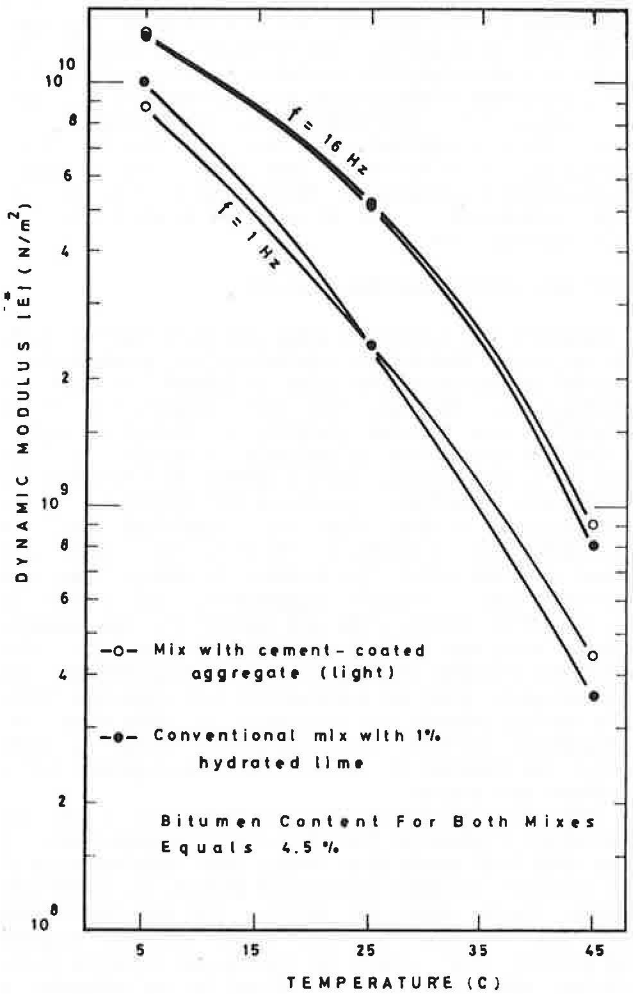
Figure 5. Effect of cement treatment on dynamic modulus of asphalt concrete.



24 percent, respectively. This was associated with an increase in the compacted voids.

2. When compared on the basis of approximately equal compacted voids, asphalt mixes with the medium and heavy cement treatments proved respectively 21 and 35 percent higher in stability than mixes with light cement treatment (4.9 percent cement).

3. The index of retained strength (immersion-compression ratio) increased from less than 60 percent for untreated mixes to almost 100 percent for mixes made with cement-coated aggregates at any of the coating levels investigated.

4. The use of cement-coated aggregates improved temperature susceptibility of mix stiffness in the low-frequency range of 1-4 Hz.

ACKNOWLEDGMENT

This study was conducted at the Road Research Center under the sponsorship of the Ministry of Public Works (Department of Roads and Drainage) of Kuwait. We wish to thank A. Allam for doing the laboratory testing and F. Behn for reviewing the text.

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

Abridgment

Factors Affecting Unconfined Compressive Strength of Lime-Bituminous-Emulsion-Treated Clay

RAYMOND K. MOORE

A one-half 2^7 fractional factorial experiment design was used to evaluate the effect of soil type, lime content, molding moisture content, modification curing time, bituminous emulsion type, bituminous emulsion content, and curing temperature on the unconfined compressive strength of compacted specimens after a four-week postcompaction curing period. Analysis-of-variance techniques were used to determine the significant main effects, two-factor interactions, and three-factor interactions at alpha levels of 1 and 5 percent. In general, for the range of variables used in this research, the un-

Table 1. Factors and levels used.

	Level	
Factor	Low	High
Soil type	Houston Clay (HC)	Permian Red Clay (PRC)
Lime content[a]	3	8
Molding moisture content[a]	15	20
Modification curing time (days)	0	2
Bituminous emulsion type	CRS-2	SS-2
Bituminous emulsion content[a]	6	12
Curing temperature (°F)	75	110

[a]Percent by air dry weight of soil.

Table 2. ANOVA for unconfined compressive strength.

Source of Variation	Degrees of Freedom	Mean Square	F-Value[a]	Significance Level (%)
A	1	36 130	49.06	1
G	1	32 572	44.23	1
C	1	21 301	28.92	1
AxD	1	7 933	10.77	1
DxExF	1	7 114	9.66	1
CxG	1	6 498	8.82	5
AxG	1	6 196	8.41	5
BxC	1	5 681	7.71	5
E	1	5 006	6.80	5
AxF	1	4 572	6.21	5
AxCxG	1	4 425	6.00	5
BxCxG	1	4 239	5.76	5
Residual	51	600	-	-
Total	63	-	-	-
Within treatments, treated alike	12	736	-	-

Note: A = soil type, B = lime content, C = molding moisture content, D = modification curing time, E = bituminous emulsion type, F = bituminous emulsion content, and G = curing temperature.

[a]Critical F-values: $F(1, 12, 0.01) = 9.33$, $F(1, 12, 0.05) = 4.75$.

confined compressive strength of lime-bituminous-emulsion-stabilized soils was increased by using (a) 8 percent lime rather than 3 percent lime, (b) 20 percent molding moisture rather than 15 percent molding moisture, (c) curing temperature of 110° F rather than 75° F, (d) chloritic clay rather than a smectic clay, (e) two-day modification curing period after lime pretreatment of the smectic clay, and (f) SS-2 asphaltic emulsion instead of the CRS-2 emulsion. The correct emulsion content percentage appears to be a function of the individual soil type.

The research reported here was designed to investigate selected mixture design, construction, and environmental factors and their interactions that affect the bituminous emulsion stabilization of clay soils pretreated with hydrated high-calcium lime. This combination stabilization strategy appears to be complex, since the interaction of additives and various construction and environmental variables could make a mixture design process difficult to standardize and construction difficult to control.

EXPERIMENT DESIGN

The factors and levels used in the experimental investigation are given in Table 1. These factors represent a number of mixture design, construction, and environmental variables that have been shown to influence lime and bituminous stabilization of clay soil. It is therefore reasonable to use these variables in a study of a combination stabilization strategy by using lime and bituminous emulsion.

The experiment design used a one-half 2^7 fractional factorial. All main effects were confounded with six-factor interactions, two-factor interactions were confounded with five-factor interactions, and three-factor interactions were confounded with four-factor interactions. It was assumed that all six-factor, five-factor, and four-factor interactions were negligible. The estimate of experimental error was determined by randomly selecting 12 duplicate treatment combinations from throughout the factor space, and a replicate error was calculated by comparing the duplicate specimen with the factorial specimen. This technique has been used in other stabilization experiments that used statistical design techniques in the design and analysis of the experimental data (1).

SPECIMEN PREPARATION AND TESTING

Individual quantities of lime and soil were weighed in separate containers according to predetermined levels to minimize the time required for specimen preparation. The specimens were prepared by first measuring the desired quantity of distilled water, selecting the proper preweighed quantities of lime and soil, dry mixing, adding water, and blending by hand until a uniform appearance was attained. If no modification curing time was specified for the specimen, the bituminous emulsion was added and mixed by hand until the mixture of soil, lime, and emulsion had a uniform appearance. If a two-day modification curing time was specified, the mixture was covered and allowed to cure for two days. The moisture content was determined before curing, and any moisture loss by evaporation was replaced after the curing period had expired. At this time, the bituminous emulsion was added and mixed by hand until the mixture of soil, lime, and emulsion had a uniform appearance.

The soil mixtures were compacted in a Harvard Miniature Compaction Mold by using a scaled model of the ASTM D697 compaction hammer that weighed 0.53 lb to simulate standard compactive effort (25 blows per layer, three layers per mold). The specimens were extruded from the compaction mold, weighed, wrapped in plastic wrap, sealed to ensure no moisture loss, marked, and stored at the desired curing temperature until the proper test day. Following the four-week curing period, the specimens were removed one at a time from their respective temperature chambers, weighed, and tested to failure in unconfined compression by using a strain rate of 1 percent/min.

STATISTICAL DATA

The analysis-of-variance (ANOVA) results are given in Table 2 for main effects, two-factor interactions, and three-factor interactions found to be significant at alpha levels of 1 and 5 percent.

DISCUSSION OF RESULTS

The ANOVA data in conjunction with an analysis of treatment combination means indicated that the unconfined compressive strength of lime-bituminous-emulsion soils was increased by using the following:

1. Permian Red Clay (PRC) rather than Houston Clay (HC),
2. 8 percent lime rather than 3 percent lime,
3. 20 percent molding moisture rather than 15 percent molding moisture,
4. Two-day modification curing period after lime pretreatment of HC,
5. SS-2 bituminous emulsion rather than CRS-2 emulsion, and
6. Curing temperature of 110°F rather than 75°F.

Soil Type

PRC is a reddish-colored medium-plastic chloritic

(CL) soil common to Central Oklahoma with a mineralogical profile dominated by chlorite. Mica composes approximately 10 percent of the soil, and the remainder is illite and smectite.

HC is a yellowish-grey soil of the Alabama Black Belt; 30-45 percent of the total soil is smectite. Kaolinite constitutes about 25 percent of the clay fraction. The unified classification is CH.

Soil type was a significant main effect in two-factor interactions with modification curing time, curing temperature, and bituminous emulsion content and in a three-factor interaction with molding moisture content and curing temperature.

Lower unconfined compressive strengths were associated with HC. Clay soils that have a high surface area create mixability difficulties, even with lime pretreatment, which produces an uneven distribution of bituminous emulsion. Furthermore, the lime-treated HC appears to have a more fragile matrix of clay agglomerations, as proposed by Ford (2). The chloritic PRC would have better mixing characteristics with, perhaps, a stronger matrix of clay-particle agglomerations.

Lime Content

Although lime content does not appear significant as a main effect, it does affect the unconfined compressive strength through a two-factor interaction with molding moisture content and through a three-factor interaction involving molding water content and curing temperature. Higher unconfined compressive strengths were associated with the 8 percent lime content.

Eight percent lime is sufficient for free calcium to remain after the modification of both PRC and HC soils. The presence of bituminous emulsion does not appear to eliminate the formation of lime-soil pozzolanic compounds during the postcompaction period.

Molding Moisture Content

Molding moisture content was a significant main effect in a two-factor interaction with curing temperature and in three-factor interactions with soil type, lime content, and curing temperature. Higher unconfined compressive strengths were associated with the 20 percent moisture content.

The series of significant molding moisture content interactions is commonly associated with lime-soil treatment, since the development of lime-soil pozzolanic products is dependent on the presence of adequate water. Furthermore, the higher moisture content would also beneficially influence the densification of the soil system, since the 20 percent moisture content is approximately the optimum of the lime-treated PRC and HC. The distribution of the bituminous emulsion during the mixing process would also be facilitated at the higher moisture content with less risk that the SS-2 emulsion would break prematurely.

Modification Curing Time

Modification curing time was not a significant main effect. However, the factor was significant in a two-factor interaction with soil type and in a three-factor interaction with bituminous emulsion type and bituminous emulsion content.

The modification curing period of two days improved the mean unconfined compressive strength of HC, but it was detrimental to PRC. This interaction suggests that a modification curing period may be advisable for clay soils with a high percentage of smectite but that less-active clays should be stabilized with bituminous emulsion immediately after modification lime and moisture have been added and thoroughly mixed. Furthermore, the interpretation of the three-factor interaction suggests that the effect of modification curing time on unconfined compressive strength will also be related to the emulsion percentage used.

Emulsion Type

Rapid-set emulsions have little or no ability to mix with an aggregate or with soil-aggregate mixtures. Typical applications of CRS-2 emulsions include surface treatment, penetration macadam, and single or multiple coarse-aggregate seal coats (3, ASTM D2397-71).

Slow-set emulsions are designed to mix with fine aggregate. Typical applications of SS-2 as a specific emulsion are not given in general reference data (3, ASTM D977-73). However, SS-2 emulsion only differs significantly from the more frequently referenced SS-1 by having a higher viscosity. Typical values for SS-1 are a minimum Saybolt Furol viscosity at 77°F of 20 s and a maximum of 100 s (ASTM D977-73) as compared with 40 s and 400 s of the SS-2 used in this study. Therefore, the typical applications of SS-2 would be those of SS-1 and would include cold plant mix, sand mix, slurry seal coat, tack coat, fog seal, dust layer, and mulch.

Certainly the CRS-2 emulsion would not be used or recommended for soil-bituminous stabilization, and it is not the intention of this study to evaluate its use. The emulsion type was helpful in better defining the complex interactions among soil, construction, and environmental factors investigated although it has no potential application in mixture design for lime-bituminous-treated clay soils. The SS-2 does have a potential application for field use, but the focus of the research does not have its evaluation in terms of mixture design as an objective.

The use of anionic emulsion (SS-2) with lime pretreatment produced a higher mean unconfined compressive strength than did the cationic emulsion (CRS-2). Since the CRS-2 is not manufactured for mixing with fine-grained soils, a tendency for poor mixtures would be expected. Visual inspection of the compacted specimens confirmed the poor mixability of CRS-2 emulsion with the fine-grained lime-modified soils. Another minor reason for the poor mixability may be that the clay platelets become saturated with calcium and have a net positive charge. Therefore, the flocculated and agglomerated groups of clay platelets would repel the cationic charged emulsion. Future research by using a CSS emulsion should be designed to investigate the influence of this surface-chemistry-oriented repulsion hypothesis for lime-modified soil.

Curing Temperature

Curing temperature had a significant effect on the unconfined compressive strength as a main effect as well as in two two-factor interactions and two three-factor interactions, as shown in Table 2. In all cases, the curing temperature of 110°F was associated with higher strengths than a 75°F curing temperature. The higher curing temperature would encourage the formation of pozzolanic compounds through the chemical interaction of the free lime and clay soil. The increased curing temperatures could also encourage a continuation of emulsion dispersion within the soil mass after compaction during the four-week curing period. The higher degree of dispersion could produce higher unconfined compressive strengths.

CONCLUSIONS

The experimental results are indicative of the complexity inherent in this combination stabilization strategy. An improved understanding of the effect of emulsion type on the engineering and physical properties of the lime-treated clay is needed. Potential physical interactions involving clay surface chemistry and emulsion chemistry require investigation, since they may influence the ability of the bituminous emulsion to be satisfactorily dispersed during mixing. Other test data are needed to define tensile properties, stress-deformation characteristics, and the response of the material to moisture penetration.

ACKNOWLEDGMENT

The research reported here was sponsored by the Research Grant-in-Aid Program, Auburn University, Auburn, Alabama. I am indebted to Gregory Rosser, who assisted in the preparation and testing of the soil specimens. I also gratefully acknowledge the cooperation of the Hunt Oil Company, Tuscaloosa, Alabama, which provided the asphaltic emulsions used in the research effort.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements.

Laboratory Test Method for Predicting Moisture-Induced Damage to Asphalt Concrete

ROBERT P. LOTTMAN

A laboratory test method is described for the prediction of moisture damage in dense-graded asphalt concrete mixtures. The method consists of obtaining diametral (or indirect) tensile-strength and modulus ratios of compacted specimens subjected to vacuum saturation with water and to freeze-plus-warm-water-soak accelerated moisture conditioning. Test results for dry specimens are used to form the ratio bases. The ratios are used to predict short-term and long-term field damage. Fatigue curves for two mixtures exposed to the dry, vacuum-saturation, and accelerated moisture conditioning of the test method are presented to show effects of moisture on fatigue life. A tentative relationship shows a correlation between tensile-strength ratios obtained by the test method and pavement fatigue-life ratios. An example of the practical use of the correlation is shown. Results are presented from a five-year field evaluation study conducted by seven highway agencies on eight pavement test sections to determine whether the test method's predictive ratios and stripping tendencies correlate with field results. Short-term ratios from laboratory vacuum saturation were reached at four years of pavement age or before. Long-term ratios from laboratory accelerated moisture conditioning ranged from 0 to 0.80; they were reached at five years for some pavements and probably will be reached in a few more years for the other pavements. This ratio is considered one of maximum moisture damage to minimum moisture damage. Visual stripping in the field cores appears similar to the predicted laboratory stripping. Agency-determined layer coefficients decreased due to the loss of moisture cohesion from the associated stripping observed in the field.

The destructive influence of moisture in dense-graded asphalt concrete has been recognized for decades. Laboratory tests have been developed to predict potential moisture damage. The purpose of the tests is to assess the redesign of asphalt mixtures (changes of aggregate type, asphalt, and compaction and addition of antistripping treatments) prior to paving in order to minimize the damage.

Immersion-compression and Marshall-type tests on asphalt concrete mixtures evaluate the effect of water on the asphalt concrete mixture in a compacted state in order to find the interaction of all the mixture constituents. The evaluation methods relate the wet strength to the dry strength either as a ratio or as a percentage of retained strength. Highway agencies have developed specifications for the ratios or retained percentages; low values imply high moisture damage and the necessity to redesign or alter the asphalt concrete mixture being evaluated.

Moisture mechanisms that cause damage have been the objective of studies by many investigators. Simulation of the mechanisms to produce closer field-related moisture-damage conditioning in the laboratory should give more realistic predictive damage ratios. The following are some of the major moisture-damage mechanisms that cause stripping or mixture softening or both:

1. Pore pressure of water in the mixture voids due to wheel-loading repetitions; thermal expansion-contraction differences produced by ice formation, temperature cycling above freezing, freeze-thaw, and thermal shock; or a combination of these factors;
2. Asphalt removal by water in the mixture at moderate to higher temperatures;
3. Water-vapor interaction with the asphalt-filler mastic and larger aggregate interfaces; and
4. Water interaction with clay minerals in the aggregate fines.

Added to the importance of simulating the proper moisture-damage mechanism in laboratory tests is the selection of methods to measure damage. Loss of bond due to stripping seems to be measured more directly by tensile-type tests. Also, moisture-damaged asphalt concrete loses cohesion and the pavements crack and deteriorate, especially when severe stripping is observed. Cracking and some of the deterioration result from repeated tensile stress (or strain) in the field due to wheel loads. Thus,