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Use and Properties of Emulsified Asphalt Mixtures in Low-Volume Roads

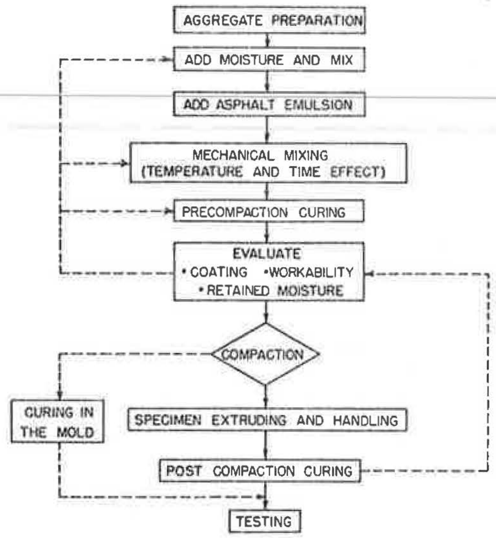
MICHAEL S. MAMLOUK AND LEONARD E. WOOD

The use of cold-mixed, emulsified asphalt mixtures in low-volume roads has been widely accepted by highway engineers in the past few decades. A comprehensive experimental investigation has been performed in order to characterize a marginal-quality mixture prepared by mixing sand and gravel with emulsified asphalt. A mix preparation procedure has been developed that simulates the cold-mixing operation usually used in the pavement of low-volume roads either in base courses or in surface treatment. The emulsion mixture properties were evaluated by using Marshall and Hveem procedures at ambient temperature. The tensile and resilient characteristics of the mix were obtained at three different temperatures. The effects of emulsion content, curing, and vacuum saturation were investigated. The influence of adding a small amount of portland cement was also evaluated. Finally, the properties of the emulsion mixture and asphalt concrete were compared. Significant results were obtained, which provide the highway engineer with a better understanding of the integral behavior of the emulsified asphalt mixture. This may help in increasing the use of emulsified asphalt as a binding agent in the pavement of low-volume roads in a more optimal way.

Low-volume roads represent a major portion of the highway system in the United States as well as in other parts of the world. In spite of their widespread distribution, low-volume roads have not received much attention and have been kept in a mostly unsurfaced condition. A major problem currently facing highway agencies is the continuous deterioration of these roads because of the increasing traffic loads and volume. Compounding the problem is the continuous increase in maintenance costs due to the increasing cost of materials, labor, and equipment. On the other hand, the use of hot-mixed asphalt concrete in maintaining or surfacing these roads may not be cost effective because of the large amount of energy associated with this operation. New low-cost, environmentally sound pavement materials should be used in order to reduce the cost of construction and maintenance of such low-volume roads.

The use of emulsified asphalt mixtures in the construction of low-volume roads has received wide acceptance by highway engineers because of the ecological performance and economic advantages of these mixtures. Unlike asphalt cement, emulsified asphalt reduces or eliminates heating requirements when it is mixed with aggregate. This has a significant effect on reducing energy demands and air pollution. Either road mix or plant mix can be used for the preparation of emulsified asphalt mixtures. The most critical shortcoming of emulsified asphalt mixtures, however, is the relatively low strength at early ages and the slow development of strength, which is controlled by the rate of water loss in the mixture. In addition, the possibility of erosion and a drop in strength due to the presence of water in the system before the final curing can be important. A thorough understanding of the integral behavior of the mixture would be useful in implement-

Figure 1. Preparation and testing procedure of emulsified asphalt mixture.



ing it in the paving of low-volume roads.

A comprehensive experimental investigation was performed in order to characterize a marginal-quality mixture prepared by mixing sand and gravel with emulsified asphalt. A mix preparation procedure has been developed that simulates the cold-mixing operation usually used in the construction of low-volume roads, either in base courses or in surface treatment. The effects of several techniques, ingredients, and environmental conditions on various mixture properties were evaluated.

MATERIALS

Aggregate

An aggregate of marginal quality, which was a mixture of sand and gravel consisting approximately of 50 percent calcareous and 50 percent siliceous pieces, was used in this study. About 60 percent of the gravel particles retained on the 4.75-mm (No. 4) sieve had crushed faces. One dense-aggregate gradation was used that fell within the gradation band of ASTM D 3515; nominal maximum size was 19 mm (3/4 in). Aggregate gradation and other properties are shown below:

Property	Amount
Sieve size (% passing)	
19.0 mm (3/4 in)	100
12.5 mm (1/2 in)	75
9.5 mm (3/8 in)	67
4.75 mm (No. 4)	47.5
2.36 mm (No. 8)	38.5
0.6 mm (No. 30)	21
0.15 mm (No. 100)	9
0.075 mm (No. 200)	2.5
Apparent specific gravity	2.707
Bulk specific gravity	2.607
Absorption (%)	1.20

Emulsified Asphalt

One high float emulsified asphalt type and grade, HFMS-2s (ASTM D 977), was used. The physical properties of the emulsion were as follows [t°C = (t°F - 32)/1.8]:

Property	Amount
Saybolt Fural viscosity at 25°C	50^+
Residue by distillation (%)	70
Penetration of residue after distillation (25°C, 5 s, 100 g)	200^+
Specific gravity of residue after distillation at 25°C	1.010

Asphalt Cement

An AC-15 type of asphalt cement was used in the preparation of the asphalt-concrete mixture with the following original properties [1 cSt = 0.01 cm^2/s; t°C = (t°F - 32)/1.8]:

Property	Amount
Penetration (25°C, 5 s, 100 g)	65
Kinematic viscosity at 135°C (cSt)	313
Flash point, Cleveland open cup (°C)	328
Specific gravity at 25°C	1.014

EXPERIMENTAL STUDY

Mixture Preparation

Mixing and specimen preparation of these types of bituminous mixtures are affected by a number of factors in the asphalt emulsion mixture component system. More effort needs to be expended in controlling and handling than with the traditional hot-mix types. The main factors that have been evaluated in order to provide an adequate method for preparing and testing the asphalt emulsion mixture specimens were coating of aggregate, workability of mix, and trend of moisture retained in the specimens before and after compaction (curing rate). The different steps considered in this investigation are discussed below (Figure 1).

The dry aggregate was blended by combining the different aggregate sizes to meet the desired gradation. The aggregate was used at a room temperature of 22°C (72°F) in the asphalt emulsion mixture. The initial moisture content was added to the aggregate and mixed thoroughly by hand. The purpose of adding moisture to aggregate before mixing with asphalt emulsion is to prevent balling-up of fine-grained particles and to provide a uniform coating of asphalt emulsion on aggregate particles.

The asphalt emulsion was combined with the cold wet aggregate by using a mechanical mixer. Hand mixing was also used to overcome the segregation of fine and coarse aggregates during the mechanical mixing.

Precompaction Curing

The effect of curing on the amount of moisture retained in the mixture before compaction (mix in the loose condition) was investigated. It was found that the mixture can be easily handled if it is cured for 1 h at 60°C (140°F) and then mixed for 30 s before compaction. This precompaction curing process is necessary not only for removing some of the excess water, but also to compensate for the high energy provided in the field during the mixture preparation. It was found also that the precompaction curing provided a better coating of aggregate and easier mixture handling than the case of a completely cold process. This method of precompaction curing resulted in a mixture temperature of about 45-50°C (113-122°F) after 1 h at 60°C, which is considered reasonable for cold asphalt emulsion mixtures.

Compaction

Marshall specimens of 102-mm (4-in) diameter and about 64-mm (2.5-in) height were prepared by using 50 blows of the mechanical Marshall compaction hammer on each side of the specimen. This compacting effort was selected to duplicate the actual conditions of the pavement in the field under medium traffic. Specimens used in tests other than the Marshall test, however, were compacted by using a fixed-roller gyratory compaction machine. Twenty revolutions of the gyratory machine with 1.38 MPa (200 psi) and one-degree gyration angle were used. Both methods of compaction were found to give specimens with similar unit weights.

Postcompaction Curing

It was found that curing the specimens out of the mold was beneficial as far as the rate of moisture loss was concerned. An out-of-the-mold curing condition provides more surface area for the moisture to leave the specimen as compared with curing in the mold. Since the properties of emulsified asphalt mixtures are highly affected by curing, several levels of curing were evaluated, which range between one and seven days at room temperature. The long-term curing condition was simulated by placing the specimens in a forced-draft oven at 49°C (120°F) for three days. After curing, specimens were tested at different conditions.

Test Procedures

Marshall-size specimens were fabricated following the mix preparation procedure just discussed. Water was added to aggregate at a rate of 3 percent by weight of dry aggregate. The contents of three emulsified asphalt mixtures that provided residue contents of 2.5, 3.25, and 4 percent of the aggregate dry weight were evaluated. After curing, the bulk specific gravities of the specimens were determined according to ASTM D 1188. The surface was dusted with zinc stearate instead of being coated with paraffin to obtain faster results with a minimum change in moisture content during submersion in water.

Specimens were tested by using the Marshall machine and the Hveem stabilometer as well as the indirect-tension and the resilient-modulus equipment. Some specimens were vacuum-saturated and tested to evaluate the moisture sensitivity of the mixture (1). Also, 1 percent portland cement was added to other specimens in order to evaluate its effect on the mixture properties. Other mixture properties, such as air-void content and specific gravity, were evaluated. Three replicate specimens were fabricated and tested for each combination of factors to account for the large variability of test results. After the test was completed, specimens were broken apart and dried, and the dry weights were obtained from which the air voids were calculated. The different tests that were used in the emulsion mixture evaluation are presented in the following paragraphs.

Marshall Test

Since the emulsified asphalt mixture is relatively tender, particularly at early curing ages, the Marshall test was conducted at room temperature (22°C). Specimens were tested in both before and after vacuum-saturation conditions. The modified Marshall stability and Marshall flow values were determined. Asphalt-concrete specimens were also tested at the same temperature to allow for direct comparison with emulsified asphalt specimens.

Hveem Test

Hveem stability values (ASTM D 1560) and resistance R-values (ASTM D 2844) were determined for emulsified asphalt mixtures at room temperature by using the Hveem stabilometer. Both Hveem stability and resistance values were obtained for each specimen in one test. The vertical load applied to specimens in the Hveem stabilometer was increased up to only 22.3 kN (5000 lbf) and not 26.7 kN (6000 lbf) as specified by ASTM standard in order to reduce the excessive deformation to the specimens. Also, the test was performed at room temperature and not at the 60°C required by the ASTM method. Both dry and vacuum-saturated specimens were tested.

Indirect-Tensile Test

Tensile stresses are developed in the different pavement layers when traffic loads are applied. A high tensile strength is required for durable asphalt mixtures. Also, high stiffness values at high temperatures are needed to reduce the excessive deformation or rutting in hot weather. However, at low temperatures relatively low stiffness values are desired to eliminate or reduce cracks. Also, the tensile strain at failure is directly related to cracking of the highway pavement. The occurrence of cracking increases as the failure strain decreases.

The tensile characteristics of the aggregate-emulsion mixture were determined in the laboratory by using the indirect-tensile test. In this test, cylindrical specimens are caused to fail by applying compressive loads along a diametral plane through two opposite loading heads. This type of loading produces relatively uniform tensile stresses acting perpendicular to the applied load plane. The test was performed by using the MTS Systems Corporation electrohydraulic machine at temperatures of 10, 24, and 38°C (50, 75, and 100°F). The load was applied at a rate of deformation of 51 mm (2 in)/min by using two curved stainless steel loading strips with a width of 12.7 mm (1/2 in). Continuous recordings of load versus horizontal deformation and vertical deformation versus horizontal deformation during the load application were obtained. The test was performed on both dry and vacuum-saturated specimens. The tensile strength, Poisson's ratio, tensile stiffness, and tensile strain at failure were determined (2,3).

Resilient-Modulus Test

As traffic moves on the pavement, the vertical and horizontal stresses change so that each wheel pass can be considered as a stress pulse. The use of the dynamic tests in the evaluation of bituminous mixtures is a realistic approach because it simulates the actual stress conditions of the pavement. In this part of the study, the diametral resilient-modulus test was used to evaluate the resilient characteristics of the aggregate-asphalt mixes.

The resilient-modulus technique used in the study was similar to the procedure developed by Schmidt (4) with some modifications (Figure 2). A pulsating load of 334 N (75 lbf) was applied across the vertical diameter of the specimen every 3 s with a dwell time of 0.1 s. Two curved stainless steel loading strips with a width of 12.7 mm were used. Both vertical and horizontal deformations were recorded on a strip-chart recorder. The test was performed at temperatures of 10, 24, and 38°C. At one-day air curing, however, specimens were not firm enough to be tested at 38°C. Also, since the test is nondestructive, repeated measurements were obtained from the same specimens at different tempera-

tures in many cases. The instantaneous resilient modulus and the resilient Poisson's ratio were obtained (2). In addition, the mixture properties were evaluated for both dry and vacuum-saturated conditions.

ANALYSIS OF RESULTS

The performance of the emulsified asphalt mixture in low-volume roads is a function of many factors, such as quality of the materials, loading characteristics, and environmental conditions. The stability of the mix is a function of both cohesion and internal friction, which in turn depend on the material properties, mix ingredients, density, and curing conditions. In this study, the effects of the different factors were statistically analyzed. A level of significance of 5 percent was used in the analysis. A discussion of various test results is presented in the following paragraphs.

Effect of Curing

Curing is a very influential factor in the stability of the emulsified asphalt mixture. Curing breaks the emulsion and allows water to evaporate, which leaves the asphalt residue adhering to the aggregate particles. The ultimate curing condition may be achieved in the field within 120 days of curing, depending on weather conditions (5). Laboratory results showed that the Marshall stability increased from an average of 4.77 kN for one-day air curing to an average of 9.04 kN for three-day oven curing (1070 and 2030 lbf, respectively). On the other hand, the average modified Hveem stability increased

Figure 2. Resilient-modulus test apparatus.

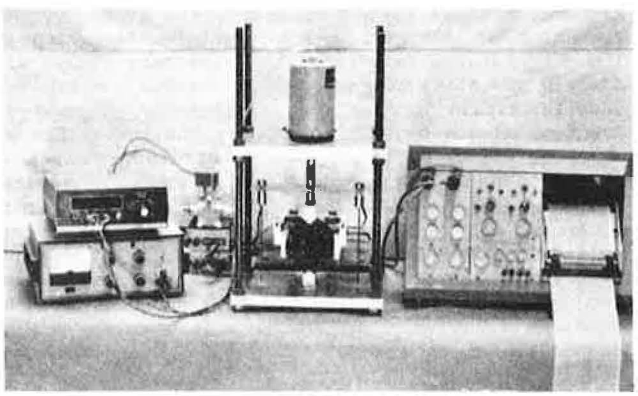


Figure 3. Effect of curing, portland cement, and asphalt residue content on Marshall stability at 22°C.

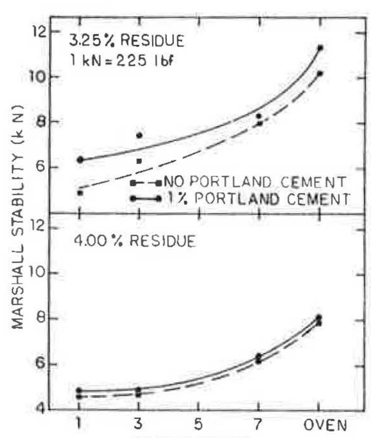


Figure 4. Average Marshall stability and resilient modulus at 22°C for various curing conditions.

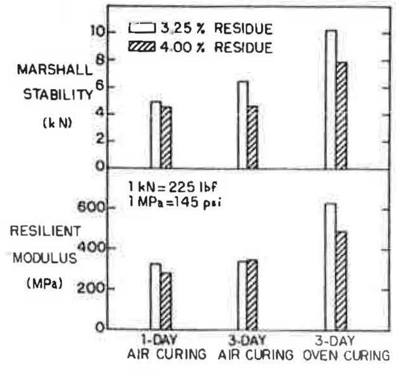


Figure 5. Effect of curing on percentage of air voids and bulk specific gravity of compacted specimens.

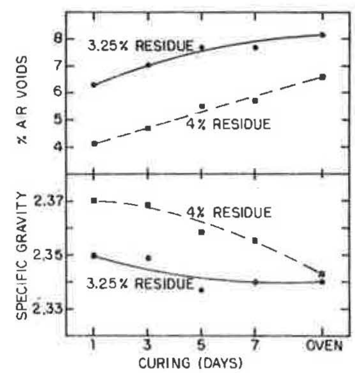


Figure 6. Average Hveem stability and resistance at 22°C for different residue contents and curing conditions.

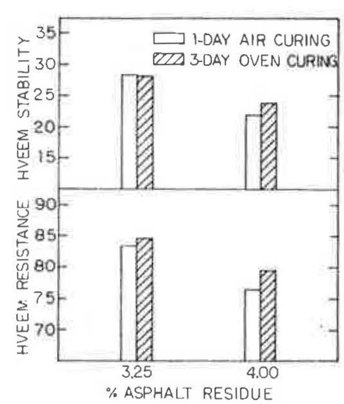
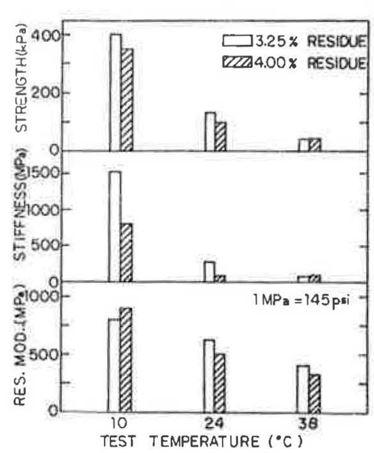


Figure 7. Effect of test temperature on tensile strength, tensile stiffness, and resilient modulus for oven-cured specimens.



slightly from 25 to 26, and the average Hveem resistance increased from 80 to 82 when curing was changed from one day of air curing to three days of oven curing.

The effect of curing on the tensile and resilient properties was apparent. The average tensile strength at room temperature and one day of air curing was 83 kPa (12 psi), whereas it was 117 kPa (17 psi) at three days of oven curing. The tensile stiffness, on the other hand, increased from 33 MPa (4714 psi) to 194 MPa (28 136 psi) when curing was changed from one day of air curing to three days of oven curing. The failure strain at room temperature, however, decreased from 0.011 m/m (0.361 ft/ft) at one day of air curing to 0.008 m/m (0.000 088 ft/ft) at three days of oven curing. Finally, the resilient modulus at room temperature was 304 MPa (44 020 psi) at one day of air curing and 560 MPa (81 290 psi) at three days of oven curing. The effect of curing at different levels on the Marshall and resilient properties is shown in Figures 3 and 4.

The curing levels had a large influence on the air voids and specific gravity of the mixture (Figure 5). Curing increased the amount of air voids in the emulsion mixture because of the water evaporation. The average amounts of air voids were 5.2 percent and 7.4 percent at one-day air curing and three-day oven curing, respectively. Moreover, the bulk specific gravity dropped from 2.356 to 2.342 when curing was changed from one day of air curing to three days of oven curing.

Effect of Asphalt Residue Content

The asphalt residue acts as a binder between aggregate particles. A sufficient asphalt residue content is needed to ensure a durable and stable mix so that the demands of traffic will not result in distortion or displacement. On the other hand, air voids in the compacted mix are necessary that allow for a slight amount of additional compaction under traffic loading without flushing, bleeding, or loss of stability yet are low enough to keep out harmful air and moisture.

The experimental results indicated that higher values of Marshall stability and lower values of Marshall flow were obtained at lower asphalt residue content (see Figures 3 and 4). An average Marshall stability of 7.53 kN (1690 lbf) was obtained at 3.25 percent residue versus 6.03 kN (1360 lbf) at 4 percent residue, while the Marshall flow increased slightly from 8 to 10 units at the same residue contents. On the other hand, the average Hveem stability and resistance values were 28 and 84 at 3.25 percent residue content, whereas they were 23 and 78 at 4 percent residue content, respectively, as may be seen in Figure 6. Moreover, the averages of tensile strength, tensile stiffness, and resilient modulus were higher at 3.25 percent residue content than the average at 4 percent residue content in most cases, as shown below (1 kPa = 0.145 psi, 1 MPa = 145 psi, 1 m/m = 3.28 ft/ft):

Avg Mixture Property	Residue Content (%) 3.25	4
Tensile strength (kPa)	106	94
Tensile stiffness (MPa)	159	68
Failure tensile strain (10^{-4} m/m)	85	108
Resilient modulus (MPa)	430	371

Increasing the emulsion content in the mixture fills the voids between aggregate particles and consequently increases the bulk specific gravity. The average amounts of air voids were 7.4 and 5.3 percent at 3.25 and 4 percent residue contents, respectively. The corresponding values of specific gravity, however, were 2.343 and 2.357 for the two asphalt residue contents, respectively.

Effect of Temperature

Emulsified asphalt as well as other asphaltic materials are temperature susceptible. Increasing the temperature decreases the viscosity of the asphalt residue and in turn softens the emulsion mixture. In this study, the indirect-tensile and the resilient-modulus tests were performed at three different temperatures (10, 24, and 38°C), which represent a wide range of temperatures in the field. It was noted that a high test temperature caused hair cracks to develop early during the test before complete failure. Low-tensile-strength, stiffness, and resilient-modulus values were obtained as temperature increased from 10 to 38°C (Figure 7). The average tensile strength decreased 86 percent when the test temperature increased from 10 to 38°C. Also, the average tensile-stiffness and resilient-modulus values decreased 61 and 50 percent, respectively, by increasing the test temperature as before. The tensile strain at failure, however, was not significantly affected by changing the test temperature.

Effect of Vacuum Saturation

When the emulsion mixture is exposed to water, the possibility of removal of the asphalt film from aggregate particles increases, especially before the mixture has been completely cured. The study of the water effect on the emulsion mixture properties is an essential part of the evaluation process. The effect of water on the performance of the asphalt emulsion mixture was evaluated by using a modification of the Asphalt Institute water-sensitivity test (1). According to this method, specimens were subjected to a vacuum saturation of 30 mm Hg for 1 h and then submerged in water for 24 h at room temperature. Vacuum-saturated specimens were tested and compared with the corresponding dry specimens.

A general reduction in the Marshall stability of vacuum-saturated specimens was observed when they were compared with dry specimens as illustrated in Figure 8. The largest stability loss was observed at early curing stages. On the other hand, there was no appreciable change in Marshall stability for oven-cured specimens, particularly for mixtures with high emulsion content. Meanwhile, the difference between the tensile strengths before and after vacuum saturation was not large, and a consistent trend was not observed. Also, the total tensile strain at failure was not highly affected by vacuum saturation. In addition, the resilient-modulus values were not greatly influenced by vacuum saturation, as demonstrated in Figure 9. Mixtures that contained 3.25 percent residue were affected by vacuum saturation more than mixtures that contained 4 percent residue. The amount of moisture absorbed by the mixture during vacuum saturation did not exceed 2.5 percent by weight of dry aggregate for any mixture included in the study.

Effect of Adding Portland Cement

In spite of the potential advantages that can be attained by using the emulsified asphalt mixture, it possesses some relatively unfavorable characteristics such as the slow curing rate and the low resistance to water damage, especially at early ages.

Figure 8. Average Marshall stability for dry and vacuum-saturated specimens after different curing periods.

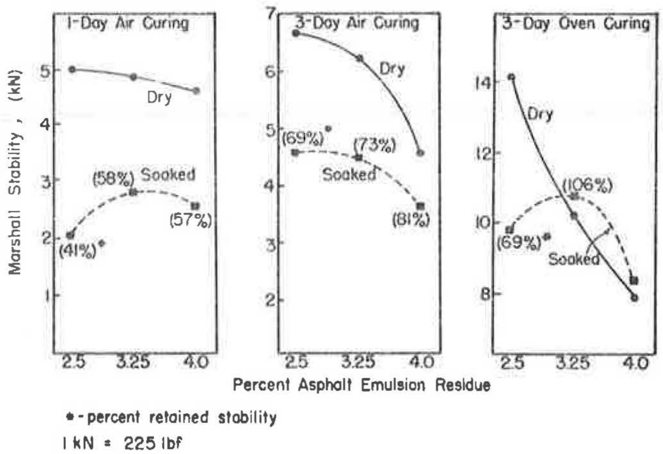


Figure 9. Average resilient modulus at 22°C for dry and vacuum-saturated specimens after different curing periods.

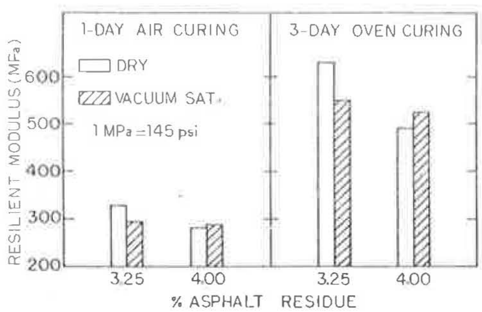


Table 1. Average bulk specific gravity and Marshall stability at 22°C for emulsion and asphalt-concrete mixes.

	Specific Gravity		Marshall Stability (kN)	
	Residue Content (%)		Residue Content (%)	
Mixture	3.25	4	3.25	4
Emulsion air cured for				
1 day	2.350	2.361	4.900	4.633
3 days	2.349	2.369	6.331	4.626
5 days	2.337	2.358	8.192	6.561
7 days	2.340	2.355	8.006	6.435
Emulsion oven-cured for 3 days	2.340	2.343	10.206	7.873
Asphalt concrete	2.340	2.404	35.362	40.868

These tend to limit its use as a high-quality paving material. The use of small percentages of portland cement as an additive to the emulsion mixture improves its characteristics, especially its resistance to water damage. In this study, 1 percent portland cement was added to some emulsion mixtures in order to investigate its effect on the mixture properties. The portland cement was added to the wet aggregate and mixed immediately before the emulsion was added.

During the mixing and preparation process, the mixtures that contained 1 percent portland cement appeared wetter and had relatively less coating than mixtures prepared without portland cement additive. Also, the test results showed higher amounts of moisture retained in those mixtures than in mixtures with no cement additive. In addition, cement-treated emulsion mixtures had lower bulk specific gravity than other mixtures. However, the amount of air voids was not appreciably altered by the use of portland cement.

The effect of portland cement on the Marshall stability at 22°C was apparent, especially at early curing ages and for mixtures with low emulsion contents, as shown in Figure 3. The average increase in Marshall stability due to the adding of portland cement was 29 percent for one-day air-cured specimens with 3.25 percent residue content, whereas the average increase in Marshall stability was only 2 percent for oven-cured specimens with 4 percent residue content. On the other hand, the flow values were not significantly affected by the use of portland cement as an additive to the emulsion mixture.

The use of portland cement improved the resistance of the emulsified asphalt mixture to water damage. The effect of adding portland cement was more beneficial and apparent for mixes with low emulsion contents and at early curing conditions. The percentage of reduction in Marshall stability at 22°C due to vacuum saturation for mixes with and without portland cement at early curing conditions is shown below:

	Reduction in Marshall Stability (%)	
Residue (%)	1 Day Air Curing	3 Days Air Curing
With portland cement		
2.5	19	8
3.25	19	16
4	25	21
Without portland cement		
2.5	59	31
3.25	42	27
4	43	19

Comparison between Emulsion Mixes and Asphalt Concrete

Hot-mixed asphalt-concrete specimens were prepared by mixing aggregate with asphalt cement (AC-15) according to ASTM D 1559. The asphalt cement was added to aggregate at rates of 3.25 and 4 percent by weight of dry aggregate in order to allow for a direct comparison with the emulsion mixes. Fifty blows of the mechanical Marshall hammer were applied on each side of the specimen. Specimens were tested by using the Marshall apparatus at a room temperature of 22°C, which is the same test temperature at which the emulsion mixes were tested. Specimens were tested in both dry and vacuum-saturated conditions following the same procedure used with the emulsion mixtures.

The average values of the bulk specific gravity and the Marshall stability at 22°C for both emulsion and asphalt-concrete mixtures are presented in Table 1. The bulk specific gravities of the emulsion mixtures and asphalt concrete were similar at 3.25 percent asphalt residue content. However, the average bulk specific gravity of asphalt-concrete specimens was slightly higher than that of the emulsion mixture at 4 percent residue content. On the other hand, asphalt concrete resulted in larger values of Marshall stability at 22°C as compared with the emulsion mixtures, as shown in Table 1. Moreover, the average Marshall flow at room temperature of all emulsion-mix specimens was 9, whereas it was 12 for all asphalt-concrete mixes. Also, the emulsified asphalt mixtures were affected by vacuum saturation more than asphalt-concrete mixtures. The average

retained Marshall stability of all emulsion mixtures after vacuum saturation was 80 percent, whereas the average for asphalt-concrete specimens was about 90 percent.

CONCLUSIONS

Based on the preceding experimental investigation, the following conclusions are derived.

1. Curing increases the Marshall stability at room temperature, the tensile strength, the tensile stiffness, and the resilient modulus of the mixture. Curing decreases the amount of moisture retained in the mixture and consequently the bulk specific gravity decreases. The air voids, on the other hand, are increased by curing.
2. The Marshall stability decreased when the asphalt residue content was increased from 2.5 to 4 percent, especially for oven-cured specimens. In addition, Hveem stability at room temperature, Hveem resistance, tensile strength, tensile stiffness, and resilient-modulus values decrease by increasing the residue content. The amount of air voids dropped from 7.4 to 5.3 percent when the residue content increased from 3.25 to 4 percent by weight of dry aggregate.
3. The emulsion mixture is sensitive to temperature. High test temperatures cause hair cracks to develop early during the test before complete failure for both indirect-tensile and resilient-modulus tests. Low tensile strength, tensile stiffness, and resilient-modulus values are obtained at high temperatures.
4. A general reduction in Marshall stability at room temperatures is observed after vacuum saturation. Other mixture properties are not largely affected by vacuum saturation. The amount of moisture absorption did not exceed 2.5 percent by weight of dry aggregate during the vacuum-saturation process.
5. Portland cement increases the Marshall stability at room temperature, especially at early curing ages and for mixtures with low emulsion contents. Also, portland cement increases the moisture retained in the mix, decreases its bulk specific gravity, and increases its resistance to water damage.
6. Emulsified asphalt mixes resulted in bulk specific gravities close to those of asphalt-concrete mixes with similar contents of asphalt residue. Large values of Marshall stability at 22°C were obtained for asphalt-concrete specimens as compared with emulsion-mix specimens. Neither oven-cured emulsion mixes nor asphalt-concrete mixes were greatly affected by vacuum saturation.

ACKNOWLEDGEMENT

The financial support for this study from the Federal Highway Administration and Indiana State Highway Commission is duly acknowledged. Sincere thanks are extended to A.A. Gadallah for participation in the experimental and statistical analysis. Appreciation is also extended to companies that provided the materials and to those who helped in performing the tests and preparing the manuscript.

The contents of this paper reflect our views, and we are responsible for the facts and accuracy of the data.

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Stabilization of Silt: A Case Study for Low-Volume Roads in Saudi Arabia

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Although there is generally a reasonable justification for using lime stabilization for clays and cement or bitumen for sandy soils, no such generalization exists for silts. The range of the applicability of several stabilization techniques to silts is investigated. The main objective of the investigation was to determine the type and quantity of stabilizer(s) suitable for silty soils, which dominate the surface geology of Saudi Arabia. A soil-cement-bitumen model that results in the best mixture performance is presented, and optimum additive percentages are suggested. A physicochemical explanation for such performance is provided. The analysis is based on experimental results obtained from compaction, California bearing ratio, unconfined compression, and modified Marshall tests. It is shown that modification of the silt with 2-3 percent cement followed by stabilization with about 4 percent bitumen gives overall a satisfactory mixture. Such a mixture may be used in the construction of low-volume, low-cost roads or as a subgrade material for paved roads. The proposed mix design is more favorable from the standpoint of strength, durability, and economics than bitumen or cement stabilization, the use of which would require at least 7 and 8 percent, respectively, as minimum stabilizer contents.

During the past decade, the Saudi Arabia Ministry of Communications (MOC) constructed more than 20 000 km of low-volume roads in accordance with the national policy for social and economic development. These low-cost or "agricultural" roads serve thousands of rural communities. In addition, some 30 000 km of paved highways are in use or under construction for which costly borrow materials are being used for the subgrade or subbase.

The MOC is placing increasing emphasis on the