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REFERENCES

1. H. L. Lehmann and V. Adam. Application of the Marshall Method to Hot Mix Design. Louisiana Department of Highways, 1959.
2. J. Y. Welborn and others. The Relation of Absolute Viscosity of Asphalt Binder to Stability of Asphalt Mixtures. ASTM, STP 328, 1968.
3. Symposium on Viscosity Grading of Asphalts. HRB, Highway Research Record 350, 1971.
4. S. C. Shah. Asphalt Cement Consistency Study—Field Evaluation of Viscosity and Penetration-Graded Asphalt Cements. Research and Development Section, Louisiana Department of Transportation and Development, April 1977.
5. A. B. Brown and others. Rate of Change of Softening Point, Penetration, and Ductility of Asphalt in Bituminous Pavements. Proc., AAPT, Vol. 26, 1957.
6. P. S. Kandhal and M. E. Wenger. Asphalt Properties in Relation to Pavement Performance. TRB, Transportation Research Record 544, 1975, pp. 1-13.
7. D. Y. Lee. Asphalt Durability Correlation in Iowa. HRB, Highway Research Record 468, 1973, pp. 43-60.
8. D. I. Anderson and others. Evaluation of Viscosity Graded Asphalt Cements in Utah. Materials and Research Division, Utah Department of Transportation, Jan. 1976.

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Evaluation of Properties of Asphalt-Emulsion-Treated Mixtures by Use of Marshall Concepts

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Findings are reported of a laboratory investigation concerning the effect of asphalt emulsion content, added moisture content, and aggregate gradation on the design parameters and properties of asphalt-emulsion-treated mixtures (AETMs) by use of Marshall equipment. The evaluation was conducted at different curing stages of the mix. One type of aggregate (sand and gravel), one type and grade of asphalt emulsion, a modified Marshall method for preparing and testing AETM specimens, and autographic Marshall equipment that produced a continuous record of load deformation were used in the study. The evaluation resulted in a number of significant results. AETM properties are an outcome of a complex array of factors. Evaluating the mix properties in relation to only a single factor is not sufficient; the interaction of these factors influences the behavioral properties of AETMs and must be considered in the evaluation. The study also showed that water-sensitivity tests must be an integral part of the Marshall design procedure for AETMs.

This study reports the findings of a laboratory investigation that evaluated the effect of asphalt emulsion content, added moisture content, and aggregate gradation on the design parameters and properties of asphalt-emulsion-treated mixtures (AETMs) by using Marshall equipment. The evaluation was conducted at different curing stages of the mix. One aggregate type (sand and gravel) and one type and grade of asphalt emulsion were used along with a modified Marshall method developed by Gadallah, Wood, and Yoder (5) for preparing and testing AETM specimens and autographic Marshall equipment that produced a continuous record of load deformation.

The evaluation of AETM properties resulted in a number of significant results. AETM properties are an outcome of a complex array of factors. Evaluating the mix properties in relation to only a single factor is not sufficient; the interaction of these factors influences the behavioral properties of AETMs and must be considered in the evaluation.

EQUIPMENT AND MATERIALS

Marshall Equipment

The Marshall equipment used in the study consisted mainly of a mechanical compaction hammer and an autographic stability apparatus. The mechanical compaction hammer was used for compacting the standard Marshall specimens at 50 blows/side.

The stability apparatus used in this investigation is essentially the same as the standard Marshall equipment, but it provides a continuous recording chart for load (lb) versus deformation (0.01-in units) throughout the testing range from which stability and flow values can be obtained (since this equipment is calibrated in U.S. customary units of measurement, no SI equivalents are given). Figure 1 shows a typical trace for the Marshall test.

Mineral Aggregate

One type of aggregate, which consisted mainly of terrace sand and gravel, was used in this investigation. Three aggregate gradations that lie within an Indiana State Highway Commission (ISHC) gradation size 73B with a maximum size of 19 mm (0.75 in) were used (Figure 2): The first gradation (MG) follows the midspecification of the ISHC

Figure 1. Typical trace for the Marshall test.

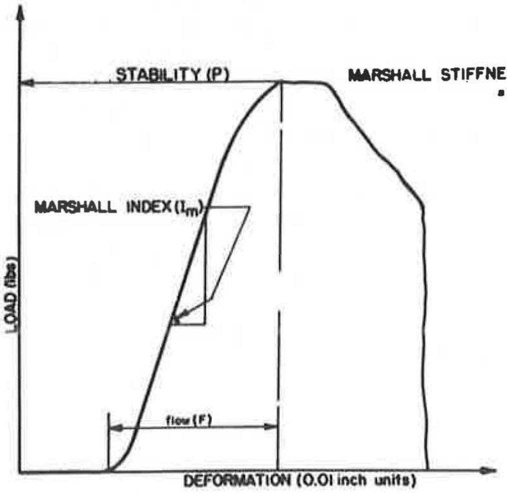
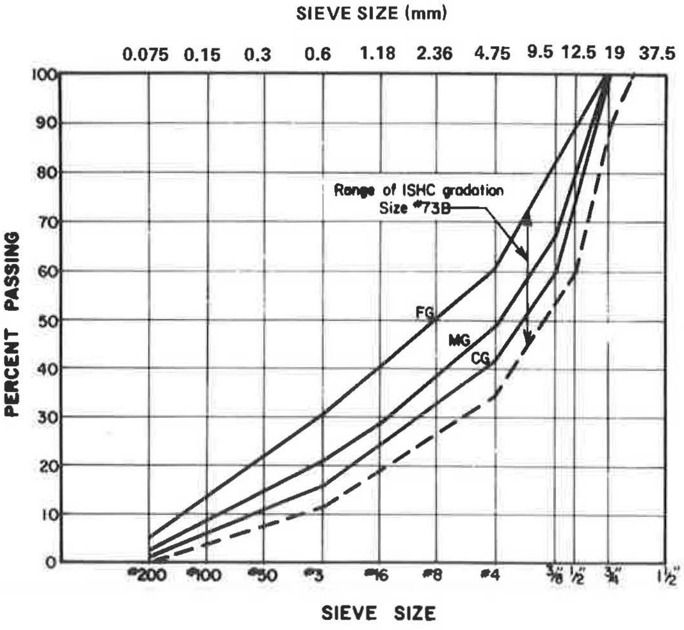


Figure 2. Aggregate gradations.



73B gradation band, the second gradation (FG) follows the upper limit of the gradation band, and the third gradation (CG) was selected between the midpoint and the lower limit of the gradation band to provide better handling and control of the mix. The test properties of the aggregate used are given below [0.075-mm (no. 200) nonplastic filler]:

Property	Gradation FG	Gradation MG	Gradation CG
Apparent specific gravity	2.699	2.707	2.710
Bulk specific gravity, SSD	2.603	2.607	2.608
Absorption, %	1.13	1.20	1.24

Asphalt Emulsion

ISHC designation AE-150 mixing grade emulsified asphalt was used in this study. The physical properties of the asphalt emulsion, which was formulated and provided by the K. E. McConnaughay Laboratory in Lafayette, Indiana, are as follows [t°C = (t°F - 32)/1.8]:

Property	Value
Residue by distillation, %	70.0
Penetration of residue after distillation, at 25°C, 5 s, 100 g	188.0
Specific gravity of residue after distillation, at 25°C	0.986

TESTING PROCEDURE

The following is a summary of the procedure that was used for preparing and testing AETM specimens (5):

1. The aggregate was prepared in 1200-g batches based on the aggregate gradation required.
2. The required amount of initial moisture (distilled water) was added to the cold aggregate and mixed thoroughly.
3. The aggregate-water mixture was left for 10 to 15 min before the asphalt emulsion was added.
4. The amount of asphalt emulsion that is needed to provide a certain asphalt emulsion residue in the mix was added cold to the wet aggregate and mixed by using a mechanical mixer for about 2 min and a 30-s hand mix with a spoon during the mixing period.
5. The mix was cured for 1 h in a forced-draft oven at 60° C (140° F) and then remixed for 30 s.
6. The mix was compacted by using 50 blows on each side of the specimen with the Marshall compaction mechanical hammer.
7. The compacted specimens were left in the mold for about 30 min before they were extruded.
8. The samples, which measured 10.2 cm (4 in) in diameter by 0.75 m (2.5 ft) in height, were then left to cure at room temperature [~21°C (~72° F)] for the required curing time before testing. Whenever the design called for the "ultimate" curing condition, the AETM specimens were cured for 3 d in a forced-draft oven at 48° C (120° F). The specimens were then permitted to adjust to room temperature before testing. Generally, 4 h were enough for the samples to adjust.
9. The cured AETM specimens were tested at room temperature by using Marshall equipment to determine Marshall indexes. Before testing, analyses of density and air voids were performed.
10. Whenever the design called for conducting water sensitivity analysis, the method reported by the Asphalt Institute laboratory (2) was used. In this method, the specimens were subjected to 1 h of vacuum at 30 mm Hg. After the 1-h period, water at 21° C (72° F) was drawn into the vacuum chamber, submerging and vacuum saturating the specimens. The vacuum was released, and the specimens were then transferred to a 21° C water bath where they remained for 24 h. Before testing for Marshall indexes, the saturated surface-dry weight of the specimens was determined. The percentage of water absorption was then obtained.

EXPERIMENTAL DESIGN

The effect of aggregate gradation, asphalt emulsion residue, and added moisture contents on the properties of AETMs was evaluated. Three aggregate gradations were used in the study. The gradations were selected within ISHC gradation size 73B and identified as FG, MG, and CG (Figure 2).

Figure 3. Factorial design for study of the effect of aggregate gradation on AETM properties.

Curing time •condition	% W / Agg. Gradation	F.G.			M.G.			C.G.		
	%AE (residual)	2.5	3.25	4.0	2.5	3.25	4.0	2.5	3.25	4.0
1 day	1.5%	X	X	X	X	X	X	X	X	X
	3%	X	⊗	X	⊗	⊗	⊗	X	⊗	X
3	1.5									
	3	X	⊗	X	⊗	⊗	⊗	X	⊗	X
7	1.5	X	X	X	X	X	X	X	X	X
	3	X	X	X	X	X	X	X	X	X
ult. cond.	1.5									
	3	X	⊗	X	⊗	⊗	⊗	X	⊗	X

Note:

1- X dry test
2- ○ water sensitivity test
3- The ANOVA was conducted for mix combinations within the two blocks (1 and 7 days air-dry curing)

Two replications of the experiment (blocks) were used to provide more inference on the analysis and evaluation of the effect of aggregate gradation together with percentage asphalt emulsion (AE) and percentage added moisture (W). Curing time at 1 and 7 d represented the two blocks (Figure 3). Using the two levels of curing provided the necessary information about the main effects: aggregate gradation, asphalt emulsion content, and added moisture content and their interactions. In addition, all interaction effects were evaluated in relation to the curing factor. However, no testing for the effect of curing time (1 versus 7 d) was available in this study mainly because of the restriction on randomization caused by the blocking effect.

Figure 3 shows the factorial design for the study. The two blocks are shown within the heavy lines for 1 and 7 d of curing. Three levels of aggregate gradation, three levels of asphalt emulsion content (throughout this paper, asphalt emulsion content refers to the asphalt emulsion residue content in the AETM), and two levels of added moisture content were incorporated in the design. In addition to these two blocks, several mix combinations were tested at 3 d of curing and the ultimate curing condition, as shown in Figure 3. The later mixes were not used in the analysis of variance. However, reference is made to these test results whenever it is necessary to provide a general trend for the curing effect and for the water sensitivity analysis.

The AETM properties were analyzed within the framework of a fixed-effect, randomized, complete block design—RCBD (1). The curing time (1 and 7 d) corresponded to the blocks of RCBD. The detailed analysis is presented elsewhere (4).

Response Variables

The response (dependent) variables that were used to evaluate AETM properties by using the modified Marshall method were as follows:

1. Wet density (γ_w), which refers to the density of the mix, including the moisture portion of it, at the time of testing, and dry density (γ_d), which was determined by excluding the moisture portion in the specimen;
2. The percentage of moisture retained in the specimen (WC_o), at the time of testing expressed as percentage by weight of the dry aggregate;
3. The percentage of total liquid at the time of testing (TL) (percentage AE residue plus percentage WC_o);
4. The percentage of voids in the mix, including (a) percentage of air voids (V_A), which represents the percentage of air voids available in the mix but excludes the voids that are filled with moisture, and (b) percentage of total voids (V_T), which represents the total amount of voids available in the mix and includes the air voids (V_A) and the voids filled with moisture (V_W);
5. Marshall stability P, measured at a room temperature that was maintained at approximately 21°C (72°F);
6. Marshall flow F, the maximum deformation that occurs as the specimen reaches failure, expressed in units of 0.25 mm (0.01 in);
7. Marshall stiffness S_m, determined as the ratio of Marshall stability and flow ($S_m = P/F$); and
8. Marshall index I_m, which is represented by the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall equipment.

Two new parameters, S_m and I_m, provide measures for the mix characteristics at the failure condition and throughout the loading process respectively (Figure 1). It is believed that the use of these two parameters in conjunction with the traditional Marshall design parameters would provide better control and evaluation of AETMs.

ANALYSIS OF RESULTS

Percentage of Moisture Retained in the Sample

The percentage of moisture retained in the AETM samples was significantly affected by all factors and their interactions except the interaction between curing, gradation, and added moisture content, which was not significant.

Figure 4 shows the percentage of moisture retained at the time of testing for the specimens cured for 1 and 7 d as a function of aggregate gradation, percentage AE, and percentage W. The percentage of moisture retained (WC_o) ranged between 0.5 and 1.6 percent (by weight of the dry aggregate). At 7 d of curing, the difference in percentage WC_o attributable to varying aggregate gradation, percentage AE, or percentage W was relatively less than that observed for specimens cured for 1 d. In addition, for 1-d specimens (Figure 4a), the effect of aggregate gradation and percentage of added moisture on the percentage WC_o values was more pronounced at the low asphalt content. This effect was reduced as asphalt content was increased. For 7-d specimens (Figure 4b), the range of percentage WC_o was small for FG and MG aggregate mixes at different percentages of AE and W. However, there was relatively large variation in percentage WC_o for CG aggregate mixes.

In view of these results, it can be concluded that at early curing conditions (e.g., 1 d) the effect of aggregate gradation and added moisture content on percentage WC_o depends on the asphalt content in the mix. The higher the percentage of AE, the less is the variation in percentage of WC_o that results from changing aggregate gradation or adding moisture content or both. However, after relatively longer periods of curing (e.g., 7 d), the effect of the interaction between aggregate gradation and percentage W is not significantly apparent.

Dry and Wet Unit Weights

The main factors—aggregate gradation, percentage AE, and percentage W—significantly affected the dry and wet unit weights of the AETM specimens. In addition, aggregate gradation and percentage AE had a greater effect on dry and wet unit weights than added moisture content (percentage W) (this is based on the mean square value that is attributed to each factor in the analysis of variance). It was also noted that all two-factor interactions were significant except the interaction between aggregate gradation and added moisture content, which was not significant. The most significant two-factor interaction was the interaction between curing time and added moisture content.

The relation between dry unit weight (γ_d) and aggregate gradation, percentage AE, and percentage W for the two curing periods is shown in Figure 5. It is apparent that, the higher the asphalt content in the mix is, the higher the γ_d values are. Besides, the CG gradation samples resulted in higher dry unit weights than the MG gradation samples. The FG gradation samples resulted in the least dry unit weights.

Marshall Stability

Marshall stability (P) was significantly affected by all the main factors as well as by most of the two-factor and three-factor interactions. In comparison with the effects of asphalt emulsion and added moisture, aggregate gradation showed the most significant effect on the stability values. Figure 6 shows the stability values in relation to aggregate gradation, asphalt emulsion content, and added moisture content for the two curing periods. Presenting the data in this form aids in providing a better understanding of the effect of the main factors and their interactions.

For specimens cured for 1 and 7 d, FG gradation provided the highest stability at all levels of percentage AE and percentage W. The lowest stability values were obtained for mixes with CG gradation. The MG-gradation mixes resulted in a higher stability than the CG-gradation mixes. It should be noted that the difference between FG and MG grain-size distributions was twice the difference between MG and CG grain-size distributions (Figure 2). This affected the characteristics of the stability results. The Marshall stabilities provided by the MG mixes were

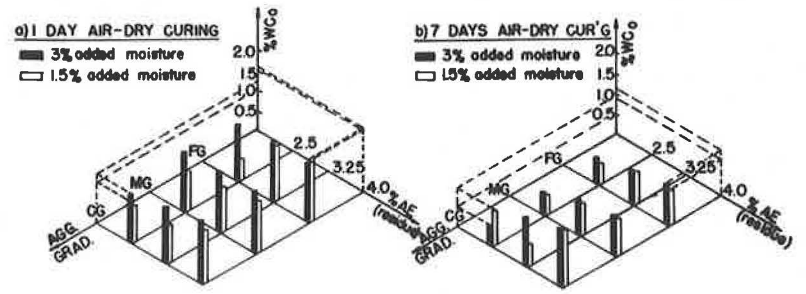


Figure 4. Effect of interaction among aggregate gradation, percentage AE, and percentage W on percentage WC_0 for two curing periods.

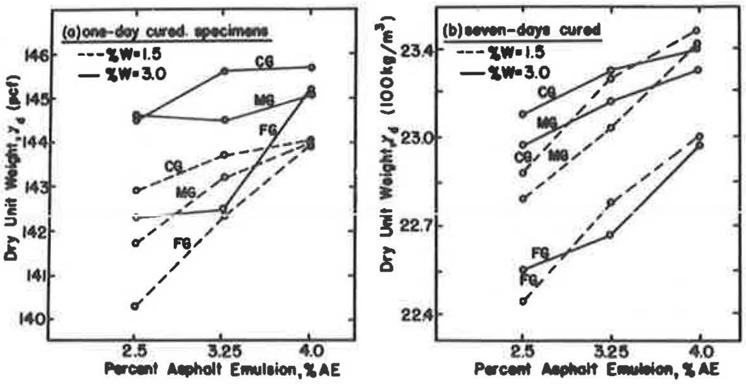


Figure 5. Effect of aggregate gradation, AE, and W on γ_d.

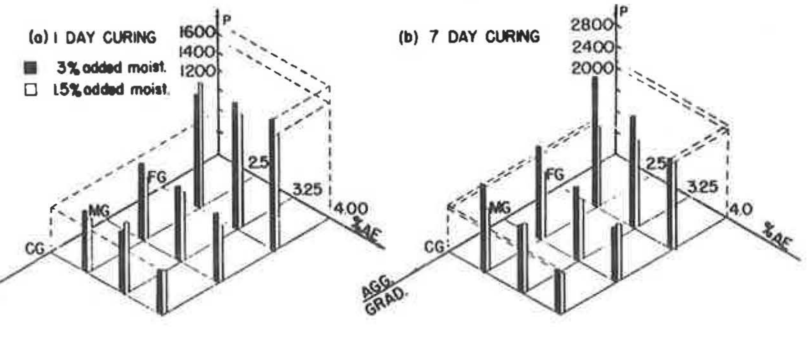
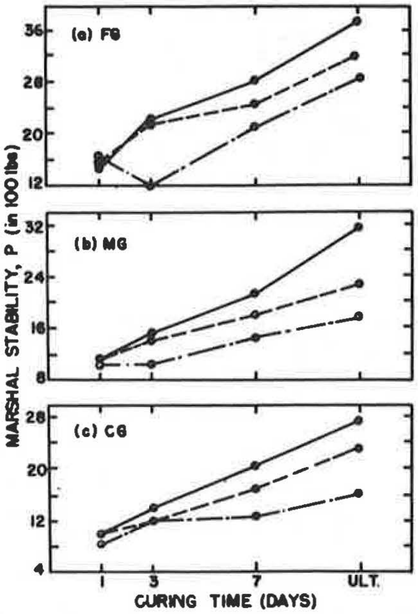


Figure 6. Effect of aggregate gradation, percentage AE, and percentage W on P.

Figure 7. Effect of aggregate gradatión and percentage AE on P as a function of curing time.



NOTE
ALL MIXES ARE WITH 3% ADDED MOISTURE
—— % AE=2.5
--- % AE=3.25
—·— % AE=4.0

closer to those of the CG mixes than to those of the FG mixes.

The effect of asphalt emulsion content on AETM stability is not significantly apparent at early stages of curing (1-d air-dry curing), mainly because of the nature of the asphalt emulsion present in the mix at that time. However, the significant effect of percentage AE becomes increasingly important during the curing process, when the asphalt emulsion residue gradually starts to affect the mix properties (Figure 6).

The AETM with FG and MG gradations produced, in general, higher stability values for mixes with 3 percent W than for mixes with 1.5 percent W. However, the effect of added moisture content for CG mixes was very small or was reversed when the CG gradation was compared with the remaining two gradations. This is caused by the fact that FG and MG gradations have more surface area than the CG gradation and thus require relatively larger amounts of liquid for adequate coating and strength. This is more apparent when one considers the results of 7-d curing, which show that, if the samples were evaluated after 1-d curing, the effect of the added moisture on the strength of the AETM (P in this case) could have been underestimated. Evaluating the AETM properties after relatively long periods of curing would provide more understanding of the role of each of the liquid components in the mix, especially the added moisture content.

The increase or gain in stability values through the curing process for the different aggregate gradations and asphalt emulsion contents is shown in Figure 7. The more the aggregate gradation shifts toward the fine limit of the gradation band, the steeper will be the curing trend and consequently the more rapidly the AETM will develop its strength (represented here as the Marshall stability). This can be demonstrated by a comparison of the stability trends for the different gradations at any specific percentage AE (Figure 7). In addition, the gain in stability through the curing process depends on the asphalt emulsion content. The lower the asphalt emulsion content is in the mix, the greater the gain in stability that will be attained through the curing process.

Marshall Flow

Values of the Marshall flow ranged between 6 and 8.5 for all mix combinations after 1 d of curing. The flow range for specimens cured for 7 d was from 6.0 to 11.5. In general, the curing time and its interaction with the added moisture content had the most significant effect on the flow values.

Larger amounts of asphalt emulsion resulted in higher flow values. Increasing values of F occurred as a result of extending the curing time before testing the specimens. This is a direct result of the fact that during the curing process the mix loses a portion of the available moisture and this in turn makes the role of the emulsion residue in the mix more apparent in terms of an increase in flow values.

In addition, aggregate gradation significantly affected flow values. The FG aggregate provided the mix with relatively lower flow characteristics; this was more apparent in mixes with low asphalt emulsion content.

Marshall Stiffness and Marshall Index

Asphalt emulsion content, added moisture content, and their interaction significantly affected the Marshall stiffness (S_m) and Marshall index (I_m) values (Figure 8). But asphalt emulsion content showed a greater influence on S_m values than added moisture content. Generally, by decreasing the percentage AE, both S_m and I_m will increase as the mix becomes less plastic and the slope of the load-deformation curve will be steeper. The same trend holds for the effect of percentage W. I_m trends are about the same as S_m trends but have higher values because of the nature of the parameters themselves. The index values represent the slope of the linear portion of the load-deformation curve, whereas the stiffness values represent the slope of the line that connects the initial or starting loading point with the failure point.

Aggregate gradation was the most significant factor that affected both I_m and S_m. The more the aggregate gradation shifts toward the fine limit of the gradation band, the higher will be the resulting stiffness parameters (I_m and S_m). Curing time and percentage AE also significantly affected these two parameters. The interaction effect of percentage AE and percentage W is important in influencing the I_m and S_m values. However, this effect also depends on the curing factor (especially in the case of I_m).

It is important to note the effect of interaction between aggregate gradation, percentage AE, and percentage W at the two curing periods (Figure 8). I_m and S_m values for FG aggregate mixes were higher for samples with a high percentage of added moisture, but the trend was reversed by increasing percentage AE to 4 percent. It should be noted that the difference was reduced through the curing process (1 versus 7 d). For the MG aggregate mixes, the trend depends on percentage AE residue. For FG mixes, relatively low added moisture content (1.5 percent) provided the mix with higher I_m and S_m at the two curing periods than did 3 percent added moisture. In general, the higher the amount of initial moisture that is used in FG mixes, the higher the measured strength parameters will be.

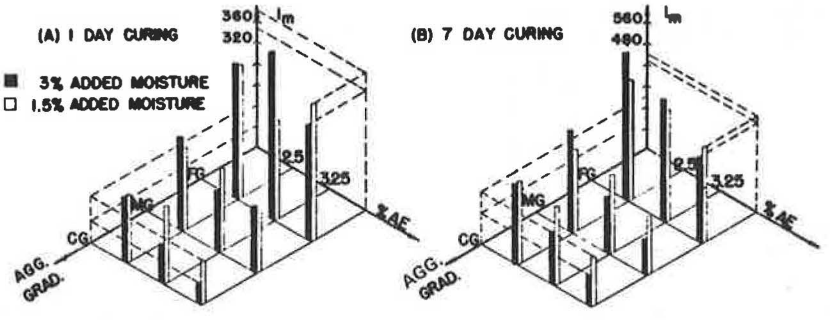
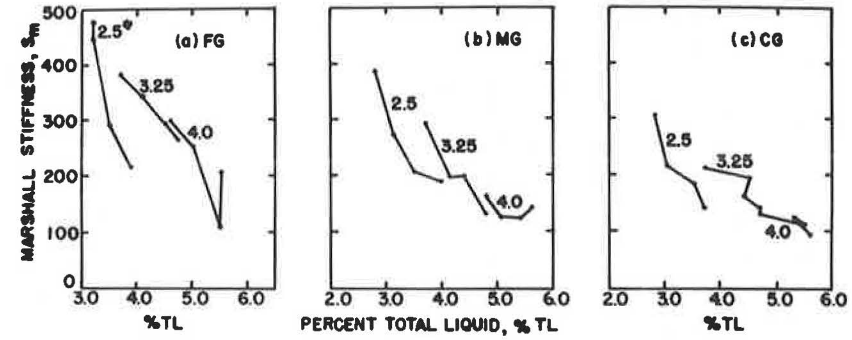


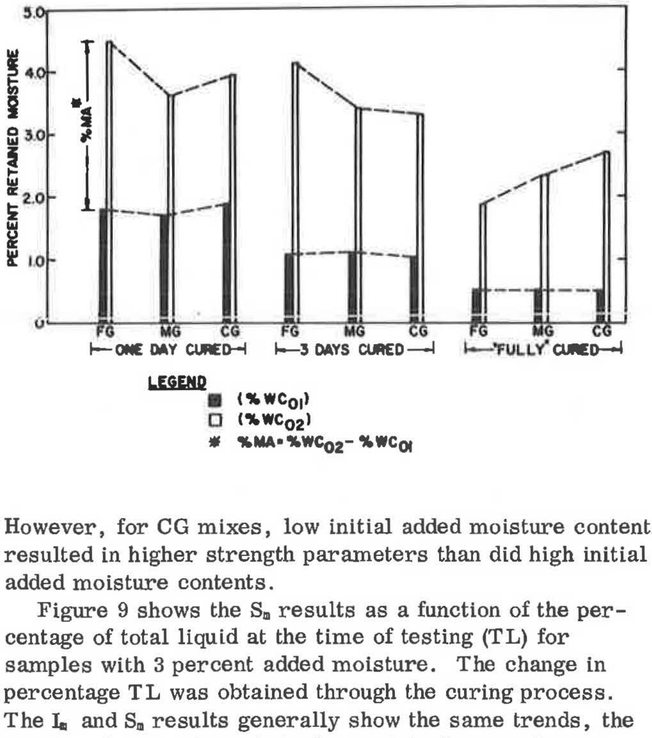
Figure 8. Effect of aggregate gradation, percentage AE, and percentage W on I_m.



NOTE 1- 3% ADDED MOISTURE
2-* % AE RESIDUE

Figure 9. Relation between S_m and percentage TL for different aggregate gradations and percentages AE.

Figure 10. Effect of aggregate gradation on percentage MA as a function of dry curing time (3.2 percent AE and 3 percent W).



However, for CG mixes, low initial added moisture contents resulted in higher strength parameters than did high initial added moisture contents.

Figure 9 shows the S_m results as a function of the percentage of total liquid at the time of testing (TL) for samples with 3 percent added moisture. The change in percentage TL was obtained through the curing process. The I_m and S_m results generally show the same trends, the I_m values being relatively higher. Note the significant effect of aggregate gradation in controlling the position of the relation between S_m and percentage TL in the S_m scale (the same is true for I_m). In addition, the interaction between aggregate gradation and asphalt emulsion content is more pronounced in the graph.

RESULTS OF WATER-SENSITIVITY TESTS

AETMs containing 3.25 percent asphalt emulsion residue content and 3 percent added moisture content were used to study the effect of aggregate gradation on the results of water-sensitivity tests. The comparison study was conducted for the three aggregate gradations at three different curing periods: 1 and 3 d of air-dry curing and the ultimate curing condition (Figure 3). Therefore, it must be emphasized that the discussion that follows pertains to specific asphalt emulsion and added moisture contents.

The effect of asphalt emulsion content on the results of water-sensitivity tests was also studied but for a specific aggregate gradation (MG) and 3 percent added moisture content (Figure 3).

Percentage of Moisture Absorption

At early curing periods (1 and 3 d of air-dry curing), the percentage of moisture absorption (MA) was higher for FG mixes than for MG or CG mixes (Figure 10). However, after the mixes were cured to the ultimate condition, this relation was reversed. An increased amount of MA was obtained for the coarser gradations (given that the other mix components were the same). The percentages of moisture retained in the specimens for the different aggregate gradations before the water-sensitivity test were about the same for each curing period, and the variation in percentage WC_o before the water-sensitivity tests as a result of varying the gradation was reduced through curing (Figure 10).

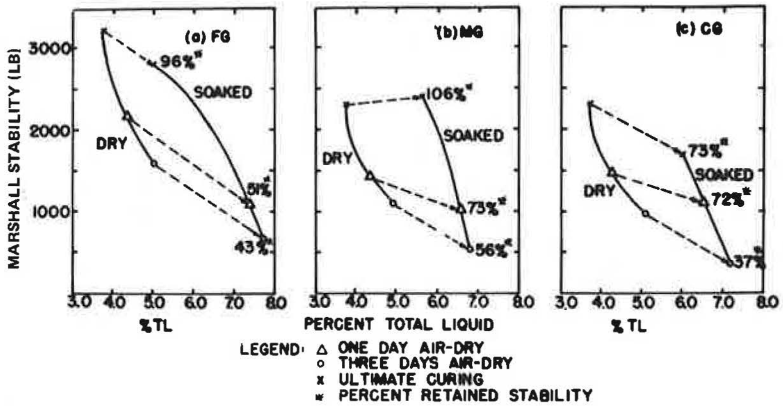


Figure 11. P-values as a function of percentage TL for air-dried and soaked specimens (3.25 percent AE and 3 percent W).

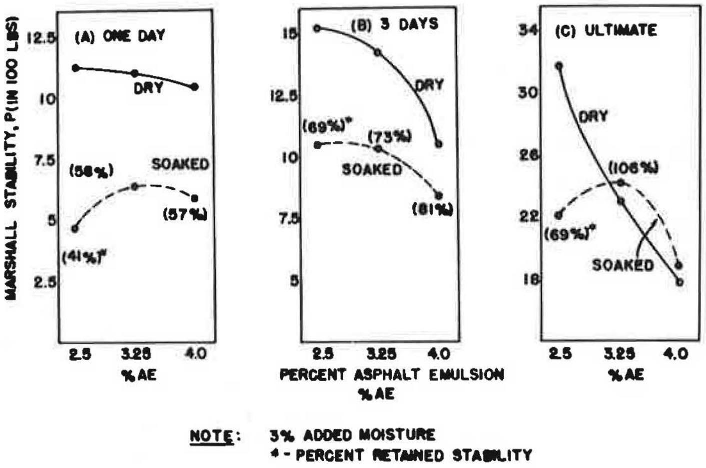


Figure 12. P for dry and soaked specimens after different curing periods (MG aggregate).

Percentage of Retained Stability

Figure 11 shows Marshall stability values as a function of percentage TL at the time of the test for both the dry and soaked specimens. The relations are shown for each aggregate gradation. The percentage of retained stability is shown between brackets on the soaked condition trends.

The dry Marshall stability increases with decreasing percentage TL through the curing process, and stability values for FG mixes are higher. The percentage of retained stability for MG mixes was higher than that for FG or CG mixes at all the curing periods. The MG gradation is closer to the maximum density gradation curve (Fuller's maximum density curve) than the other two gradations, which could be the main factor affecting the performance of the AETM.

In addition, for the same percentage TL that is available in the AETM, the stability values are dependent on the nature or the mechanism of the presence of moisture in the sample (losing moisture through air-dry curing versus gaining moisture through soaking). This is more apparent for the ultimate cured specimens subjected to the water-sensitivity test (see the data points identified by asterisk in Figure 11). The soaked stability values are much higher than the dry stability values for specimens cured for 1 d in spite of the fact that the two conditions correspond to about the same percentage TL.

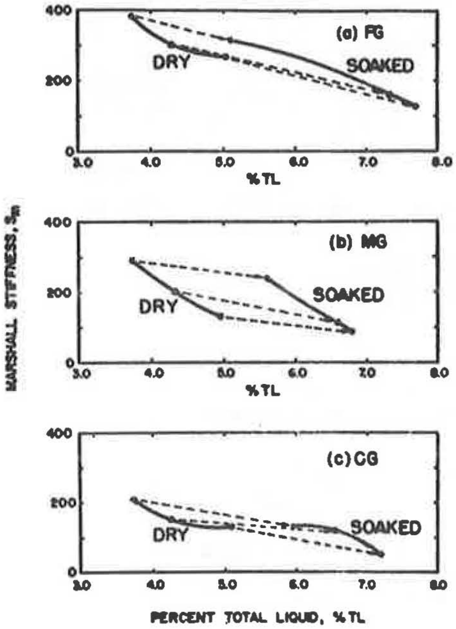
To illustrate the effect of percentage AE and curing time on AETM resistance to water, the Marshall stability values for dry and soaked conditions at the three curing periods for midgradation aggregate mixes are shown in Figure 12. A significant result of this test shows that at any curing level the percentage of retained stability increases with increasing asphalt emulsion content in the mix. In addition, relations between stability and asphalt emulsion content for the soaked samples follow a curvilinear pattern with an optimum percentage AE value that corresponds to a maximum stability value. In contrast, results of the dry test followed a decreasing trend with increasing percentage AE. Longer curing periods for the dry specimens resulted in steeper stability trends (Figure 12). However, after the samples were subjected to the water-sensitivity tests, a significant drop in stability values occurred for samples with a low asphalt residue content.

Percentage of Retained Stiffness

Marshall stiffness (S_m) responded to the water-sensitivity test in the same manner as did the stability values (Figure 13). The MG mixes provided the highest percentage of retained stiffness$[(S_m \text{ soaked}/S_m \text{ dry}) \times 100]$ of the three mixes. The CG mixes showed the least resistance to water damage. In addition, the trend for S_m versus percentage TL was also dependent on the method by which the moisture was present in the AETM system components.

It has been shown that the dry test results are not enough to provide adequate control and design of the AETM. Water-sensitivity results provide a more important indication of the performance of the mix and must therefore be an integral part of the AETM design procedure.

Figure 13. S_m as a function of percentage TL for air-dried and soaked specimens (3.25 percent AE and 3 percent W).



SUMMARY OF RESULTS

The analysis and evaluation of the test data in the study revealed a number of significant results that pertain to the effect on the mix properties of aggregate gradation, asphalt emulsion content, and added moisture content. A summary of the main results follows.

1. Aggregate gradation significantly affected all AETM properties. It should be noted that the three aggregate gradations fall within certain specified gradation limits. This draws attention to the importance of controlling the aggregate gradation in the mix. Designing the AETM by using a specific aggregate gradation curve (e.g., midpoint of the specification) does not ensure the same performance and properties of the AETM in the field because of the wide bandwidth within the specified aggregate gradation.
2. MG and CG aggregate gradations were close to the "theoretical maximum density gradation," provided an adequate range of particle sizes, and resulted in mixes with higher densities and fewer air voids than the FG mixes.
3. The percentage of total voids for a specific mix was about the same throughout the curing process. The increase in percentage V_A through the curing is accompanied by a decrease in percentage V_W of about the same magnitude.
4. FG mixes provided the highest stability values throughout the curing process. This was generally accompanied by low flow values in comparison with MG or CG mixes.
5. The effect of percentage AE on Marshall stability was not significantly apparent at the early curing condition. However, the asphalt emulsion content significantly affected the Marshall stability when the samples were allowed to cure for longer periods of time.
6. Marshall stiffness (S_m) and index (I_m) parameters show a unique trend that depends on percentage of total liquid, asphalt emulsion content, and amount of added moisture (for a specific aggregate type and gradation). S_m and I_m values decreased with increasing percentage of total liquid at the time of testing.
7. High stiffness indexes (I_m and S_m) were obtained for FG mixes in comparison with MG or CG mixes. In addition, the trends for I_m or S_m versus percentage TL were significantly dependent on aggregate gradation.
8. Marshall stiffness or index or both could be used, in addition to the conventional design parameters for the Marshall method of mix design, to better control the mix properties by setting minimum values for these two parameters.
9. The effect of aggregate gradation on percentage MA depends on the curing state. For the air-dry curing, FG mixes resulted in higher percentage MA than MG and CG mixes. However, at the ultimate condition, the FG mixes absorbed the least amount of moisture, the MG mixes the next least, and the CG mixes the most of the three.
10. The percentage of retained stability was higher for MG mixes than for FG or CG mixes at all curing levels. The percentage of retained stability for any mix combination increased through the curing process.
11. The nature of the water present in the mix (drying through curing versus soaking) affects the response parameters of the AETM.
12. The test results for the unsoaked (dry) specimens showed that Marshall stability increases with decreasing percentage AE in the mix. However, mixes with low percentage AE showed the least resistance to water damage. The shape of the relation between stability and asphalt emulsion content for soaked specimens was different from that obtained for dry samples. This difference was more pronounced when the samples were allowed to cure for extended periods of time. The percentage of retained stability for any mix combination increased through the curing process.

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The contents of this report reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. V. L. Anderson and R. A. McLean. Design of Experiments—A Realistic Approach. Marcel Dekker, New York, 1974.
2. Water Sensitivity Test for Compacted Bituminous Mixtures. Asphalt Institute, June 1975.
3. Bituminous Emulsions for Highway Pavements. NCHRP, Synthesis of Highway Practice 30, 1975.
4. A. A. Gadallah. A Study of the Design Parameters for Asphalt Emulsion Treated Mixtures. Joint Highway Research Project, Purdue Univ., West Lafayette, IN, Research Rept. 30, 1976.
5. A. A. Gadallah, L. E. Wood, and E. J. Yoder. A Suggested Method for the Preparation and Testing of Asphalt Emulsion Treated Mixtures Using Marshall Equipment. Presented at 1977 Annual Meeting of AAPT, Feb. 1977.
6. Autographic Equipment for Marshall Method. Rainhart Co., Austin, TX, Catalog 760.

7. R.J. Schmidt and P.E. Grof. The Effect of Water on the Resilient Modulus of Asphalt-Treated Mixes. Proc., AAPT, Vol. 41, 1972.
8. Symposium on Design and Construction of Pavements With Emulsions. Proc., AAPT, Vol. 44, 1975, pp. 281-365.
9. P.J. Van de Loo. Creep Testing—A Simple Tool to Judge Asphalt Mix Stability. Proc., AAPT, Vol. 43, 1974.

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Abridgment

Practical Method for Evaluating Fatigue and Fracture Toughness of Pavement Materials

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One of the most frequently occurring modes of distress in asphalt highway pavements is the fatigue cracking that results from traffic loads. Few theories have been suggested by researchers for approaching the problem of fatigue in materials in general and in pavement materials in particular. Linear fracture mechanics is one of the methods that has been used to analyze fatigue. Recent studies such as that by Majidzadeh and Kauffmann (1) show that the method is applicable to asphaltic pavement materials.

Crack behavior can be classified into three distinct modes: (a) opening, (b) in-plane sliding, and (c) tearing (Figure 1). Each crack-mode movement is associated with a stress field in the vicinity of the crack tip. The distribution of stress in the vicinity of the crack tip is a problem related to the mathematical theory of elasticity, in which it can be shown that all stress fields at the crack tip exhibit inverse square root singularities. Thus, the stress field can be expressed for the opening mode as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = (K_1/\sqrt{2\pi r})\cos(\theta/2) \times \begin{Bmatrix} 1 - \sin(\theta/2)\sin(3\theta/2) \\ 1 + \sin(\theta/2)\sin(3\theta/2) \\ \sin(\theta/2)\cos(3\theta/2) \end{Bmatrix} \qquad (1)$$

The parameter K_1, called the stress-intensity factor, governs the magnitude of the local stresses in the vicinity of the crack tip.

Paris, Gomez, and Anderson (2) first introduced the idea of relating the stress-intensity factor to rates of fatigue crack propagation. Experimental data show that the rate of crack propagation (dc/dN) is proportional to some power of the stress intensity factor; i.e., $dc/dN = AK^n$, where A and n can be characterized as material constants.

The purpose of this paper is to introduce a new method of testing for fatigue and fracture in asphaltic pavement material, a method that is believed to be superior to current procedures. Current methods are discussed and compared with the proposed one.

COMPARISON OF CURRENT AND PROPOSED TEST METHODS

Simplicity of specimen preparation, testing, and analysis of results is the basic advantage of the new method over current procedures. Currently, the determination of fatigue parameters A and n in the fatigue model $dc/dN = AK^n$ is done experimentally by testing beams placed on an elastic foundation and loaded with a cyclic load. Fracture toughness is determined by testing beams that have larger dimensions than the fatigue beams under three-point loading conditions. In the proposed new method, both fatigue testing and fracture testing use an identical experimental setup and identical specimens of discs cut from cylindrical specimens with a triangular notch (Figure 2).

Current Method

To test for fatigue, parameters A and n in the equation $dc/dN = AK^n$ are determined experimentally by testing beam specimens placed on an elastic foundation. The progress of crack growth and the corresponding number of load applications are visually observed and recorded. The steps are

1. Obtain experimental crack minus cycled (c - N) data;
2. Use either a polynomial or nonlinear exponential equation, obtain the best fit to the available experimental c - N data, and develop an analytical expression;
3. Differentiate the analytical (predicted) c - N equation to obtain the dc/dN - N relation;
4. Use the analytical expression available between the stress-intensity factor K and crack length c to develop a set of stress-intensity factor values and their corresponding dc/dN values; and
5. Find the fatigue parameter by using the information in step 4.

For the determination of fracture toughness of asphaltic materials, beam specimens 10.16 by 7.62 by 40.64 cm (4 by 3 by 16 in) are tested. The beams are notched to a depth of 1.524 cm (0.6 in) to produce a c/d ratio of 0.15. They are tested under three-point loading conditions—i.e.,