{-2})	Air Voids (%)	Bitumen Saturation (%)	VMA (%)	Permeable Voids[b] (%)
BS	Basalt	6.0	5.5	2394	2,217	37 812	114.5	15.3	114.9	6.83	54.71	15.08	4.8
HL	Hydrated lime	7.0	6.5	2362	1,933	34 580	91.9	18.3	105.6	6.02	64.45	16.93	3.9
DL	Dolomite	5.0	5.0	2454	3,072	32 912	126.9	18.1	169.7	4.65	63.09	12.59	2.8

[a]Percentages of total mixture weight, ω_{opt}, ω_{act} – optimum and actual bitumen contents, respectively.
[b]Lottman's procedures (*5*).

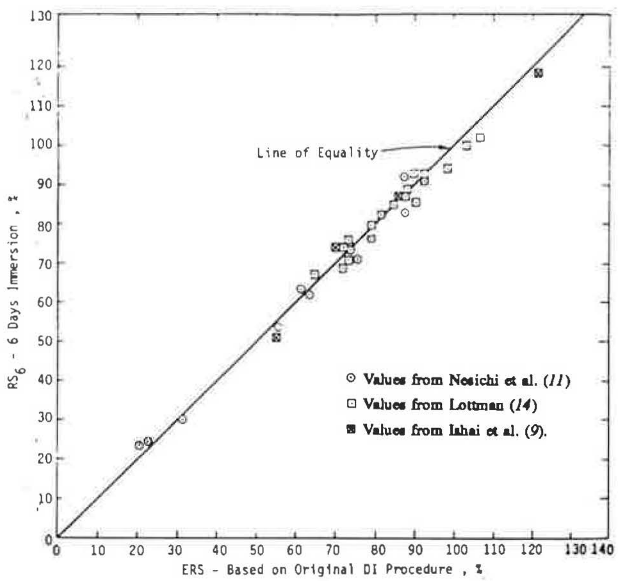

FIGURE 5 Retained strength values after 6 days of immersion versus retained strength values based on original DI procedure.

60- to 70-pen bitumen binder, HFMS-2h hot emulsion binder, PPA binder, etc.) (Table 3) was quite successful, and it was therefore decided to replace the ERS value of the original DI test with one 6-day immersion value. Practically, that means reducing the number of testing sets from five to three (0, 1, and 6 days of immersion), thus reducing the total immersion period from 14 to 6 days. The 1-day retained strength value is needed for control purposes. The switch to the shorter version of the test is supported not only by experience but also by theoretical considerations.

Modified DI Test—Theoretical Considerations

One of the interesting features of the durability curve that characterizes the behavior of mixtures under the first version of the DI test is that it can be described by the mathematical function of the form

$$S_T = S_0 e^{-KT} \quad (3)$$

where

S_0 = the initial strength value (at zero days of immersion) in strength or stability units;

TABLE 3 COMPARISON OF ERS AND RS_6 FOR VARIOUS MIXTURES

Description of Mixture	ERS (%)	RS_6 (%)	Reference
Dense-graded asphalt concrete, 5.5% 60-70 bitumen, dolomite aggregate	54	51	18
Dense-graded asphalt concrete, 7% HFMS-2h hot emulsion, dolomite aggregate	62	63	18
Dense-graded recycled mix, 2% HFMS-2h hot emulsion	75	74	18
Dense-graded asphalt concrete, PPA/VTB (43%/57%) bitumen, basalt aggregate	69	64	19
Dense-graded asphalt concrete, PPA/EXT (83%/17%) bitumen, basalt aggregate	53	48	19
Dense-graded asphalt concrete, PPA/EXT (85%/15%) bitumen, basalt aggregate	67	64	19
Dense-graded asphalt concrete, PPA/EXT (83%/17%) bitumen, dolomite aggregate	83	80	19
Dense-graded asphalt concrete 5% 60-70 bitumen, Israeli Specification 52 gradation	71	69	Unpublished data, 1987
Dense-graded asphalt concrete, 4.5% 60-70 bitumen, French LCPC gradation	86	85	Unpublished data, 1987

S_T = the strength value after T days of immersion, and

K = a constant that dictates the MD buildup rate.

In terms of relative (retained) strength values, S is replaced by RS, and the mathematical function is simplified to

$$RS_T(\%) = 100e^{-KT} \quad (4)$$

It is interesting to note that the same function was found to be applicable to other MD sensitivity tests, such as cyclic TSR tests (*14, 15*) and cyclic water vacuum saturation followed by compressive strength testing (*16*). Another inverse exponential function was used earlier by the authors to quantify reduced asphaltic pavement life from MD (*17*).

Although this function is typical of most paving mixtures, two extreme exceptions do exist: (a) stabilized or treated mixtures (e.g., where hydrated lime filler replaces at least part of the original one), which appear to strengthen during moisture exposure, and (b) extra-sensitive mixtures, which may disintegrate in less than 1 day of immersion (e.g., where glass bead filler replaces the original one). Examples of these extreme types of behavior are detailed elsewhere (*13*).

That the durability curve can be described by Equation 4 is of great practical importance for the DI test in its modified form because it provides a mathematical justification for the replacement of the original DI version by the modified one. Consider, for instance, a typical durability curve (Figure 6), which deteriorates according to Equation 4. In that case, the ERS can be computed as

$$ERS = 100\% - (1/14)\left[100 \times 14 - 100\left(\int_0^{14} e^{-KT}\, dT\right)\right] = 100 - DI \qquad (5)$$

This continuous equation is equivalent to the discrete form of Equations 1 and 2.

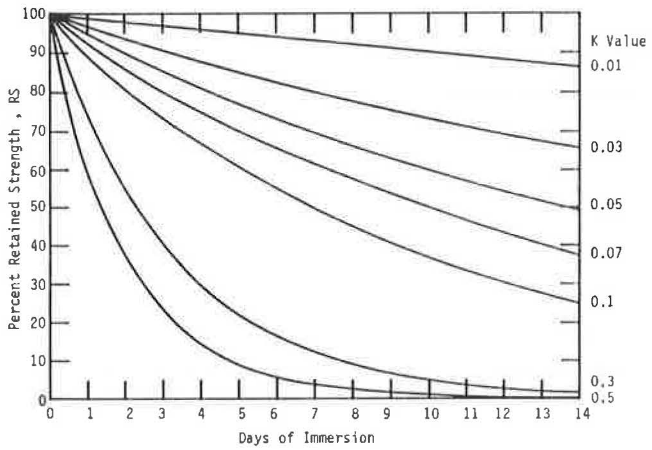

FIGURE 6 Various theoretical durability curves.

As mentioned earlier, and shown in Figure 5, calculations based on strength drops measured daily in immersed samples versus calculations based on the original DI test revealed an excellent match between durability indices in both procedures. Therefore the use of Equation 5 is justified. Moreover, RS values after 6 days of immersion can also be calculated according to

$$RS_6 = 100e^{-K6} \qquad (6)$$

The sensitivity of moisture damage behavior can be demonstrated by comparing RS results for the various K-values (Table 4 and Figure 6). This comparison proves that good agreement exists between results obtained by the original and the modified DI procedures. The large deviations at RS < 25 percent (on the order of 8 to 10 percent) are not important because the samples are in a state of severe failure.

TABLE 4 VALUES OF DI, ERS, RS_6, AND RS_{14} AS A FUNCTION OF K

K	DI (%)	ERS (%)	RS_6 (%)	RS_{14} (%)
0.01	6.68	93.31	94.17	86.9
0.03	18.34	81.65	83.50	65.7
0.05	28.08	71.91	74.08	49.6
0.07	36.26	63.74	65.70	37.5
0.10	46.18	53.82	54.90	24.6
0.30	76.55	23.45	16.50	1.5
0.50	85.73	14.27	4.97	0.1

Equation 4 can shed new light on the traditional Marshall immersion test and criteria. In many countries, the acceptance and rejection limiting criterion in this test is $RS_1 = 75$ percent. Based on Equation 4, this is equivalent to ERS $\cong RS_6 \cong 18$ percent. Israeli experience suggests that this value is far below the minimum acceptable value of ERS (or RS_6), which is about 50 percent (equivalent to $RS_1 \cong 89$ percent in the traditional test).

Assuming that the reduction in the mechanical strength in the DI test reflects moisture damage development under local conditions (hot, humid, and rainy climate), raising the immersion Marshall stability criterion RS by about 14 percent would mean multiplying the long-term equivalent retained stability criterion by a factor of about 2.8.

The ERS or RS_6 criterion is better than the 1-day (RS_1) criterion because this criterion reflects the long-term durability behavior of the mixture and the stabilization of the moisture damage development function (durability curve). At RS_1 the curve is quite steep and sensitive whereas at RS_6 (which is equivalent to ERS) the function is stabilized and flattened.

Practical Application of the Modified DI Test

The following are suggested steps for the practical application of the modified DI test:

1. Prepare three sets of identical Marshall samples or equivalent (at least two sample per set).
2. Test the sets after 0, 1, and 6 days of immersion for their Marshall stability (or other strength test).
3. Compute retained strength values after 1 and 6 days of immersion.
4. Using the expression

$$K = [\ln(RS/100)/T] \qquad (7)$$

calculate K-values for the data given in the following table.

T (days)	*RS (%)*	*Designation of K*
1	RS_1	K_1
6	RS_6	K_6
6	$RS_6 + 5$	K_6^+
6	$RS_6 - 5$	K_6^-

5. Check that the following condition exists:

$$K_6^+ < K_1 < K_6^-$$

This condition is needed to assure that the retained strengths at 1 and 6 days are compatible. If this condition is not satisfied, repeat the test.

6. Report the MD sensitivity of the mixture as the value of retained strength after 6 days of immersion (RS_6).
7. If the mixture is extra-sensitive to moisture damage ($RS_1 \rightarrow 0$) skip stages 4–6 and report its sensitivity to MD as RS_1.

8. If the mixture is treated or stabilized ($RS_1 > 100\%$, $RS_6 > 95\%$) report its MD sensitivity as its RS_6-value and skip stages 4–7.

SUMMARY, CONCLUSIONS, AND SUGGESTIONS FOR FURTHER RESEARCH

This paper has dealt with the development of a moisture damage (MD) sensitivity test for bituminous paving mixtures under hot and humid climatic conditions. The concept and test are based on characterizing the moisture damage sensitivity by long-term durability curves that express the variation of retained strength with hot immersion (60°C) times of up to 14 days. The original version of the test was modified by characterizing the MD sensitivity using the retained strength value at 6 days of hot water immersion.

Both versions of the test have been proven to be superior to the traditional 1-day Marshall immersion test in detecting sensitive mixtures. The modified version is a practical substitute for the former one, which was based on longer immersion periods (up to 14 days) and a greater number of sample sets (five versus three needed by the current procedure). The development of the test was supported by laboratory and initial field experience, as well as by theoretical considerations of behavior of mixtures during long immersion periods.

Further research is needed, however, to improve various aspects of the test, such as

1. Replacing the destructive Marshall test by more fundamental types (e.g., resilient modulus, indirect tensile), which may also result in a reduction in the number of samples needed.
2. Shortening the needed immersion period (e.g., by adding a preliminary vacuum saturation phase). This addition may accelerate MD development, and thus the same amount of MD might be caused in shorter periods.
3. Developing statistical quality control standards to use as acceptance and rejection criteria.
4. Carrying out a Lottman-type (*5*) field study to correlate these criteria with field experience.

REFERENCES

1. A. D. Dow. Discussion of Application and Present Status of the Immersion-Compression Test by J. T. Pauls and J. F. Goode. *Proc., Association of Asphalt Paving Technologists,* Vol. 16, 1947, p. 392.
2. M. A. Taylor and N. P. Khosla. Stripping of Asphalt Pavement: State-of-Art. In *Transportation Research Record 911,* TRB, National Research Council, Washington, D.C., 1983, pp. 150–158.
3. *1982 Annual Book of ASTM Standards.* ASTM, Philadelphia, Pa., 1982, Part 15, D 1075-81.
4. *Engineering and Design—Flexible Airfield Pavements—Airforce.* Em 1110-45-302. U.S. Army Corps of Engineers, Aug. 1958, Appendix V.
5. R. P. Lottman. *NCHRP Report 246: Predicting Moisture-Induced Damage to Asphaltic Concrete—Field Evaluation.* TRB, National Research Council, Washington, May 1982.
6. D. G. Tunnicliff and R. E. Root. *NCHRP Report 274: Use of Antistripping Additives in Asphaltic Concrete Mixtures—Laboratory Phase.* TRB, National Research Council, Washington, D.C., Dec. 1984.
7. T. W. Kennedy, R. B. McGennis, and F. L. Roberts. Investigation of Moisture Damage to Asphalt Concrete and the Effect on Field Performance—A Case Study. In *Transportation Research Record 911,* TRB, National Research Council, Washington, D.C., 1983, pp. 158–165.
8. R. J. Schmidt and P. E. Graf. The Effect of Water on the Resilient Modulus of Asphalt Treated Mixes. *Proc., Association of Asphalt Paving Technologists,* Vol. 41, 1972, pp. 118–162.
9. I. Ishai, J. Craus, and M. Livneh. Improvement of Stripping Resistance of Sensitive Aggregates in Bituminous Paving Mixtures. *Proc., 4th Conference on Asphalt Pavements for Southern Africa,* Vol. 1, 1984, pp. 475–484.
10. H. W. Busching, G. C. Corley, J. L. Burati, Jr., S. N. Amirkhamian, and J. M. Alewine. *A Statewide Program to Identify and Prevent Stripping Damage.* Special Technical Publication 899. ASTM, Philadelphia, Pa.
11. S. Nesichi, I. Ishai, M. Livneh, and J. Craus. *Investigation of Durability Properties of Bituminous Concrete for Highway and Airports.* Research Report 85-68. Transportation Research Institute, Technion, Haifa, Israel, June 1985.
12. V. A. Endersby, R. L. Griffin, and H. J. Sommer. Adhesion Between Asphalts and Aggregates in the Presence of Water. *Proc., Association of Asphalt Paving Technologists,* Vol. 16, 1947, pp. 411–451.
13. J. Craus, I. Ishai, and A. Sides. Durability of Bituminous Paving Mixture as Related to Filler Type and Properties. *Proc., Association of Asphalt Paving Technologists,* Vol. 50, 1981, pp. 291–316.
14. R. P. Lottman. *NCHRP Report 192: Predicting Moisture-Induced Damage to Asphaltic Concrete.* TRB, National Research Council, Washington, D.C., 1978.
15. D. W. Gilmore, J. B. Darland, Jr., L. M. Girdler, L. W. Wilson, and J. A. Scherocman. *Changes in Asphalt Concrete Durability Resulting from Exposure to Multiple Cycles of Freezing and Thawing.* Special Technical Publication 899. ASTM, Philadelphia, Pa.
16. K. Majidzadeh and R. R. Stander, Jr. Effect of Water on the Behavior of Sand Asphalt Mixtures under Repeated Loading. In *Highway Research Record 273,* HRB, National Research Council, Washington, D.C., 1969, pp. 99–109.
17. S. Nesichi and I. Ishai. A Modified Method for Predicting Reduced Asphaltic Pavement Life from Moisture Damage. Presented at the Association of Asphalt Paving Technologists Meeting, Clearwater, Fla., Feb. 1986.
18. I. Ishai, S. Nesichi, and J. Craus. *Hot Bituminous Emulsion Mixtures—Introductory Research.* Research Report 85-94. Transportation Research Institute, Technion, Haifa, Israel, March 1986.
19. I. Ishai and Y. A. Tuffour. The Use of Propane Precipitated Asphalt (PPA) in Bituminous Paving Mixtures. Presented at the Annual Meeting of the Association of Asphalt Paving Technologists, Reno, Nev., Feb. 1987.

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