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Effect of Laboratory Curing and Compaction Methods on the Stress-Strain Behavior of Open-Graded Emulsion Mixes

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Research into the curing of open-graded asphalt emulsion mixtures is described. Relations that characterize the development of the resilient modulus at different curing temperatures are developed, and comparisons are made between air curing and vacuum curing. The Marshall hammer and the vibratory air hammer are compared to determine the effects of compaction methods on resilient modulus. The results of testing at various levels of density are also reported. It was found that open-graded emulsion mixes develop final values of resilient modulus that vary with curing temperature and tend to be higher for increased curing temperatures. Vacuum curing was found to produce the highest values of resilient modulus. A comparison of methods of compaction showed that samples compacted by the vibratory hammer develop lower modulus values than samples compacted by the Marshall hammer. A comparison of test results obtained at different levels of density indicated that as density increased there was a substantial increase in modulus.

Open-graded emulsion mixes are mixtures of open-graded aggregates and emulsified asphalt, usually CMS-2. An open-graded mixture is characterized by high void contents of about 20-30 percent and less than 10 percent of the material passing the 2-mm (no. 10) screen (1). Common U.S. Forest Service specifications for aggregate gradations are given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
25	100
12.5	45-70
9.5	
4.75	0-20
2	0-6
0.075	0-2

The success of early projects led to increased use of open-graded emulsion mixes; it became evident, however, that the performance of these mixes varied. Simple modifications of methods of thickness design for hot mix were not always successful. Early failures of some projects have recently resulted in a reduction in the use of open-graded emulsion mixes by one of its largest users, Region 6 of the U.S. Forest Service (2). Although the causes of these failures have usually not been precisely determined, the emulsion mix has often been blamed whether it contributed or not. The common solution to failure is to increase the pavement thickness by adding an overlay and thus burying the problems.

As a result of this varied performance of open-graded-mix pavements, Region 6 of the U.S. Forest Service contracted with Oregon State University to develop a procedure for designing pavements with these materials. The overall objective of the project is to develop a procedure for determining layer coefficients for use in the Region 6 version of the AASHTO design guides (3). Specifically, the program includes development of

1. Test equipment and procedures to characterize stress-strain behavior of open-graded emulsion mixes,
2. A procedure for assigning layer coefficients for open-graded emulsion mixes by using the test data generated together with layered theory, and
3. A plan for extensive verification in the field of the proposed procedure to establish layer coefficients.

This paper describes work done to determine the effects of curing and compaction methods on the stress-strain behavior of open-graded emulsion mixes as a part of the first of these objectives. For hot-mix asphalt concrete, factors that are known to have a considerable effect on pavement performance include quality and gradation of aggregate, grade of asphalt, quality control of construction, and amount of traffic. These factors also affect the performance of open-graded emulsion mixes. Curing conditions also appear to have an important effect on the behavior of emulsion mixes (4).

This study examines chiefly the effects of time and temperature on curing. The effects of methods of compacting laboratory samples are also described in a comparison of a vibratory air hammer and the Marshall hammer. Finally, in an illustration of the effects of density, results from this study are compared with those obtained by the Chevron Research Company (5) in tests on identical materials.

MATERIALS

The materials used in this research are considered to be typical of materials used by Region 6 of the U.S. Forest Service in Portland, Oregon.

Aggregate

The aggregate used in all tests was provided by the materials laboratory of Region 6 of the U.S. Forest Service. This aggregate was a crushed basaltic material from Rivergate Rock Products near Portland. All material was sieved and then recombined to the gradation specifications given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
25	100
12.5	57.5
9.5	35
4.75	10
2	3
0.075	1

Common aggregate tests were performed by the Region 6 laboratory to determine aggregate properties. The results of these tests are given below ($1 \text{ g/cm}^3 = 62 \text{ lb/ft}^3$):

Property	Test Method or Specification	Amount
Rodded unit weight (g/cm^3)	AASHTO T19-74	1.67
Durability index	California test method 229	
Coarse		58.0
Fine		44.4
Specific gravity (%)	AASHTO T-85	
Bulk		2.57
Saturated surface dry		2.66
Apparent		2.81
Absorption		3.24
Los Angeles abrasion loss (%)	AASHTO T-96	18.1
Sand equivalent	California test method 217	
Air dry		63.9
Prewet		60.6

Asphalt Emulsion

The asphalt emulsion used in this work was a CMS-2 emulsion provided by Chevron USA, Inc. This is the type and source of asphalt used to date in the majority of projects constructed in the Pacific Northwest (4). The specifications and measured properties for this asphalt emulsion are given in Table 1. The emulsion content used for all experiments was equal to 6 percent of the dry aggregate weight.

Table 1. Properties and specifications of CMS-2 asphalt emulsion.

Property	ASTM Method	Specification	Actual
Viscosity at 50°C (s)	D 88	50-450	188
One-day settlement (%)	D 244	<5	-
Storage stability test, one day	D 244	<1	-
Particle charge	D 244	Positive	-
Sieve test (%)	D 244	<10	nil
Oil distillate by volume of emulsion (%)	D 244	<12	8
Residue (%)	D 244	>65	67
Penetration at 25°C	D 5	100-250	168
Ductility at 25°C, 5 cm/min (cm)	D 113	>40	-
Solubility in trichloroethylene (%)	D 2042	>97.5	-
Viscosity of residue			
At 135°C (cm^2/s)	D 2170		3.12
At 60°C (Pa·s)	D 2171		97.9

Note: $t°\text{C} = (t°\text{F} - 32)/1.8$; 1 cm = 0.39 in; $1 \text{ cm}^2/\text{s}$ = 100 centistokes; 1 Pa·s = 10 poises.

SAMPLE PREPARATION

Several factors were considered important in sample preparation. The most important are described below:

1. Coating—The amount of coating varies with the fines content of a sample because of the increased surface area. An increase in fines may break the emulsion before it has a chance to coat completely. Coating after breaking is difficult if not impossible without more cutter stock to lower the viscosity of the residual asphalt. Because of possible variation in coating, three samples were prepared for each test condition.
2. Compaction—All samples used for the curing study were compacted in a cylindrical mold by using a Marshall hammer, four lifts, and 50 blows for each lift [9.75 blows/cm (25 blows/in)]. The sample was 10 cm (4 in) in diameter and 20 cm (8 in) in height. The resulting density was between 1.77 and 1.85 g/cm^3 (110 and 115 lb/ft^3). This density was initially chosen as being representative of open-graded emulsion mixes. A subsequent survey of existing projects has shown that the average density of open-graded emulsion mixes is 1.95 g/cm^3 (121 lb/ft^3) (4).
3. Handling—Freezing of the samples was required to remove the samples from the molds, and rubber membranes were applied to facilitate handling and to help prevent the samples from slipping.

Since the Marshall hammer was observed to cause some degradation of the aggregate, an evaluation of the use of a vibratory hammer in laboratory compaction was also included as part of this study. The vibratory air hammer that was used was equipped with a 10-cm (3.9-in) diameter rigid metal foot, and compaction was accomplished by using the vibratory effects of the hammer rather than impact forces typical of the Marshall hammer.

CURING

A number of curing methods have been proposed for the testing of emulsion mixes. The methods evaluated include the following:

1. Vacuum curing—Vacuum-cured samples were encased in a thin rubber membrane and two end plates through which a vacuum was applied. Vacuum curing was done at 24°C ± 2°C (75°F ± 4°F), and resilient modulus was measured at frequent intervals.
2. Air curing—Air-cured samples were cured at 24°C ± 2°C (75°F ± 4°F). To prevent the samples from slumping, they were confined in a rubber membrane in which the ends were left open.
3. Oven curing—Oven curing of emulsion mix samples is difficult because of the tendency for the mix to slump. The confining pressure of a rubber membrane applied to these samples was sufficient to allow curing at 38°C ± 2°C (100°F ± 4°F) without slumping problems. The oven used to cure all samples allowed air to flow through it, but no forced air was used.
4. Curing at 5°C (40°F)—Samples cured at 5°C were cured in a 5°C ± 1°C (40°F ± 2°F) refrigerator. None of the samples exhibited slumping tendencies.

For each variable studied, samples were prepared in triplicate to minimize the chances of variability in testing. Initial (uncured) properties of the samples prepared and tested for this study are given in Table 2. These properties were obtained one day after sample preparation.

TEST EQUIPMENT

Two tests that can be used to measure the stress-strain characteristics of open-graded emulsion mixes are the diametral test (5) and the repeated-load triaxial test (6). The diametral test has several advantages in that it is relatively inexpensive, the small samples are easier to fabricate and handle, and the equipment is relatively easy to use. Its main limitation is that it is limited to a maximum confining pressure of 101 kPa (1 atm). This confining pressure does not replicate the high confining pressures typical of the heavy loading found on Forest Service roads (7).

The device used in the repeated-load triaxial test can be used to apply high confining pressures and to evaluate both plastic and elastic response. But the device requires a highly skilled operator, and the larger test samples are difficult to prepare, cure, and handle. Because of the ability of this device to apply high confining pressures, it was used for all tests conducted in this study. The triaxial cell used was similar to a conventional cell but larger so as to accommodate a 10×20-cm (4×8-in) specimen and the deformation-measuring devices.

The repeated stresses were applied by using a pneumatic system similar to that developed by Seed and Fead (8). The repeated deviator stresses are applied at a frequency of 20 load cycles/min and at a pulse duration of 0.1 s. The 20-cycles/min frequency allowed the sample sufficient time to recover from the previous load so that plastic deformation of the sample was not a problem.

The response of the sample to applied stresses was measured by using two linear variable differential transformers (LVDTs). To accurately record the real deformation of the sample, the LVDTs were placed inside the triaxial cell and attached to the specimen with a pair of clamps placed at the quarter points.

Table 2. Initial properties of samples of open-graded emulsified asphalt.

Sample Number	Description	Liquid Content (%)	Aggregate Moisture (%)	Density (g/cm³)	Air Voids[a] (%)
0	Uncured	6.0	0	1.81	29.3
1	Cured at 15°C	6.0	0	1.82	29.0
2				1.82	29.0
3				1.80	29.8
4	Cured at 24°C	6.0	0	1.83	28.5
5				1.80	29.7
6				1.84	28.4
7	Cured at 38°C	6.0	0	1.84	28.2
8				1.81	29.6
9				1.83	28.6
10	Vacuum cured	6.0	0	1.85	27.9
11				1.88	26.7
12				1.86	27.6
13	Compaction study	6.0	0	1.79	30.2
14				1.79	30.1
15	AR-4000	3.9	0	1.74	34.5
16				1.81	31.8
17				1.82	31.4

Note: 1 g/cm³ = 62 lb/ft³; t°C = (t°F - 32)/1.8.

[a] Specific gravity of aggregate = 2.81.

TEST PROGRAM

The basic procedure for testing elastic behavior by use of the repeated-load triaxial cell was developed in earlier tests (6, 7). To avoid effects of plastic deformation, samples were subjected to 1000 repetitions of a preconditioning stress. After preconditioning, the sample was subjected to a standard test sequence that consisted of 100 repetitions of each stress condition. Standard tests at low confining pressures (i.e., $\sigma_3 = 0$) were not conducted for uncured and partially cured samples because of slumping problems. Most tests were conducted at 24°C ± 1°C (75°F ± 2°F). All samples were allowed sufficient time to reach the test temperature before testing.

RESULTS

Uncured Specimens

Three samples were used to establish the stiffness properties of the uncured emulsion mixes as a function of confining pressure σ_3 and the sum of principal stresses θ (for the triaxial test, $\theta = \sigma_d + 3\sigma_3$ where σ_d = repeated vertical stress).

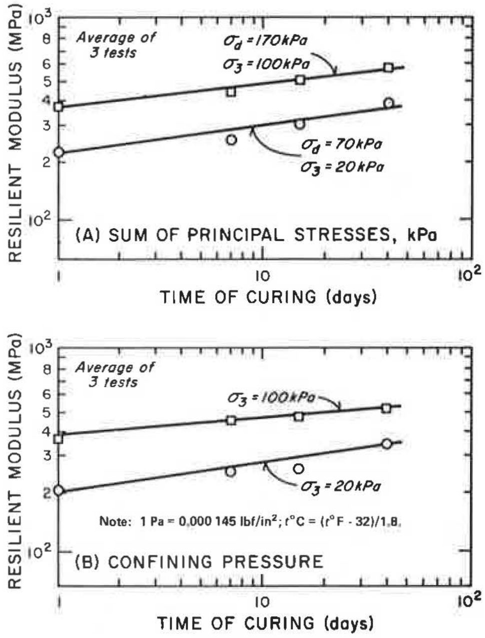
Partially Cured Specimens

The average gain in stiffness for two stress conditions for partially cured specimens is shown in Figures 1, 2, and 3. Note that in all instances there is an increase in modulus with time of curing. The rate of increase in stiffness is, however, a function of the curing temperature. It should be mentioned that, although the average results show the expected trends, some of the individual results are quite erratic. This is discussed further in a later section of this paper.

Open-Graded Hot Mix

To estimate maximum stiffness, three samples of open-graded hot mix were prepared to the same density as the emulsion mixes and tested at two temperatures [23°C and

Figure 1. Resilient modulus versus curing time for cure condition of 5°C and test temperature of 24°C.



Note: 1 Pa = 0.000 145 lbf/in²; t°C = (t°F - 32)/1.8.

Figure 2. Resilient modulus versus curing time for cure condition of 24°C and test temperature of 24°C.

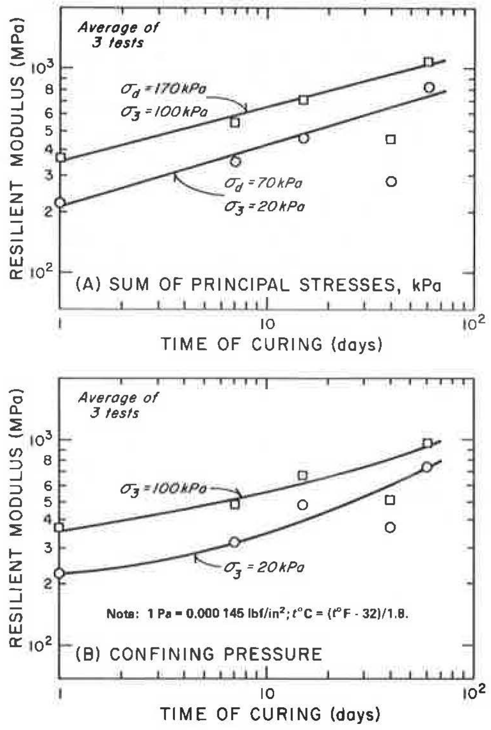
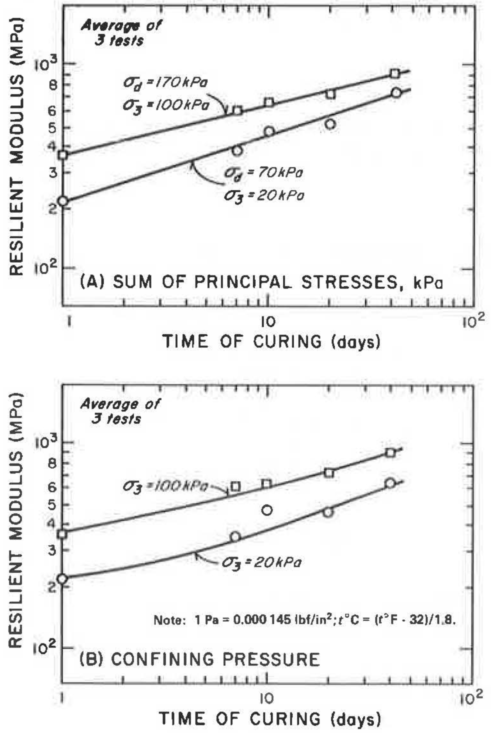


Figure 3. Resilient modulus versus curing time for cure condition of 38°C and test temperature of 24°C.



27°C (73°F and 81° F)]. All samples were tested in accordance with the standard sequence. In all instances, the modulus was affected by confining pressure σ_3. As σ_3 increased, the modulus increased. In addition to the observed stress dependency, the modulus is also affected by temperature. Figure 4 shows the effect of temperature on the modulus for two confining pressures. At 32° C (90°F), it can be expected that the modulus of open-graded hot mix will be about 483 MPa (70 000 lbf/in²). At 24° C (75°F), the modulus varies from 1069 to 1862 MPa (155 000 to 270 000 lbf/in²), depending on the confining pressure. These values, as expected, are greater than the corresponding modulus values obtained on partially cured, open-graded cold mix. These values are considered estimates only because the viscosity of the emulsion mixes and the asphalt cements did not agree closely [~100 versus ~383 Pa·s (1000 versus 3830 poises)].

Vacuum-Cured Specimens

The results of tests on the three vacuum-cured samples are summarized in Figure 5. Of particular interest is the gain in stiffness as a function of time of curing and sum of principal stresses (θ). The corresponding value of stiffness for the open-graded hot mix is also shown in Figure 5.

Figure 6 shows the development of stiffness for two stress conditions. Note that, if the curing curves are extended to the ultimate (AR-4000), approximately 300 h (or 12 days) of vacuum curing would be required to reach this value.

Compaction Study

The results of the test on samples prepared to the same density by using the Marshall and vibratory hammers are summarized in Figure 7, which shows the actual modulus values for each compaction method and their development over time. Figure 8 shows the development of modulus with time for one stress condition [σ_d = 69 kPa (10 lbf/in²), σ_3 = 21 kPa (3 lbf/in²), and θ = 131 kPa (19 lbf/in²)]. As indicated, the samples compacted by the vibratory compactor are less stiff at the early stages of curing. Although the results are limited, they do show that different compaction methods may yield different results. If vibratory compaction is used, one can expect a greater tendency to tender mixes. As the samples are cured, the effect of compaction is lessened.

Samples compacted by the Marshall hammer may show more stiffness at early stages of curing because of some crushing of the aggregates, which results in increased grain interlock. As the samples are cured, however, the stiffness of the mix results more and more from the presence of asphalt, and the resulting stiffness values are similar to one another.

Figure 4. Average modulus for open-graded hot mix versus temperature (from regression equations).

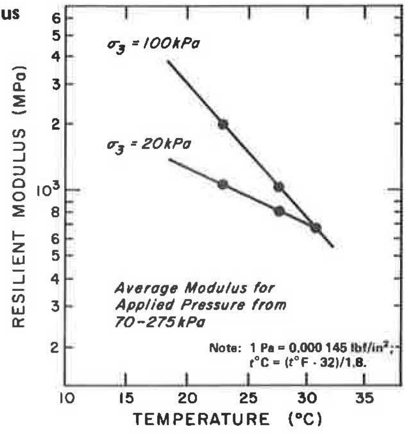
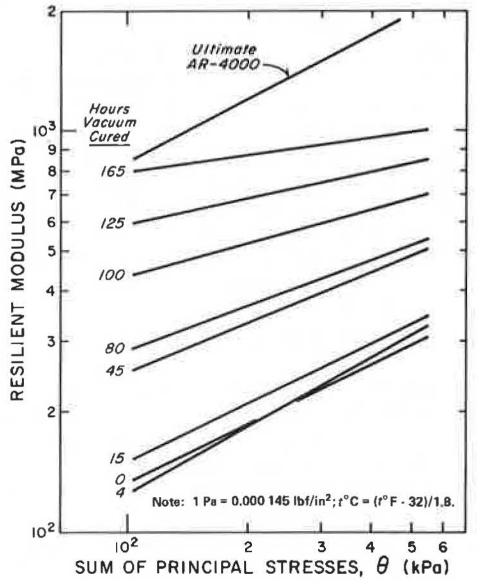
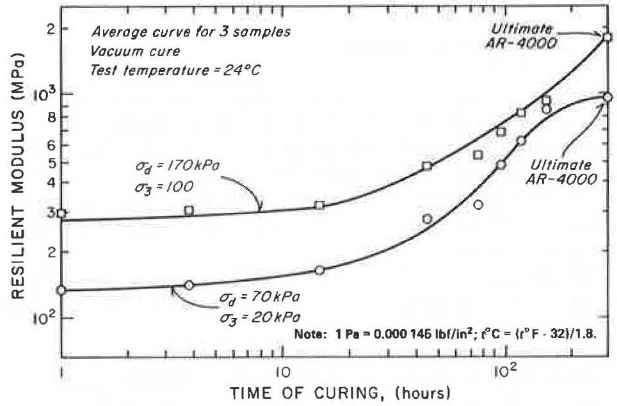


Figure 5. Resilient modulus versus sum of principal stresses.



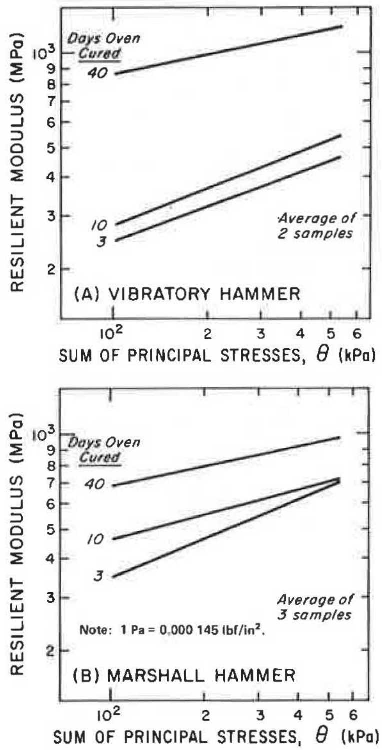
Note: 1 Pa = 0.000 145 lbf/in²; t°C = (t°F - 32)/1.8.

Figure 6. Resilient modulus of open-graded emulsion mixes versus curing time.



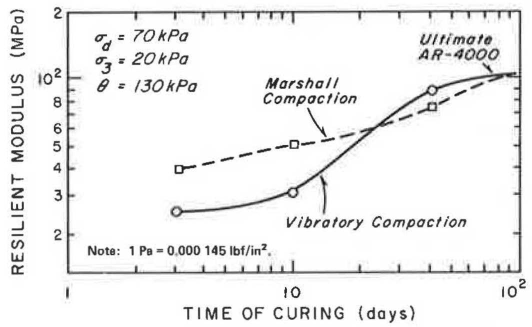
Note: 1 Pa = 0.000 145 lbf/in²; t°C = (t°F - 32)/1.8.

Figure 7. Variation in resilient modulus with curing time, type of compaction, and sum of principal stresses.



Note: 1 Pa = 0.000 145 lbf/in².

Figure 8. Resilient modulus versus curing time for specimens prepared by using Marshall and vibratory compaction procedures.



Note: 1 Pa = 0.000 145 lbf/in².

DISCUSSION OF RESULTS

Variability

It was expected that the stiffness of all of the open-graded mixes would always increase with time. However, comparison of test results for several individual samples at different durations of curing showed that gains in stiffness do not always occur in the expected manner. It was also reasonable to assume that samples that were prepared, cured, and tested in a similar manner would produce similar results. But there was considerable variation in regression coefficients for samples tested at the same stage of curing and prepared in the same way. These variations appear to be beyond any normal experimental error. Furthermore, they were considerably greater than the variations found by Chevron Research Company in tests of similar materials in which the diametral test apparatus was used.

It is suspected that much of the variation found in the samples tested at Oregon State University was caused by the following factors:

1. Sample size—The 10x20-cm (4x8-in) sample size used in the repeated-load triaxial test apparently does not cure in a uniform fashion. The smaller 6x10-cm (2.5x4-in) sample size used in the diametral procedures would probably cure more uniformly. Since all samples were cured in a membrane, curing could only take place at the exposed ends; this apparently led to the uneven curing.
2. LVDT clamps—In all tests conducted at Oregon State University, the load clamps were fastened to the sample of open-graded mix at the quarter points. It was sometimes difficult to position the LVDTs without causing some binding between the LVDT core and the LVDT itself. Part of this problem can probably be eliminated by using more rigid clamps.

Although there were variations of stiffness development for a given sample and also variations in modulus between samples for a given condition and duration of cure, the results of average sample results show the expected trend—a gradual increase in stiffness with time.

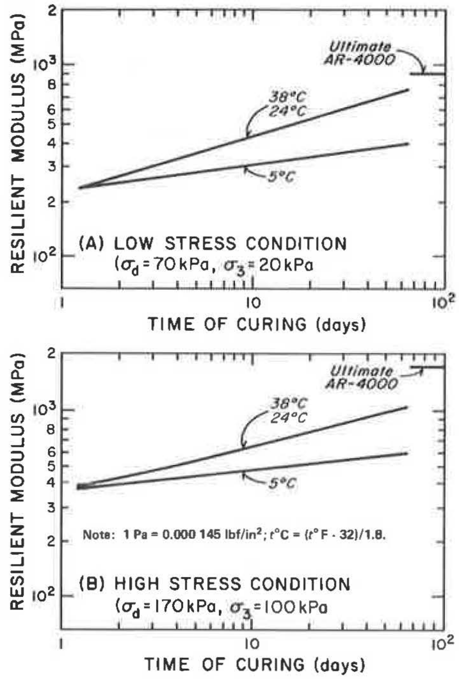
Effect of Type of Curing

The type of curing had an effect on the rate of stiffness development in the open-graded emulsion mix. Samples cured at 24°C and 38°C (75°F and 100° F) exhibited a more rapid gain in stiffness than those cured at 5°C (40°F) regardless of stress conditions. This effect, which is shown in Figure 9, indicates that projects placed during late fall or in areas where the temperature may remain around 5°C would not be expected to gain in stiffness at a very rapid rate. In fact, the stiffness at the end of 90 days of curing at 5° C is less than 50 percent that of the ultimate modulus. But this does not necessarily mean more damage or a need for thicker layers because, as we will show, the modulus would be higher if measured at 5°C.

Effect of Density

Test results presented earlier were performed on samples prepared to a density of approximately 1.77 g/cm^3 (110 lb/ft^3). Results from the survey of field performance indicated that an average density for open-graded emulsion mixes is about 1.93 g/cm^3 (120 lb/ft^3).

Figure 9. Effect of type of curing on rate of stiffness development.



Note: 1 Pa = 0.000 145 lbf/in^2; t°C = (t°F - 32)/1.8.

Tests were run by Chevron Research Company on mixes similar to those tested at Oregon State University but at densities considerably higher than 1.77 g/cm^3 (110 lb/ft^3). Densities used in the Chevron study were approximately 1.92 and 2.13 g/cm^3 (119 and 132 lb/ft^3). The average moduli for samples tested at approximately 69-kPa (10-lbf/in^2) repeated stress (σ_d) and 21-kPa (3-lbf/in^2) confining pressure (σ_3) are shown in Figure 10 together with the Oregon State University data for samples compacted to 1.77 g/cm^3. In all instances, the modulus increased with time of curing and with level of density. The rate of development, however, varied slightly.

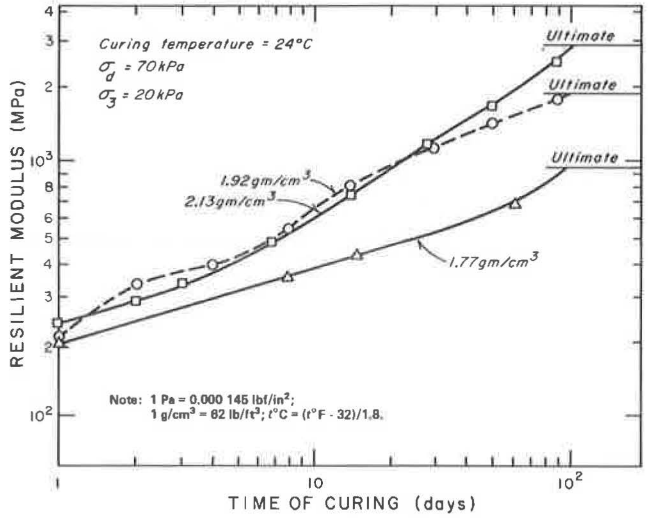
The results shown in Figure 10 were also used to develop a family of curves to show the variation in resilient modulus of open-graded emulsion mixes with density (Figure 11). This family of curves shows the dramatic effect of time of curing and density on stiffness. At 1.77 g/cm^3 (110 lb/ft^3), the modulus would range from approximately 483 to 966 MPa (70 000 to 140 000 lbf/in^2), whereas at high levels of density [2.3 g/cm^3 (132 lb/ft^3)], the modulus would range from 1725 to 2760 MPa (250 000 to 400 000 lbf/in^2). This emphasizes the importance of achieving a good density in this type of mix, particularly if stiffness is any indicator of good performance.

Effect of Type of Compaction

The limited number of tests performed on samples prepared to the same density by means of different compaction techniques indicated that there is a substantial effect on stiffness at the early stages of curing. Figure 8 shows that at early stages of curing samples prepared by using an impact hammer yield a higher stiffness than those compacted by a vibratory hammer. After approximately 20 days of curing, the stiffness values are similar, and both approach the ultimate value of the AR-4000 open-graded hot mix.

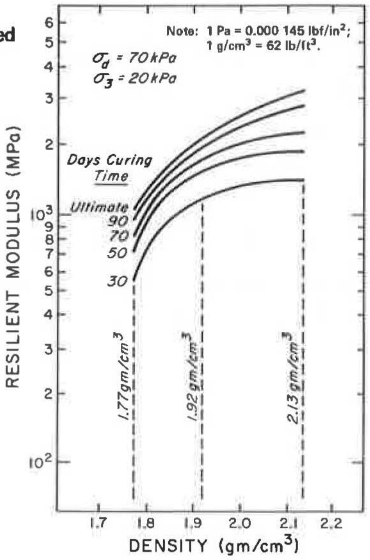
This indicates the importance of the type of compaction in the development of stiffness in emulsion mixes. Exclusive use of vibratory compactors may lead to tender mixes at early stages of curing. Beyond 20 days, however, there appears to be no significant difference

Figure 10. Resilient modulus of open-graded emulsion mixes versus curing time.



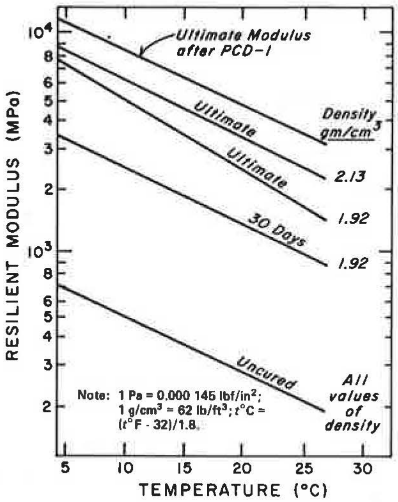
Note: 1 Pa = 0.000 145 lbf/in^2; 1 g/cm^3 = 62 lb/ft^3; t°C = (t°F - 32)/1.8.

Figure 11. Resilient modulus of open-graded emulsion mixes versus density.



Note: 1 Pa = 0.000 145 lbf/in^2; 1 g/cm^3 = 62 lb/ft^3.

Figure 12. Resilient modulus versus test temperature.



between the stiffness values obtained for the different types of compaction. Further study in this area is certainly warranted.

Effect of Temperature

Limited tests were also performed to establish the effect of temperature on the modulus of open-graded emulsion mixes. Chevron Research Company performed tests on mixes at 23°C and 5°C (73°F and 40°F). Results of these tests are summarized in Figure 12. Note that the average ultimate modulus at 23° C and at a density of 2.13 g/cm^3 (132 lb/ft^3) is approximately 2827 MPa (410 000 lbf/in^2). Samples prepared at a density of 1.92 g/cm^3 (119 lb/ft^3) had an average modulus of approximately 1965 MPa (285 000 lbf/in^2). The modulus of samples tested at 5° C ranges from 6895 to 9239 MPa (1 000 000 to 1 340 000 lbf/in^2), depending on density. The results obtained for open-graded emulsion mixes at a high level of density compare very favorably with the variation in modulus with temperature of dense-graded asphalt mixes reported by the Asphalt Institute (9). As density is lowered to 1.92 g/cm^3, the slope of the temperature-stiffness relation for open-graded emulsion mixes is not very different from that for conventional mixes. By assuming relatively constant slopes for different stages of curing, stiffness-temperature relations were also developed for 0 and 30 days of curing. This relation still needs verification.

Comparison of Laboratory and Field Modulus Values

The average density of all cores was 1.95 g/cm^3 (121 lb/ft^3); the average modulus was 1806 MPa (262 000 lbf/in^2) at a confining pressure of 21 kPa (3 lbf/in^2). From Figure 11, the laboratory-determined modulus at σ_3 = 21 kPa would vary from 1806 to 2275 MPa (180 000 to 330 000 lbf/in^2), depending on the duration of curing. It therefore appears from this limited test program that results for laboratory-prepared samples are very similar to those for field cores.

CONCLUSIONS

Open-graded emulsion mixes exhibit different rates of development of resilient modulus for different curing conditions. The final resilient modulus varies with curing conditions and is higher at higher curing temperatures. The highest resilient modulus is obtained by using a vacuum-cure procedure. This value for modulus also appears to compare well with the average modulus determined on cores taken from 14 projects. Further testing should be undertaken before this conclusion is assumed to be valid.

The variation in the development of modulus with temperature demonstrates the need to consider environmental conditions when designing and working with emulsion mixes. This work is not of adequate scope to be used to predict environmental effects on curing and modulus development. More work, including considerations of mix density, cure temperature, and humidity, would be necessary to predict environmental effects adequately.

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