Effects of Test Parameters on Resilient Modulus of Laboratory-Compacted Asphalt Concrete Specimens

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The resilient modulus of a laboratory-compacted asphalt concrete specimen is dependent on many factors, including the test system used, the test operator, the method of compaction, the level of compaction, and parameters or conditions in the test procedure such as temperature, load frequency, load duration, and load-induced diametral strain level. The results of a parametric study involving resilient modulus testing of two dense-graded hot-mix asphalt concrete mixtures compacted to two levels of air voids are presented. Three replicated test specimens were prepared for each mix at each air void level using the Marshall method of compaction. The concern was to select one combination of test temperature, load frequency, load duration, and induced diametral strain that would lead to repeatable modulus results among the replicated specimens within each group while being sensitive enough to detect differences between the two mix types and levels of air void contents of similar mix types. A pneumatic test system was used to measure resilient modulus. On the basis of a statistical analysis of the test results, it was concluded that the test conditions consisting of 0.1-sec load duration, 0.33 Hz load frequency, 50 to 75 $\times$ 10^{-4} percent induced strain (50 to 75 μstrain) at 60°F would best satisfy the repeatability criteria.

Various testing machines are available that can directly measure the resilient modulus (M_R) of an asphalt concrete (AC) specimen using repeated-load techniques. Variability in the M_R arguably can be attributed to the operation of different machines by different operators, the variations in mix designs, and the level of compaction of the AC specimens, but perhaps the most severe variable contributing to such errors is the combination of test conditions selected to perform the test.

ASTM has recommended a range of test temperatures, load duration and frequency, and induced diametral strain in the standard test method ASTM D4123. These conditions are

Temperature—41, 77, and 104°F;
Load duration—0.1 to 0.4 sec;
Load frequency—0.33, 0.5, and 1.0 Hz; and
Load/strain level—induce 10 to 50 percent of the tensile strength.

M_R can be measured as total or instantaneous, which differ in the interpretation of recoverable strain on load release; it is described in more detail in the ASTM test procedure. All of these factors can greatly influence the M_R of an asphalt concrete mixture.

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The concern of the laboratory study presented in this paper is to evaluate the effects of the M_R test conditions on replicated specimen groups. The primary objective is to develop a singular set of test conditions that leads to the most repeatable M_R results within a set of replicated specimens. The secondary objective is to evaluate the potential of the test conditions selected to differentiate between M_R results of replicated specimen groups with subtle variations in mix constituents and levels of compaction.

EXPERIMENT DESIGN

To satisfy these objectives, several variables were used in the study. These test variables can be divided into two general groups: (a) material variables (two aggregate types and two air void contents), and (b) procedural variables (ASTM test conditions as defined).

Material Variables

The specimens tested were laboratory Marshall-compacted, dense-graded hot-mix AC specimens made up of aggregates from two Oregon sources. Aggregate A is a crushed, river-run basalt aggregate. Aggregate B is a crushed hillside basalt aggregate. By visual observation, Aggregate B generally exhibits greater fractured faces, angularity, and surface roughness than Aggregate A.

An AR-4000W grade asphalt was batched with each aggregate at the optimum content recommended by the Oregon Department of Transportation (ODOT), as shown in Table 1.

Two levels of compaction were used for each aggregate type to achieve 4 and 10 percent air voids. The group prepared with Aggregate B at 4 percent air voids also contained 1 percent hydrated lime, which was slurried with the aggregate and dried before batching. The lime was used with Aggregate B only to aid in the evaluation of the effectiveness of lime as an antistripping additive, which is not evaluated in this paper. The air void contents were determined by the standard procedure given in ASTM D3203, (Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures) and reported as a percentage of total specimen volume. Bulk specific gravities were determined using ASTM D2726 (Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens); maximum

TABLE 1 ODOT Mix Designs for Dense-Graded C-Mix (HVEEM)

	Percent Passing (percentages of total aggregate by weight)		
Sieve Size	Aggregate A	Aggregate B	ODOT Specifications
3/4"	100	100	100
1/2"	98	99	95 - 100
3/8"	81	87	
1/4"	65	66	60 - 80
#10	32	33	26 - 46
#40	12	16	9 - 25
#200	5.0	4.8	3 - 8
Optimum Asphalt Content*, %	6.0	6.7	4 - 8

* Percent of total mix by weight

specific gravities were determined using ASTM D2041 (Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures).

The purpose of using varying air void contents for the test program was to detect if the test procedure would be sensitive enough to differentiate between M_R values of varying voids. The expected trend is a decrease in M_R with an increase in air voids (*1*,*2*).

Procedural Variables

The pneumatic test system shown in Figure 1 was used in this study. As described, the operator of the repeated-load diametral test system can control a fairly wide range of values for the load duration, frequency, and amplitude, along with the testing temperature. Each test specimen, therefore, was subjected to a series of tests over a range of controlled conditions as shown in Table 2. The range was selected in order to investigate the full range of test conditions specified by ASTM D4123. Table 2 illustrates that 13 out of a total of 81 test combinations were selected for the evaluation. The selection of the 13 conditions was made on the assumption that trends of M_R with respect to duration, frequency, and strain level are the same for any given material at any temperature. Therefore, the effects of duration and frequency were observed at only one temperature (77°F) and one induced strain level (75 μstrain) and the effects of temperature and induced strain level were observed at only one load duration (0.1 sec) and one load frequency (0.5 Hz). If this assumption is correct, the *F*-ratio for the two-way interaction should not be significant.

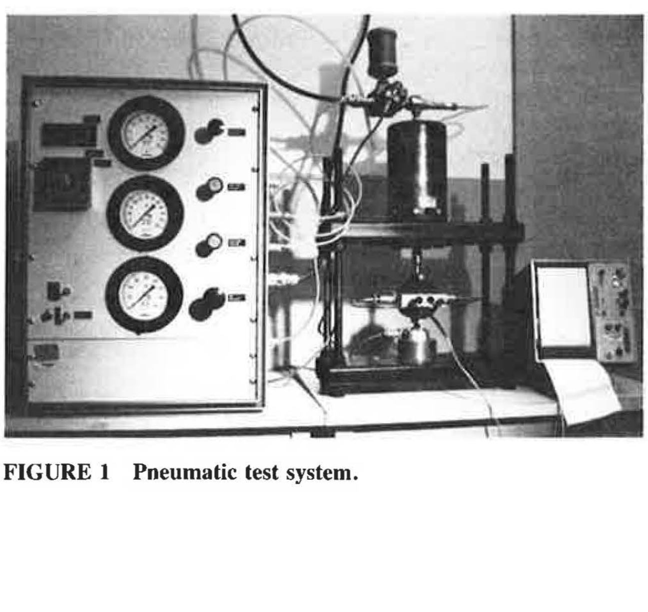

FIGURE 1 Pneumatic test system.

TABLE 2 Matrix of Test Conditions in Study

Temperature (°F)		41			77			104		
Microstrain		50	75	100	50	75	100	50	75	100
Duration (hz.)	Frequency (sec.)									
0.1	0.33					X				
	0.5	X	X	X	X	X	X	X	X	X
	1.0					X				
0.2	0.33									
	0.5					X				
	1.0									
0.4	0.33									
	0.5					X				
	1.0									

ANALYSIS PROCEDURE

The experimental design used to analyze the test results was a completely randomized design (CRD), and a two-way analysis of variance (ANOVA) was selected as the statistical tool to aid in the evaluation of the results (*3*). For this design the procedural variables or conditions were assigned as Factor *A*, and the material variables, or simply materials, were assigned as Factor *B*. Therefore, 13 levels of Factor *A* and 4 levels of Factor *B* for a total of 52 treatments ($A \times B$ interactions) could be evaluated.

An assumption of ANOVA is that experimental errors are random, independent, and normally distributed about zero mean with common variance (*3*). The *F*-ratio, a statistic computed from the ANOVA error terms, is the ratio of two independent estimates of the same variance. Where the *F*-ratio is used, a null hypothesis of equal factor means is assumed. In general terms, the ratio represents a comparison between a biased estimated variance (mean square for factors, *MSA*, *MSB*, or *MSAB*) of the experiment and an unbiased estimate of variance (mean square for error, *MSE*) of the experiment. The hypothesis of equal means is rejected in favor of unequal means if the computed *F*-ratio is larger than critical *F*-ratios for any combination of degrees of freedom and significance levels associated with a given experiment. Critical *F*-ratios are tabularized in most statistics textbooks.

The total and instantaneous M_R were measured; therefore, two ANOVA tables were generated that were similar to the one in Table 3. A comparison of precision between the two measurements can be made using the coefficient of variation, CV, (*4*, p. 13) which is defined by Equation 1:

$$CV = [(MSE)^{1/2}/x..) * 100 \text{ percent} \quad (1)$$

where *x*.. is the grand mean of all observations.

TABLE 3 Experimental Design ANOVA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Conditions (Factor A)	k-1	SSA	MSA	F_A
Materials (Factor B)	l-1	SSB	MSB	F_B
Treatments (A x B)	(k-1)(l-1)	SSAB	MSAB	F_{AB}
Error	kl(m-1)	SSE	MSE	
Total	klm-1	SSTot		

Variable definitions:

k = No. of levels of conditions = 13

l = No. of levels of materials = 4

kl = No. of treatments (each one a combination of test conditions and materials level) = 52

m = No. of observations of each treatment = 3 replicates

Calculations:

CT = CT = Correction term = $klm(x..)^2$ where x.. = Grand mean of all observations

SSA = $ml\Sigma A_k^2$ - CT x = each observation

SSB = $mk\Sigma B_l^2$ - CT

SSAB = $m\Sigma\Sigma AB_{kl}^2$ - SSA - SSB - CT

SSTot = $\Sigma\Sigma\Sigma x_{klm}^2$ - CT

SSE = SSTot - SSA - SSB - SSAB

Mean squares are determined by dividing the sum of squares by their associated degrees of freedom.

F-ratios are determined by dividing the mean squares by the mean square for error.

RESULTS

M_R tests were performed on each test specimen (4 groups × 3 replicates/group = 12 total specimens) using the repeated-load test system. The H&V pneumatic device shown in Figure 1 was used in this study. The specimens were tested at each of the 13 test conditions identified in Table 2, and corresponding total and instantaneous M_R values were recorded. The values were averaged for the three replicated specimens in each group (i.e., A4 = Aggregate A, 4 percent air voids, A10 = Aggregate A, 10 percent air voids, BL4 = Aggregate B treated with lime, 4 percent air voids, and B10 = Aggregate B, 10 percent air voids), and the results are presented in Figures 2 through 9 to illustrate the general M_R trends with respect to each test condition. Each figure representing the total M_R response is grouped with a similar figure representing the instantaneous M_R response. By general observation, the modulus decreases with increasing temperature and load duration. It is apparent that these general trends are consistent within the different material groups (shown by approximate parallel lines) for the total M_R response and inconsistent (shown by intersecting lines) for the instantaneous M_R response. The total and instantaneous M_R responses were observed to be independent of load frequency and induced strain levels; therefore, they are not shown graphically. The coefficient of variation for each observation (average of three replicates) was found to be generally greater for the instantaneous M_R response. This was expected in that the interpretation of the instantaneous measurement deflection is more judgmental than the total measurement of deflection, which leaves a greater chance for error when obtaining instantaneous M_R results (ASTM D4123).

It should be noted that tests performed at 104°F were only marginally successful for the 4 percent air void samples and could not be performed for the 10 percent air void samples. This temperature was found to be too warm, and all samples

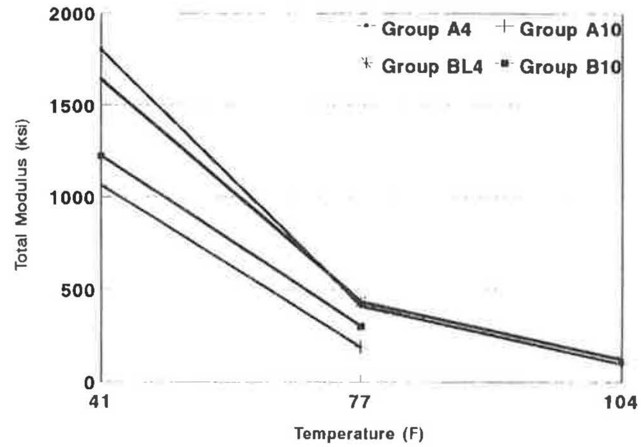

FIGURE 2 Temperature effects at 50 μstrain: total modulus.

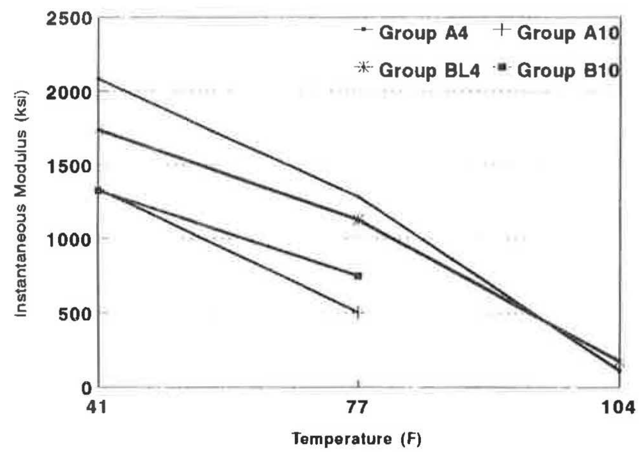

FIGURE 3 Temperature effects at 50 μstrain: instantaneous modulus.

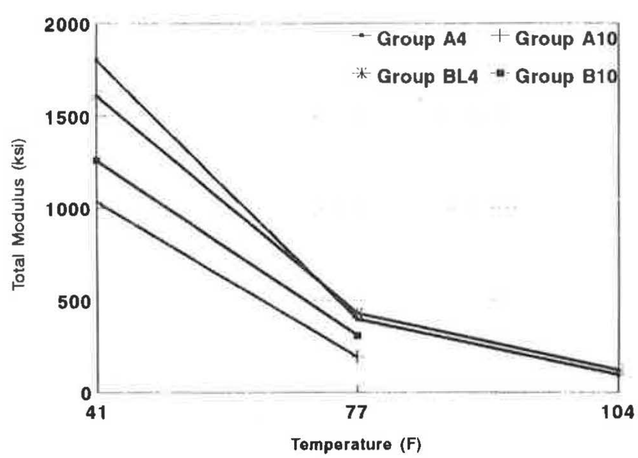

FIGURE 4 Temperature effects at 75 μstrain: total modulus.

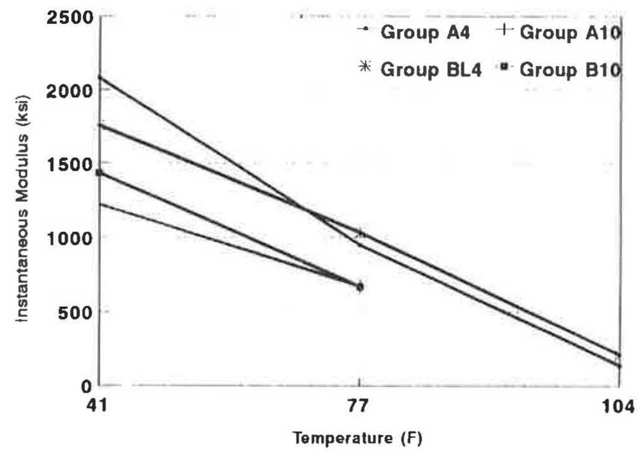

FIGURE 5 Temperature effects at 75 µstrain: instantaneous modulus.

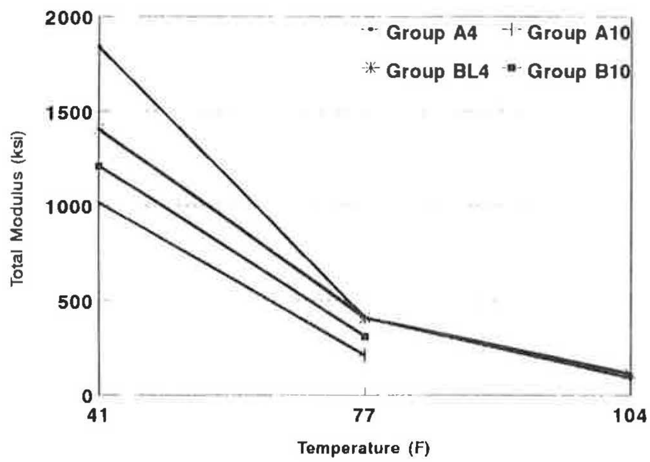

FIGURE 6 Temperature effects at 100 µstrain: total modulus.

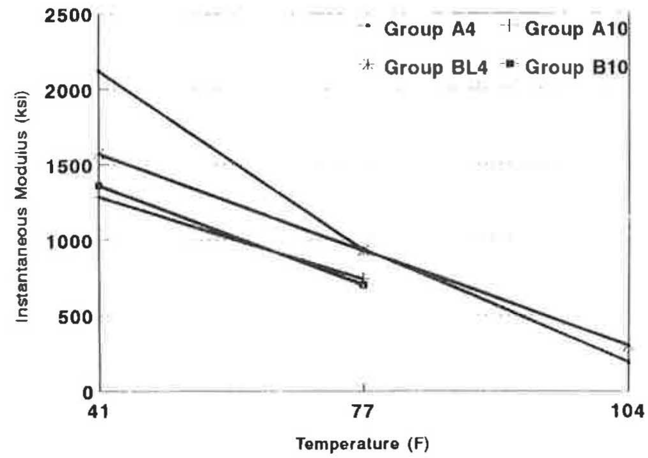

FIGURE 7 Temperature effects at 100 µstrain: instantaneous modulus.

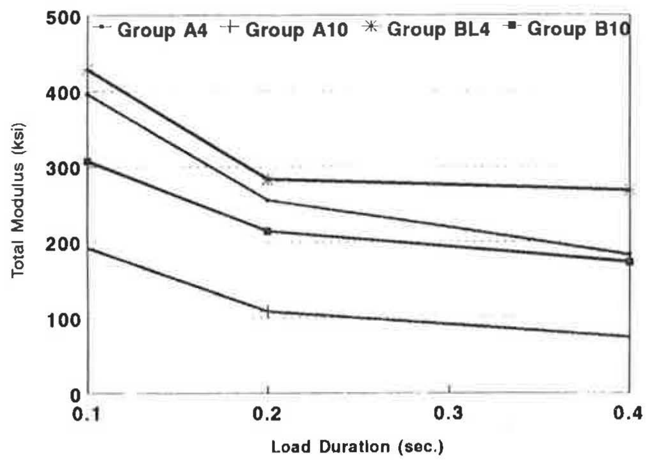

FIGURE 8 Load duration effects: total modulus.

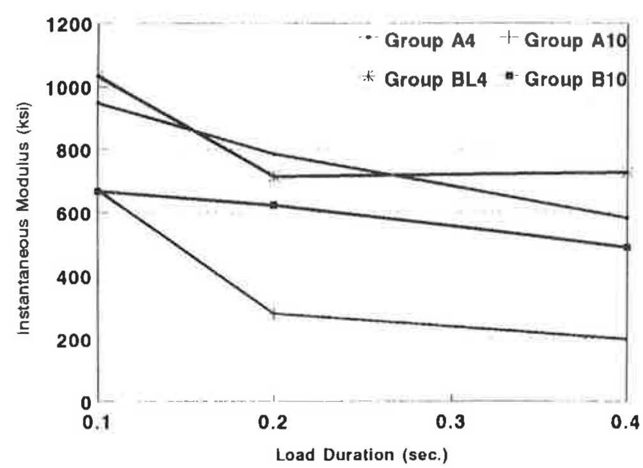

FIGURE 9 Load duration effects: instantaneous modulus.

exhibited flow (excessive permanent deformation) with only a 10-lb static seating load. Therefore, the 104°F test temperature was removed from consideration as a practical temperature, and the ANOVA in Table 3 was adjusted accordingly to reflect that only 10 levels of testing condition, Factor *A*, were considered in the analysis rather than the 13 levels originally planned.

DISCUSSION OF RESULTS

Two ANOVAs were performed at the conclusion of the M_R testing, one for the instantaneous measurement of M_R and the second for the total measurement of M_R. The ANOVAs resulted in a highly significant interaction (a significant *F*-ratio of the *AB* interaction), suggesting that Factors *A* and *B* do not act independent of each other. Unfortunately, inferences drawn from the test data at the 77°F testing temperature (i.e., general trends of M_R with respect to load duration, frequency and induced strain level) do not necessarily hold true at the 41°F testing temperature.

Because Factors *A* and *B* do not act independent of each other, the results can be summarized in a two-way table of *AB* means as shown in Tables 4 and 5 for the instantaneous and total measurements, respectively, and comparisons of *AB* means can be made.

At the onset of the experiment, both measurements were expected to detect significant differences between material

TABLE 4 Mean Instantaneous M_R of Four Types of Material Under Different Levels of Settings [ksi ($n=3$)]

	CONDITIONS*									
	1	2	3	4	5	6	7	8	9	10
Temperature(°F)	41			77						
Frequency (hz.)	0.5			0.5	0.33	0.5			1.0	0.5
Duration (sec.)	0.1			0.1	0.1	0.1	0.2	0.4	0.1	0.1
Microstrain	50	75	100	50	75					100
MATERIALS**										
A4	2085	2083	2121	1283	1109	948	785	582	866	935
BL4	1743	1758	1571	1125	867	1033	714	726	921	928
A10	1336	1223	1284	503	576	672	281	199	820	738
B10	1327	1435	1362	746	759	668	624	490	772	699
Average	1623	1625	1585	914	828	830	601	499	845	825

* Conditions are combinations of temperature, load frequency and duration, and microstrain level.
** Materials are combinations of aggregate type, air void content and additive type.

TABLE 5 Mean Total M_R of Four Types of Material Under Different Levels of Settings [ksi ($n=3$)]

	CONDITIONS*									
	1	2	3	4	5	6	7	8	9	10
Temperature(°F)	41			77						
Frequency (hz.)	0.5			0.5	0.33	0.5			1.0	0.5
Duration (sec.)	0.1			0.1	0.1	0.1	0.2	0.4	0.1	0.1
Microstrain	50	75	100	50	75					100
MATERIALS**										
A4	1801	1801	1840	410	398	396	256	183	392	409
BL4	1642	1610	1406	433	504	429	283	268	436	409
A10	1063	1033	1017	187	175	192	108	74	231	211
B10	1224	1259	1211	300	353	306	214	173	344	310
Average	1433	1426	1369	333	358	331	215	175	351	335

* Conditions are combinations of temperature, load frequency and duration, and microstrain level.
** Materials are combinations of aggregate type, air void content and additive type.

groups at any test condition combination. Differences between material groups at any test condition combination can be made using the t-test statistic. The t-test tests the hypothesis that means are equal against the alternative that the means are different (5). The t-statistic is computed as follows:

$$t = (x_{ij} - x_{i'j'})/(2MSE/m)^{1/2} \quad (2)$$

where

x_{ij} = mean M_R at the ith level of material and the jth level of conditions,
$x_{i'j'}$ = mean M_R at the ith' level of material and the jth' level of conditions ($x_{ij} \neq x_{i'j'}$),
$(2MSE/m)^{1/2}$ = standard error for differences between AB means,
MSE = mean square for error of the appropriate experiment, and
m = number of replications at each AB level.

The computed t-statistic is compared to a tabularized critical t-value at the appropriate level of significance and associated degrees of freedom. These critical t-values can be found in most statistics textbooks. Differences of material means at each level of setting combinations were compared in Tables 4 and 5, and the means that were not significantly different were marked with links as shown. A link drawn on the left side of the column indicates that the particular combinations

of test conditions uniquely defining that column did not result in M_R values that could successfully differentiate between mixtures composed of different aggregates at the same level of air voids. Likewise, a link drawn on the right side of the column indicates that the particular combinations of test conditions uniquely defining that column did not result in M_R values that could successfully differentiate between similar mixtures compacted to different levels of air voids. These comparisons were made at the 0.05 α-level. The tables illustrate that differences between material groups are most apparent at 41°F. It is also apparent from these tables that the total M_R measurement differentiates between material changes better than the instantaneous M_R measurement at the lower temperature. Also, the computed CV of the total M_R experiment was 11.9 percent as compared with the 12.5 percent CV computed from the instantaneous experiment, suggesting that the total measurement is relatively more precise.

The conclusions, from the ANOVA, strongly suggest 41°F as the preferred testing temperature. The conclusion is supported by the fact that at this temperature, the test procedure yields M_R values that differ significantly between material changes. The test procedure does not give a strong differentiation of M_R results at 77°F.

The 41°F test procedure requires special conditions, namely, a cold environment in which to work. The closer the test temperature is to ambient temperature, the more practical the test will be. If the test temperature is significantly different than ambient, heat loss or gain becomes a problem and an individual test can take an impractical amount of time. Therefore, a temperature between 41° and 77°F needed to be explored as a practical alternative.

This was done with samples compacted to 4 and 8 percent air voids for each aggregate type (sample groups therefore consisted of A4, B4, A8, and B8, as defined). Four replicates were compacted and tested for total M_R at temperatures of 41, 50, 60, and 77°F. A summary of the test results is shown in Table 6. An ANOVA was done by partitioning the temperatures as blocks in a randomized block design and selecting the four material groups as treatments (*6*). These results are presented in the ANOVA Table 7. The ANOVA table shows that there exists highly significant differences between treatment means, and blocking was successful in removing one source of variation from the experimental error (shown as significant *F*-ratios).

TABLE 6 Supplemental Temperature Study: Total M_R ksi ($n = 4$)

	Blocks of Temperature			
	1	2	3	4
Treatments	41°F	50°F	60°F	77°F
A4	2595	1882	1271	496
B4	2717	2213	1686	771
A8	1768	1189	725	208
B8	1831	1421	960	322
block mean =	2228	1676	1160	449
SS(Tr)j =	74135	633310	517904	180039
MS(Tr)j =	247712	211103	172635	60013
F(Tr)j =	13.53	11.53	9.43	3.28

TABLE 7 Supplemental Temperature Study, ANOVA

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F-ratio
Treatments	3	1909595	636532	34.76**
Blocks	3	6886178	2295393	125.36**
Error	9	164793	18310	
Total	15			

** Significant at the 0.01 α-level

The primary concern in this supplemental temperature study was to determine if some intermediate temperature between 41 and 77°F would lead to M_R values that strongly differentiate between treatment means. This was done by computing the individual contribution of variability among blocks (MST_{bl}) to the overall variability of the experiment (MSE), shown as a partial *F*-ratio identified as $F(\mathrm{Tr})_j$ of Table 6. This analysis suggests choosing the largest *F*-ratio among blocks, which implies the largest contribution to the overall experimental variability, or in other words, the block (temperature) that results in M_R values most different with respect to material groups.

The 41°F temperature again leads to the most discriminate M_R values, shown as a high partial *F*-ratio [$F(\mathrm{Tr})_j$] in Table 6. However, by elevating the test temperature to 50 and 60°F, the results still appear to discriminate highly between material groups; at 77°F, this generalization does not seem warranted. The relationship between 41 and 77°F with respect to material sensitivity is consistent with those found earlier.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

From this study, the following conclusions can be made:

1. M_R results obtained shown a high degree of material sensitivity at 41°F and a low degree at 77°F.
2. The total measurement led to results with a higher degree of material sensitivity than the instantaneous measurement did. The total measurement is also comparatively more precise than the instantaneous measurement.
3. There is evidence that indicates little change in the ability of the test procedure to differentiate between material changes when total M_R is tested at 41, 50, or 60°F. This is shown in the partial *F*-ratio row of Table 6.
4. There is insufficient evidence that indicates differentiation between material changes at 77°F testing temperature, shown as a low partial *F*-ratio in Table 6.

Recommendations

From the evaluation of these study results, it is recommended that the test conditions of 0.1-sec load duration, 0.33 Hz load frequency, 50 to 75 μstrain, and 60°F be used as the standard procedure to be used with the repeated-load test system and

the M_R reported as a total M_R. These test conditions are critical when a relative comparison of two or more mix types is to be made or when subtle differences of one mix type are to be detected, such as strength sensitivity to gradation, asphalt content, and moisture damage.

REFERENCES

1. R. G. Hicks et al. *Identification and Quantification of the Extent of Asphalt Stripping in Flexible Pavements in Oregon—Phase II*. Report FHWA-OR-85-3. Materials Division, Oregon Department of Transportation, Salem, 1985.
2. E. L. Dukatz, Jr., and R. S. Phillips. The Effect of Air Voids on the Tensile Strength Ratio. *Proc., Association of Asphalt Paving Technologists*, Vol. 56, 1987, pp. 517–537.
3. J. Devore and R. Peck. The Analysis of Variance. In *Statistics—The Exploration and Anslysis of Data*, West Publishing Company, St. Paul, Minn., 1986, pp. 594–600.
4. R. G. Petersen. Completely Randomized Design. In *Design and Analysis of Experiments*, Marcel Dekker, Inc., New York, N.Y., 1985.
5. J. Devore and R. Peck. Inferences Using Two Independent Samples. In *Statistics—The Exploration and Analysis of Data*, West Publishing Company, St. Paul, Minn., 1986, pp. 373–374.
6. R. G. Petersen. Randomized Block Deisgn. In *Design and Analysis of Experiments*, Marcel Dekker, Inc., New York, N.Y., 1985, pp. 34–47.