can be adequately modified through the addition of new "soft" asphalt cements without incorporating recycling additives.

3. Emissions in recycling are a function of many factors, including mix temperature, the grade of new asphalt added, the amount of new aggregate added, the amount of water added, plant production, and weather conditions.
4. Considerable variability in material properties can be expected. The variability in the original mix is compounded by unequal aging of the asphalt cement and further compounded by variability in the additions of new asphalt and rock.

A considerable amount of research work needs to be done in the area of recycled asphalt paving mixtures and in the design of thicknesses based on the use of these materials. At the present time, no long-term information on the in-service performance of these paving materials is available. More work needs to be done to evaluate fundamental material properties and their correlation with (a) types and amounts of softening agents, (b) types and gradations of additional aggregate, and (c) types of mixing techniques. As more of the problems are solved, recycling can become a workable construction alternative to meet changing requirements in the supply of materials.

ACKNOWLEDGMENT

The project described in this paper was constructed under the administrative supervision of John Sheldrake and the direct control of Loren Weber. It required assistance and cooperation from offices and individuals too numerous to mention. Each person's contribution is sincerely appreciated. We extend special thanks, however, to R.G. Hicks of Oregon State University for his efforts in the organization and review of this report.

Financial support for the data collection, sampling, and testing was furnished by the Federal Highway Administration. Support for analysis and evaluation was provided by the Department of Civil Engineering and the Transportation Research Institute, Oregon State University.

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 Oregon Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Publication of this paper sponsored by Committee on Flexible Pavement Construction.

Effect of Portland Cement on Certain Characteristics of Asphalt-Emulsion-Treated Mixtures

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Findings are reported of a detailed laboratory investigation to evaluate the use of portland cement (1 percent of weight of dry aggregate) as an additive to asphalt-emulsion-treated mixtures (AETMs) and to study the effect of the interaction of portland cement with aggregate gradation and asphalt emulsion content on the design parameters and properties of AETMs by use of Marshall equipment. The evaluation was conducted at different curing stages of the mix. One type of aggregate (sand and gravel) and one type and grade of asphalt emulsion were used in the study. A modified Marshall method was used for preparing and testing the specimens. The evaluation of AETM properties produced a number of significant results. The use of portland cement as an additive to the AETM proved to be beneficial in improving its properties. This result must be viewed with caution, however, since it was found that the effect of portland cement on AETM performance was significantly influenced by aggregate gradation, asphalt emulsion content, added moisture content, and curing

stage. The experiments also showed that, because of its importance in the evaluation of AETM properties, the water-sensitivity test should be an integral part of the Marshall design procedure for AETMs.

In spite of the potential advantages of using asphalt-emulsion-treated mixtures (AETMs), they possess some relatively unfavorable characteristics, especially at early curing stages, that limit their use as high-quality paving material. A slow curing rate accompanied by slow development of strength and low resistance to water damage, especially at early curing condition, are the main factors of concern in dealing with the AETM. The use of small percentages of portland cement as an additive improves these characteristics, especially the resistance of an AETM to water damage.

This paper reports the findings of a detailed laboratory investigation of the effect of the interaction of portland cement (1 percent by weight of dry aggregate) with aggregate gradation and asphalt emulsion content on the design parameters and properties of AETMs. One type of aggregate (sand and gravel) and one type and grade of asphalt emulsion were used in the study. The evaluation was conducted at different curing stages of the mix. Autographic Marshall equipment that produces a load-deformation trace was used.

EQUIPMENT AND MATERIALS

The equipment and materials used in this investigation, including the Marshall equipment, stability apparatus, mineral aggregate, and asphalt emulsion, are described elsewhere (1).

TESTING PROCEDURE

The testing procedure used in this study is the same as that described by Gadallah and others (1, 2). Whenever the design called for the use of portland cement (1 percent by weight of dry aggregate) as an additive to the AETM, the portland cement was added to the wet aggregate and mixed immediately before the asphalt emulsion was added.

EXPERIMENTAL DESIGN

The main purpose of this study was to evaluate the use of portland cement as an additive to AETMs and the effect on certain AETM characteristics of the interaction between portland cement and aggregate gradation and asphalt emulsion (AE) content (throughout this paper, asphalt emulsion content refers to the asphalt emulsion residue content in the AETM). The use of additives, aggregate gradation, percentage AE, and curing time were included in the analysis and evaluation. The added moisture content (percentage W) was fixed to one level: 3 percent by weight of the dry aggregate. However, some limited tests conducted at selected mix combinations incorporated the use of 1.5 percent added moisture content (see Figure 1).

With the exception of percentage air voids in the mix, the response (dependent) variables that were used in this study were the same as those used in the previous study by Gadallah and others (1).

ANALYSIS OF RESULTS

Percentage Moisture Retained in the Sample

During mixing and preparation, the mixtures that contained 1 percent portland cement appeared wetter and had relatively less coating than the mixtures prepared without portland cement additive. However, the cement-treated AETM appeared relatively drier during testing. Generally, this had been the case for all mix combinations.

The test results showed that the percentage moisture retained in the sample (percentage WC_o) was higher for cement-treated AETM samples (AETM that contained 1 percent portland cement) than for the AETM. Figure 2 shows the average percentage of moisture retained for AETM and cement-treated AETM samples. Each data point in the graph represents the average percentage WC_o of the three cells (different percentages of AE) at each curing time and aggregate gradation. The difference in percentage WC_o was about 0.5 percent after one day of curing for all aggregate gradations. This difference decreased as curing progressed.

Dry Unit Weight

The use of 1 percent portland cement in the AETM significantly affected the dry unit weights of the mixtures. In general, the AETM samples had higher dry unit weight (γ_d) than those of the cement-treated AETM. Figure 3 shows γ_d values for both AETM and cement-treated AETM as a function of curing time, aggregate gradation, and percentage asphalt emulsion. It can be seen that the general trend of the effect of portland cement—a decrease in γ_d—does not hold for all mix combinations. In a few cases, the cement-treated AETM provided higher dry unit weights. This is more apparent for mixes that contain FG aggregate after seven days of air-dry curing.

Marshall Stability

The effect of portland cement on values of Marshall stability (P) is influenced by aggregate gradation and percentage AE. The effect on P of the interaction among curing time, aggregate gradation, percentage AE, and portland cement is shown in Figure 4. Among specimens cured for one day, the effect of portland cement is more significant for mixes that contain MG aggregate. In addition, the effect of portland cement is more apparent at low AE contents, and it improves the mix stability for all aggregate gradations. However, when the percentage AE in the mix is increased, aggregate gradation starts influencing the role of portland cement in the mix, reducing its effect. When CG aggregate was used, portland cement did not improve the stability of the mix and in most cases produced a reverse effect. This reduction in stability could be expected because of the relatively poor coating that was obtained when CG aggregate was used with portland cement.

The effect of portland cement was more apparent at the early stages of curing. After relatively long periods of curing, the use of portland cement produced an increase in stability but not in the same degree as that produced at early curing stages (see the results for seven-day curing in Figure 4). The effect of aggregate gradation on the role of portland cement in the mix after seven days of curing was less than its effect for samples cured for one day.

The effect of percentage AE on the stability values of the AETM and cement-treated AETM is more apparent after relatively longer curing periods than at the early stages of curing. In addition, Marshall stability values decreased with increasing percentage AE in the mix (Figure 4).

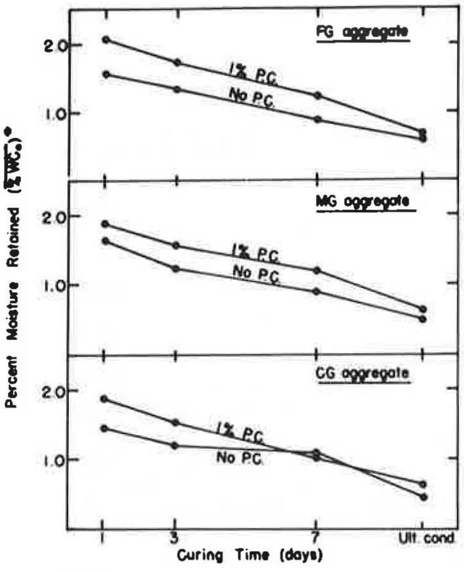
The AETM response parameters depend on the percentage of total liquid (TL) that is available in the mix

Figure 1. Factorial design for study of effect of various factors on AETM properties.

Additives	Curing time • condition	% W*	F.G.			M.G.			C.G.		
		Agg. Gradation % AE (residual)*	2.5	3.25	4.0	2.5	3.25	4.0	2.5	3.25	4.0
(NO P.C.)	1day	1.5%									
		3%	x	⊗	x	⊗	⊗	⊗	x	⊗	x
	3	1.5									
		3	x	⊗	x	⊗	⊗	⊗	x	⊗	x
	7	1.5				x	x	x			
		3	x	x	x	x	x	x	x	x	x
	ult.† cond.	1.5				x	x	x			
		3	x	x	x	x	x	x	x	x	x
(1% P.C.)*	1	1.5									
		3	x	⊗	x	⊗	⊗	⊗	x	⊗	x
	3	1.5									
		3	x	⊗	x	⊗	⊗	⊗	x	⊗	x
	7	1.5				x	x	x			
		3	x	x	x	x	x	x	x	x	x
	ult.† cond.	1.5				x	x	x			
		3	x	x	x	x	x	x	x	x	x

Note:
X = dry test
O = water sensitivity test
* = percent by weight of the dry aggregate
† = 3 days curing at 120°f

Figure 2. Effect of portland cement on percentage WC_o in the sample.



NOTE:
1 3% added moisture for all test samples
2 * each data point in the graph represents the average %WC₀ of the 3 mix combinations that contained different % AE

at the time of testing (see Figure 5). Since the cement-treated AETM held more retained moisture than the AETM, percentage TL was more for samples treated with portland cement. In spite of the increase in percentage TL for cement-treated AETM over that for AETM, a gain in stability occurred in most of the cases depending on the aggregate gradation used. The significant effect on stability that is obtained by the use of 1 percent portland cement can be seen in Figure 5, where the stability results for the cement-treated AETM are shown with those for the AETM as a function of percentage TL at the time of testing. The change in percentage TL was obtained through the curing process. For mixes that contain FG and MG aggregates, a substantial increase in stability was obtained by the use of 1 percent portland cement. That is, at a specific percentage TL the cement-treated AETM provided much greater stability than the AETM. However, the use of portland cement with CG-aggregate mixes was not beneficial, especially at a high percentage AE, where a drop in stability occurred.

Marshall Flow

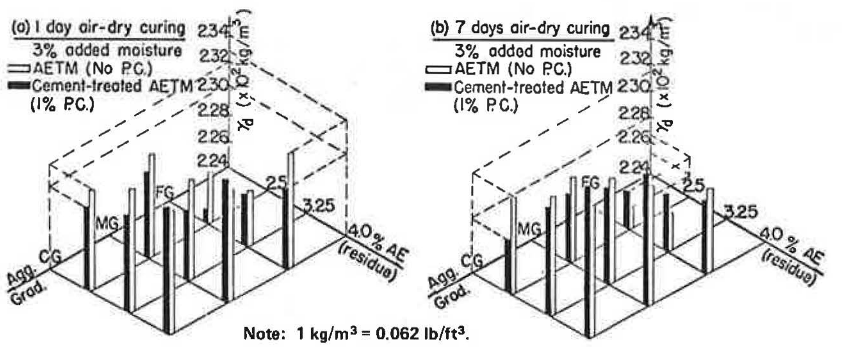
Flow values were not significantly affected by the use of portland cement as an additive to the AETM. The use of portland cement generally reduced flow values for most of the mix combinations, but this difference is not significant because the reduction or, in some cases, the slight increase in flow values that was produced could be expected as a variation in the three replicates of the mix.

Marshall Stiffness and Marshall Index

Asphalt emulsion content, aggregate gradation, and their interaction significantly affected values of Marshall stiffness (S_m) and Marshall index (I_m) (see Figure 6). Generally, when percentage AE is decreased, 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. Marshall index trends are about the same as Marshall stiffness 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.

In addition, the use of portland cement in AETM together with the other main factors under study significantly affected the I_m values. However, the S_m values were not significantly affected by the use of portland cement in the AETM. This resulted from the nature of the S_m variable, which is obtained by the direct relation $S_m = P/F$. Flow values F were not significantly affected by portland cement, and they varied randomly

Figure 3. Effect of portland cement on γ_d as a function of aggregate gradation and percentage AE residue.

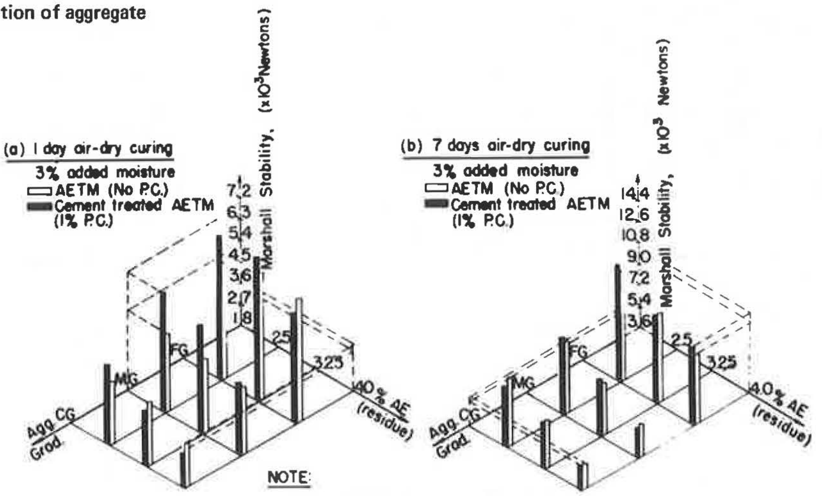


Note: 1 kg/m³ = 0.062 lb/ft³.

in such a way that they reduced the effect of portland cement on S_m.

Figure 6 shows I_m as a function of aggregate gradation and percentage AE residue for the two curing periods. For specimens cured for one day, the I_m values increased when portland cement was used in the AETM, especially at a low percentage AE. The effect of the portland cement was reduced at a high percentage AE, e.g., 4 percent. In addition, aggregate gradations are shown to have a significant effect on the behavior of portland cement in the mix. The test data for specimens cured for seven days (Figure 6) show that the cement-treated AETM had higher values than the AETM in almost all mix combinations. The gain in I_m values attributable to the use of portland cement was decreased through the curing process. This leads to the conclusion that, although the effect of portland cement on I_m values at early curing periods varies and depends on aggregate

Figure 4. Effect of portland cement on P as a function of aggregate gradation and percentage AE residue.



NOTE:
1 lb. = 4.5 Newtons

Figure 5. P as a function of percentage TL for AETM and cement-treated AETM.

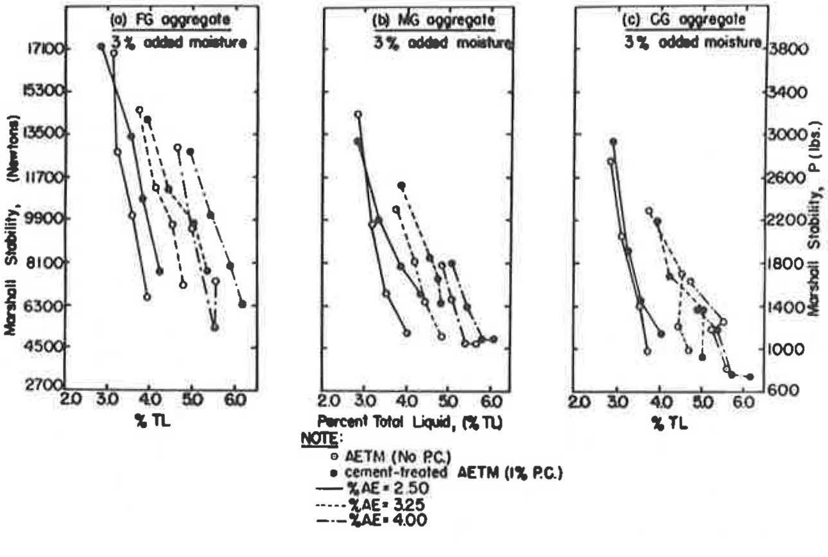


Figure 6. Effect of portland cement on I_m as a function of aggregate gradation and percentage AE residue.

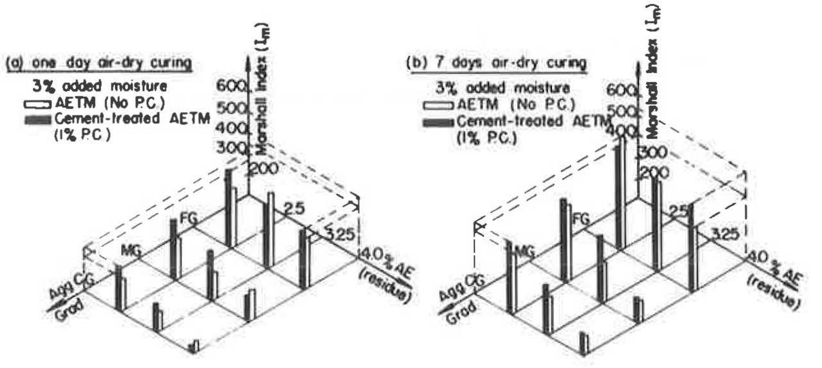


Figure 7. I_m as a function of percentage TL for AETM and cement-treated AETM.

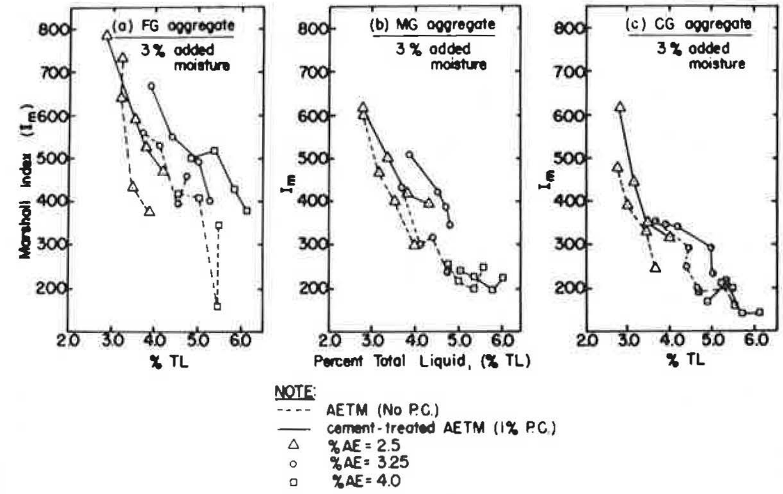


Figure 8. Percentage MA for AETM and cement-treated AETM specimens.

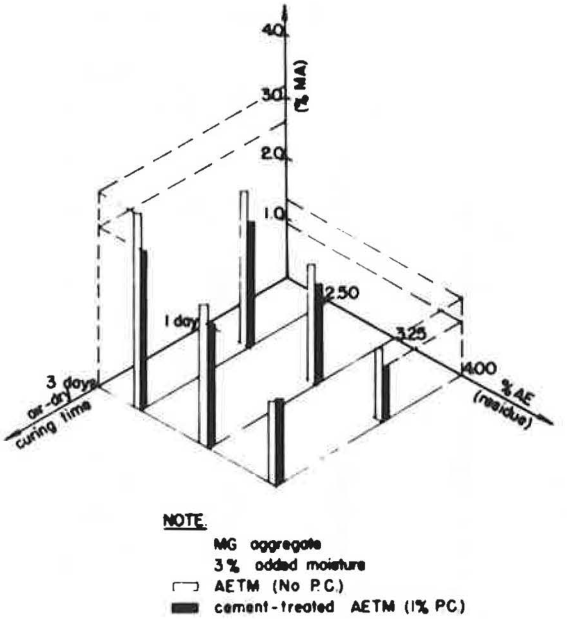
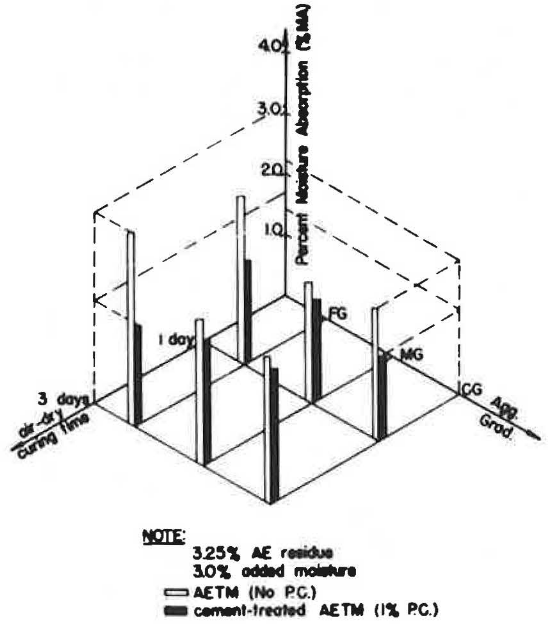


Figure 9. Effect of portland cement on percentage MA for various aggregate gradations.



gradation and percentage AE, its effect after relatively longer periods is beneficial (as far as the increase in I_m is concerned) at almost all levels of aggregate gradation and percentage AE.

S_m followed approximately the same trend as I_m, but the change in S_m values in response to the use of portland cement was less pronounced than the change in I_m values. Again, this is a result of the difference in the nature of the two measures of stiffness. I_m is a measure of the mix characteristics during the duration of loading, whereas S_m is a measure of the mix characteristics at the failure condition and is directly related to the stability and flow values of the mix.

I_m as a function of percentage TL is shown in Figure 7. The trends were obtained by using test results at different curing periods. An increase in the I_m values was obtained by using 1 percent portland cement as an additive to the AETM. At a specific percentage TL available in the specimen, the cement-treated AETM showed a pronounced and significant increase in I_m. The effect of portland cement also depends mainly on aggregate gradation and percentage AE residue. No gain in I_m or S_m was obtained when CG aggregate was used, especially with a high percentage AE.

RESULTS OF WATER-SENSITIVITY TESTS

Most of the water-sensitivity tests were conducted for mix combinations that contained MG aggregate and for two curing periods—one and three days of air-dry curing. Mix combinations that contained FG and CG aggregate were selected for purposes of comparison (as shown earlier in Figure 1) for mix combinations that contained 3.25 percent AE and 3 percent added moisture.

Percentage Moisture Absorption

As Figure 8 shows, cement-treated AETMs have less moisture absorption (MA) than AETMs without portland cement. The effect of portland cement in reducing percentage MA is more apparent at a low percentage AE and decreases with an increase in percentage AE. Adding portland cement to the AETM improves the bonding between the components of the mixture and consequently reduces the amount of moisture that is permitted to enter through the system.

Figure 9 shows that portland cement was beneficial in reducing percentage MA in all three aggregate gradations. FG-aggregate mixes showed the largest reduction in percentage MA. Reduction in percentage MA through the use of portland cement resulted in a lower percentage TL being available in the cement-treated AETM than in the AETM, which in turn contributed to the higher parameters of retained strength that were obtained for the cement-treated AETM.

Percentage Retained Stability

The use of 1 percent portland cement significantly improved retained stability in the AETM. The results for dry and soaked stability for AETM and cement-treated AETM at two different curing times are shown in Figure 10. The percentage retained stability for mixes that contained MG aggregate increased to a range of 75 to 81 percent and 79 to 92 percent, respectively, for specimens cured for one and three days; these ranges compare with ranges of 41 to 58 percent and 69 to 81 percent for the AETM without portland cement. The asphalt emulsion content affected the role of portland cement. The effect of portland cement was more pronounced at a low percentage AE, e.g., 2.5 percent. Percentage retained stability increased with increasing percentage AE for the AETM but decreased with increasing percentage AE for the cement-treated AETM.

In addition, mixes made with FG or CG aggregate are shown to gain resistance to water damage when they are treated with portland cement (see Figure 11). In an earlier discussion that dealt with the effect of portland cement on the dry stability of AETMs, it was shown that the CG-aggregate mixes did not show an appreciable gain in stability when portland cement was used (and, in some mix combinations, showed a slight decrease in stability). It is important, however, to note that using portland cement with CG-aggregate mixes appreciably improved their resistance to water damage. This is another example of the importance of water-sensitivity tests in evaluating the performance of AETMs; using only the results of dry tests is not sufficient for understanding and controlling AETM performance.

Figure 10. Dry and soaked P for AETM and cement-treated AETM (MG aggregate, 3 percent W).

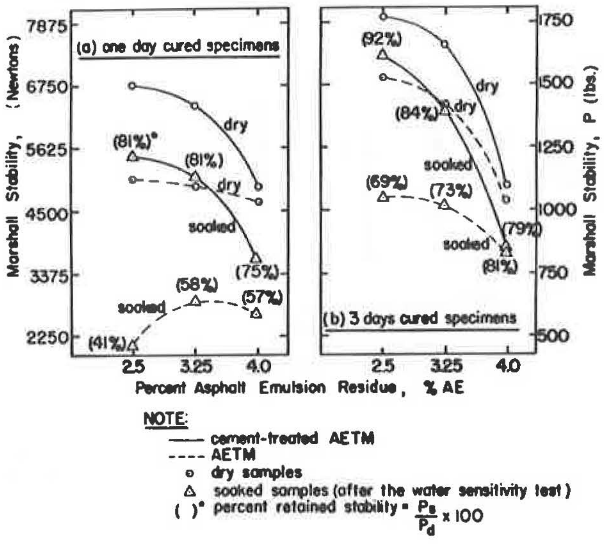


Figure 11. Effect of portland cement on P for various aggregate gradations.

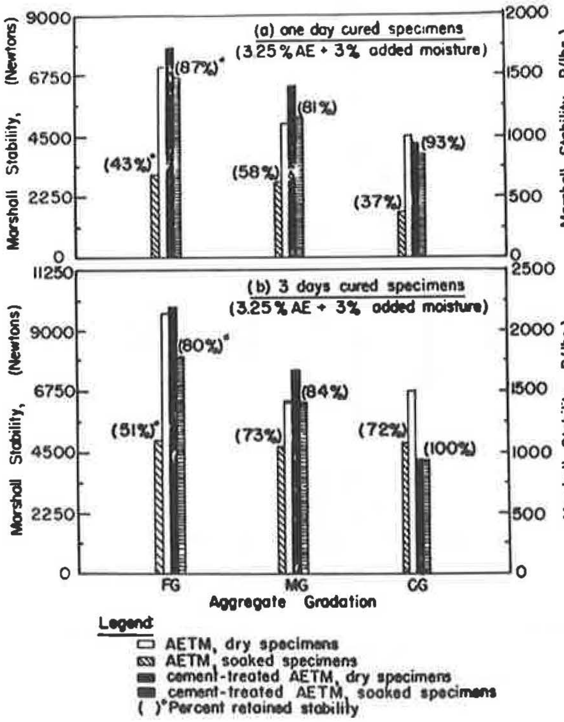


Figure 12. Percentage S_m for AETM and cement-treated AETM (MG aggregate, 3 percent W).

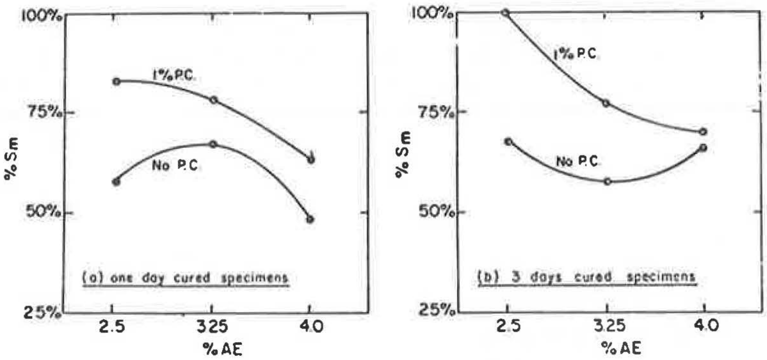
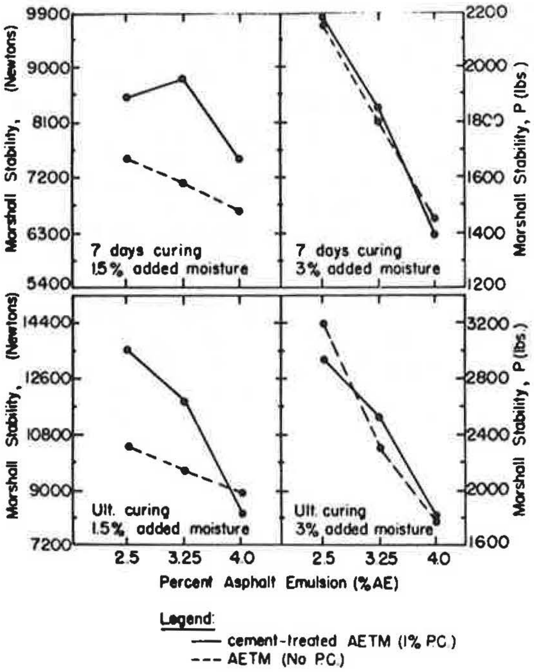


Figure 13. Effect of percentage W on role of portland cement (MG aggregate).



Percentage Retained Marshall Stiffness

The cement-treated AETM showed higher retained S_m values than the AETM when subjected to the action of water. In Figure 12, percentage S_m represents the ratio between S_m after the water-sensitivity test and S_m for the dry samples.

EFFECT OF ADDED MOISTURE CONTENT ON THE ROLE OF PORTLAND CEMENT

To examine the effect of added moisture content (percentage W) on the role of portland cement in the AETM, we examined the results for the limited tests that were run on the cement-treated AETM (MG aggregate and 1.5 percent added moisture) at two curing periods: seven days of air-dry curing and the ultimate curing condition. The effect of portland cement on the AETM properties was more apparent for samples with 1.5 percent W than for samples with 3 percent W.

Figure 13 shows the S_m results for the two levels of added moisture under study (1.5 versus 3 percent). In the figure, the effect of portland cement is more pronounced for samples with less added moisture, which indicates that percentage W affects the action of portland cement in the AETM system.

This parameter is presented here as an example. The other parameters were slightly affected but not to the same degree as P, S_m, and I_m. It should be noted that this portion of the tests was limited and was not intended to provide a detailed evaluation.

SUMMARY OF RESULTS

The use of portland cement as an additive to AETMs has proved to be beneficial in improving the properties of such mixtures. This result must be viewed with caution, however, since it has been found that the effect of portland cement on the performance of AETMs is significantly influenced by aggregate gradation, asphalt emulsion content, and curing stage. The reported results pertain to AETMs that contained 3 percent added moisture. The significant findings can be stated as follows:

1. AETMs showed less coating when treated with 1 percent portland cement. The cement-treated AETM appeared to be drier than the nontreated AETM during the testing.
2. Cement-treated AETM had a higher percentage WC_o than nontreated AETM specimens. However, a portion of this moisture has combined with the portland cement.
3. In general, nontreated AETM specimens possessed higher γ_d than cement-treated specimens, but, since the effects of interaction between portland cement and curing and percentage AE were significant, each case should be studied separately.
4. The effect of portland cement on stability values was influenced by aggregate gradation and percentage AE. At a low percentage AE, the use of portland cement was beneficial in increasing S_m values for all aggregate gradations used. However, when the percentage AE in the mix was increased, the role of portland cement was affected by aggregate gradation. The use of portland cement in CG-aggregate mixes was not beneficial and in some cases resulted in a reduction in stability. This could be attributed to the poor coating that was observed when CG aggregate was treated with portland cement.
5. The effect of portland cement on stability was more apparent at the early curing stage.
6. In spite of the increase in percentage TL that resulted from the use of portland cement, the trends for stability versus percentage TL showed a significant gain in stability when AETMs were treated with portland cement (note that this was also dependent on aggregate gradation).
7. In a limited study, added moisture content affected the role of portland cement in the AETM. The use of 1.5 percent W enhanced the effect of portland cement by increasing the stability values over values for specimens with 3 percent W.
8. F-values were not significantly affected by the use of portland cement. In our opinion, F-values alone are the least significant parameter in explaining AETM performance.
9. Portland cement significantly increased I_m values, but S_m values were not significantly affected because S_m is dependent on P and F. Since F-values were not significantly affected by portland cement and the change in F attributable to the use of portland cement varied, the effect of portland cement on S_m values was reduced.
10. Test results for the unsoaked (dry) specimens showed that S_m increases with decreasing percentage AE in the mix. But mixes with low percentage AE showed the least resistance to water damage. The percentage of retained stability increased through the curing process for all mix combinations.
11. The use of portland cement improved AETM properties and the resistance of AETMs to water damage. The effect of portland cement was more beneficial and apparent for mixes with low percentage AE. The effect of portland cement on resistance to water damage was especially valuable at early curing stages. The use of portland cement improved the resistance to water damage of all three aggregate gradations, especially the CG aggregate.

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Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.

Fatigue Performance of a Bituminous Road Mix Under Realistic Test Conditions

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A study whose purpose was the verification of Miner's rule for estimating the cumulative damage resulting from the phenomenon of fatigue is reported. A repeated-bending apparatus driven by a minicomputer, which was devised to generate and control stress or strain waves of variable amplitudes, is described. The fatigue behavior of a bituminous mix subjected to nine different loading patterns (simple, random, and block) was determined. The influence of rest periods of different lengths was studied for these cases. It is concluded that (a) to the extent that the spectrum of load amplitudes is known, a prediction method derived from Miner's law is applicable with an acceptable accuracy for random sequences that include no rest periods and (b) rest periods markedly increased fatigue life for the three loading patterns considered. These initial conclusions were used to derive a generalized form of Miner's law for loading conditions in which both stress amplitudes and the duration of rest periods are variable. This generalized law was verified by simulating actual conditions of traffic loading in fatigue tests.

Intensive worldwide laboratory research on the mechanical properties of bituminous mixes has led to the establishment of methods of estimating fatigue performance (or number of loading cycles at failure). One of the major criticisms of these methods concerns the simplicity of applied loading. It is a fact that the continuous cycles of loading of constant stress or strain amplitude generally applied in laboratory tests are not realistic enough to simulate the compound-loading conditions to which a road material is subjected under actual traffic loads.

To take account of compound loading in structural design methods, Miner's law is used. Miner's law assumes a linear cumulative effect of damage irrespective of the true history of the applied loads. Several authors who have made experimental investigations to estimate the degree of accuracy of this law (1-6) have come to different conclusions depending on the type of loading history used.

In fact, the experimental approach to realistic conditions may be manifold: Even when it ignores variations in temperature, the realistic test history must include a succession of loading cycles followed by rest periods that are distributed randomly in both duration and size according to statistical distributions that reflect traffic characteristics. Fundamental understanding of such a process can only be attained through a stepwise progression in the degree of complexity of test conditions.

Enough is now known about the fatigue process under simple loading to allow a better understanding of more complicated loading patterns. For this reason, the Centre de Recherches Routières has undertaken an experimental research project to study realistic fatigue testing.

EXPERIMENTAL PROCEDURE

The mechanical part of the apparatus used in this research is identical to that used in earlier investigations (7): Trapezoidally shaped specimens 9×3 cm at the base, 35 cm in height, and 3 cm thick are fixed at their larger bases and submitted to a bending force that acts tangentially to their smaller bases by means of an electromagnetic exciter. Transducers fitted to the tops of the