Mix-Design Procedures for Open-Graded Emulsion Mixes

R. G. HICKS, JEAN WALTER, AND RONALD WILLIAMSON

Three mix-design procedures for open-graded asphalt emulsion mixes (Chevron USA, Inc.; U.S. Forest Service Region 6; and Federal Highway Administration Region 10) are summarized. The basic steps used in each method and the major differences among the methods are discussed. Finally, the results of a limited round-robin test program are presented that indicate very little difference in the recommended emulsion and water contents for the three methods. All three procedures are reasonably simple and require little time when compared with those for dense-graded emulsion mixes. However, there is still a need to adopt a standard method of evaluating the strength (or stiffness) of the mix to obtain layer coefficients. Currently, the diametral modulus appears to be the most promising test method available.

Open-graded emulsion mixes are mixtures of open-graded aggregate and emulsified asphalt, generally CMS-2. An open-graded mixture is characterized by a high void content, on the order of 20-30 percent, and less than 10 percent of the material passing the 2-mm (No. 10) screen. The mixtures are cold mixed in a pugmill and then placed and compacted on the roadway by using conventional equipment and construction procedures. Open-graded mixtures possess high permeability, which aids in curing, facilitates the removal of ground and surface water that can weaken the structural section, and minimizes the chances of hydroplaning. Open-graded mixes also appear to be more flexible than dense-graded mixes, causing an increase in resistance to fatigue and reflection-type cracking (1,2).

Open-graded emulsion mixes have been used extensively since 1965 in the Northwest in the construction of low-volume county and Forest Service roads that carry gross loads of as much as 890 kN (200 000 lbf). These mixes have several advantages over hot mix. They generally require less energy to produce, reduce air pollution, and do not create a fire hazard. They are often more economical than a hot mix, especially when long haul distances are required. In recent years, however, there have been reports of wide variations in the performance of open-graded mixes. Early failures of some projects have resulted in a reduction in use of open-graded emulsion mixes by one of its largest users, Region 6 of the U.S. Forest Service (2). Factors that contribute to reported failures include (a) poor (or no) mix design, (b) poor construction practices and production control, and (c) inadequate structural design.

This paper provides a summary of mix-design procedures for open-graded emulsion mixes used by three sources: Chevron USA, Inc., Region 6 of the U.S. Forest Service, and Region 10 of the Federal Highway Administration (FHWA). The steps used in each method to determine emulsion and water contents are presented, and the differences in the methods are discussed. Finally, the results of a limited "round-robin" study are presented to show the differences in the emulsion and water contents obtained by each method.

STEPS IN MIX DESIGN

In all emulsion-mix-design procedures, the ultimate objective is to determine the type and amount of emulsion needed to make a satisfactory mix. To do this, one must undertake the steps outlined below. If all of the steps are carried out, the chances of a successful project are increased considerably.

Select an Appropriate Aggregate

The gradation of the aggregate in open-graded mixtures is very important. Based on construction experience to date (1), no more than 10 percent passing the 2-mm (No. 10) sieve or 2 percent passing the 0.074-mm (No. 200) sieve is recommended. For open-graded mixes, a large amount of air voids in the compacted mix (about 20-30 percent) is necessary. A large percentage of fine aggregate and/or surface area can cause early breaking of the emulsion, result in improper coating and poor mix workability at laydown, and possibly slow the rate of strength development.

Another important factor in the success of open-graded emulsion mixes is the inherent stability of the aggregate, which depends on particle interlock as well as hardness and durability. Crushed aggregates are recommended. The recommended minimum amount of fractured faces is 60-75 percent (3).

Select the Type of Emulsion

In selecting the type of emulsion, consideration must be given to the aggregate type and gradation and climatic conditions. Medium-set emulsions are normally used for open-graded emulsion mixes. They are designed to break during mixing or shortly thereafter and allow compacting operations to be completed without any difficulty.

Medium-set emulsions can be anionic or cationic, depending on the electrical properties of the asphalt particle surface. If the emulsifiers used provide a negative surface charge, the emulsion is anionic. A positive surface charge occurs in cationic emulsions. Cationic emulsions can be used with almost all types of aggregates because practically all aggregate types possess a negative surface charge. Cationic emulsions extend the paving season since they can be used in cooler weather. In addition, since they will break without evaporation, they are not as easily damaged by sudden showers, which means that they will not wash away quite as readily (4).

The choice between cationic and anionic grades depends on the aggregate as well as on the mix coating, curing, and adhesion characteristics. The viscosity of an emulsion increases with increasing asphalt residue content and with decreasing penetration grade. High-viscosity emulsions (CMS-2 and CMS-2h) are preferred for use in open-graded mixes to minimize runoff and to provide greater film thickness and durability.

Select the Amount of Water and Emulsion

The procedures used to select emulsion and water contents differ among agencies; all agencies, however, prepare trial mixtures, and the one selected is usually the one that gives the most satisfactory results in terms of workability, coating percentage, and film thickness.

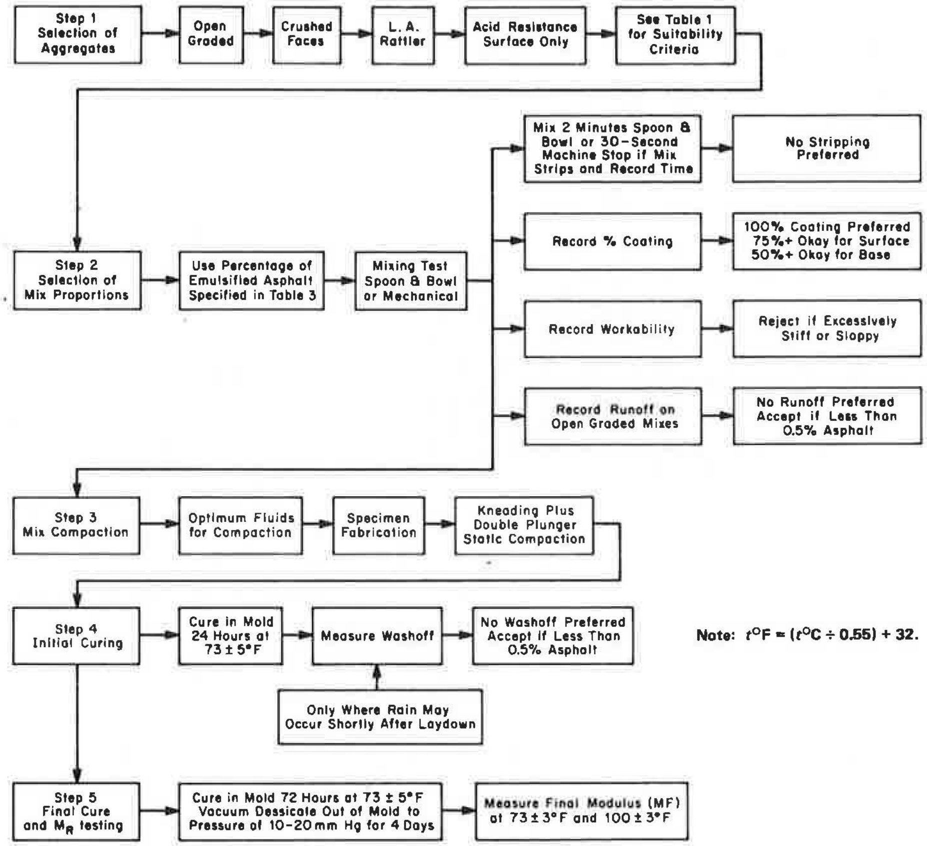
Compact the Mix

Laboratory specimens are normally fabricated at optimum fluid content (asphalt plus water), by first using a kneading compactor and then a double-plunger static load. Emulsified asphalt mixes must be compacted in the field to at least 95 percent of laboratory density to provide necessary aggregate interlock. Proper compaction is important if the mix is to achieve its design strength or stiffness.

Cure the Specimen and/or Subject It to Moisture

Under favorable curing conditions, properly designed emulsified-asphalt mixes can be opened to heavy traffic within 45 min to 1 h or to controlled traffic immediately. Rain damage is of concern in open-graded mixes during and shortly after construction. Open-graded mixes that

Figure 1. Testing schedule for emulsified-asphalt mixes: Chevron procedure.



incorporate CMS-2 and CMS-2h emulsion have been placed during light rain without difficulty, but in heavy rain the emulsion may wash off. The mix is susceptible to washoff until the emulsion breaks. The resistance of a particular mix to possible early damage from rainfall is measured by the washoff test in the Chevron procedure.

Test the Specimen

Various standard strength tests are carried out to ensure a stable mix and to select the appropriate thickness so that the mix will not rut or crack under load. The test most commonly used to evaluate this property is the diametral modulus (5).

CHEVRON PROCEDURE

Figure 1 shows the steps involved in using the Chevron procedure to test emulsified-asphalt mixes (6).

Selection of Aggregate

The types of aggregates considered suitable for open-graded emulsified-asphalt treatment include blast-furnace slag, coral, volcanic cinder, gravel, ore tailings, crushed ledge stone or rock, reclaimed aggregates, or other inert material. These aggregates must meet the requirements given in Table 1.

Selection of Emulsified Asphalt

Both anionic and cationic emulsified asphalts can be used. Medium-set emulsions are preferred for open-graded mixtures. However, other factors, such as job climatic conditions, the availability of water, and of course the availability of the product, influence the choice. The table below provides guidelines for selection of medium-setting emulsified asphalts other than CMS-2 and CMS-2h (note that CMS-2s grade is not used with open-graded mixes):

Grade Designation	Use as Aggregate	Rain Resistance	Construction Method
CMS 2s	Dry or damp low-sand-content gravels; well-graded or silty sands	Resistant to early rainfall	Travel plant or in-place mixing
MS 1 and MS 2	Dry or damp processed open-graded aggregates	Resistant to early rainfall	Central mix or travel plant

Selection of Mix Proportion

For open-graded mixes, trial mixes are prepared by using various emulsion contents. The batch weight used is a function of the maximum aggregate size, as given below, and should conform to the gradation specified (1 mm = 0.039 in; 1 kg = 2.2 lb):

Nominal Maximum Particle Size (mm)	Minimum Batch Weight (kg)
19.00	1.20
12.50	0.75
4.76	0.50

The emulsion content is selected from those given below:

Open-Graded Aggregate	Approximate Emulsified-Asphalt Content (percentage by weight of aggregate)
Coarse	4.5-6.5
Medium	5.0-7.0
Fine	6.0-8.0

Table 1. Open-graded aggregates suitable for emulsified-asphalt mixes.

ASTM Designation	Category	Aggregate		
		Coarse[a]	Medium[b]	Fine[c]
C136	Gradation (percentage passing by weight)			
	38.1 mm	100		
	25.4 mm	95-100	100	
	19 mm	-	90-100	
	12.7 mm	25-60	-	100
	9.5 mm	-	20-55	85-100
	4.75 mm	0-10	0-10	-
	2.36 mm	0-5	0-5	0-10
	1.18 mm	-	-	0-5
	0.595 mm	-	-	-
	0.297 mm	-	-	-
	0.149 mm	-	-	-
	0.075 mm	0-2	0-2	0-2
D2419	Sand equivalent (%)	-	-	-
C131	Maximum loss (Los Angeles rattler at 500 revolutions)	40	40	40
California 205-E[d]	Minimum crushed faces (%)	65	65	65
C88	Soundness (five cycles)	-	-	-
D3042	Maximum acid resistance[e]	10	10	10

Note: 1 mm = 0.039 in.

[a]Thickness of coarse aggregate = 76 mm.
[b]Thickness of coarse aggregate = 51-76 mm.
[c]Thickness of coarse aggregate = 25-51 mm.
[d]State of California test method.
[e]Applicable to limestone surface mixes.

It is then mixed with aggregate that contains a minimal amount of water. (With porous aggregates, the emulsified-asphalt content should be increased by a factor of approximately 1.2. Porous aggregates are those that absorb more than 2 percent water by dry weight when tested by using ASTM C127.) The liquid materials are thoroughly mixed, and the workability is noted. The process is repeated by increasing the emulsion and/or water content until satisfactory results are obtained.

Upon completion, the mix is poured onto a 0.841-mm (No. 20) wire-mesh screen funnel and allowed to drain for 30 min. The runoff is collected in a tared can under the funnel, placed in a 110° ± 5°C (230° ± 9°F) oven, and dried to a constant weight. The percentage of runoff is computed as (final weight - tared weight)/batch aggregate weight x 100. The sample is removed from the screen funnel, and the emulsion content is selected by considering the following:

1. Coating—The coating is evaluated by visually examining the air-dried samples;
2. Workability—The mixing operation should be easy to perform;
3. Runoff—No runoff is preferred, but less than 0.5 percent is acceptable; and
4. Job conditions—Such factors as the availability of water, weather conditions, and the mixing process also influence the selection of the type and grade of emulsified asphalt.

Specimen Fabrication

The mix specimen is fabricated at optimum emulsion and moisture content by using a compactive effort similar to that obtainable in the field. Enough mix is poured into a mold to form a specimen that is 101.6 mm (4 in) in diameter by 63.5 mm (2.5 in) high. Preliminary compaction is accomplished by applying approximately 20 tampings at 1723.5 kPa (250 lbf/in^2). Finally, a 178-kN (40 000-lbf) static load is applied by using the double-plunger method. This is currently being changed to 89 kN (20 000 lbf) to minimize aggregate degradation.

Initial Curing and Washoff Test

The washoff test measures the ability of an open-graded mix to withstand rain damage. This test is required only if rain is anticipated shortly after laydown.

The compacted sample, still in the mold, is first cured at a temperature of 22° ± 3°C (73° ± 5°F) for 24 h and then placed on a pedestal and wire screen. About 200 cm^2 of water is poured over the sample, and the washoff is collected in a tared container that is placed under the screen. The mix is allowed to drain for 30 min. The container is dried to a constant weight at a temperature of 110° ± 5°C (230° ± 9°F), and the weight of the residual asphalt washoff is determined as follows: Percentage of washoff = (weight of residual asphalt washoff/weight of specimen aggregate) x 100.

Final Cure and Diametral Modulus Testing

A different sample is cured in a mold for 72 h at 22° ± 3°C (73° ± 5°F) and then vacuum desiccated out of the mold for four days at 10-20 mm (0.4 to 0.8 in) of Hg. The diametral resilient modulus (M_R) test is used to determine the structural contribution of the mix in the pavement (5). The test is performed at 22° and 38°C (73° and 100°F) by using a 0.1-s pulse load applied every 3 s across the diameter of the test specimen. For open mixes, the test is normally performed by using a confining pressure. The horizontal deflection to the applied load is measured by a pair of transducers mounted in a yoke that is clamped to the specimen. M_R is calculated as follows:

$$M_R = [P(\mu + 0.2734)/t\Delta] = 0.6234(P/t\Delta) \quad (1)$$

where

P = dynamic load (lbf),
μ = Poisson's ratio (normally assumed to be 0.35),
t = thickness of the specimen (in), and
Δ = horizontal deflection (in).

The results of this step are not currently used in selecting mix proportions.

U.S. FOREST SERVICE PROCEDURE

Figure 2 summarizes the design procedure for open-graded emulsion mixes used by Region 6 of the U.S. Forest Service (7). The individual steps are described below.

Selection of Aggregate

The aggregate gradation suggested by the Forest Service (7) is given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
25.4	100
12.5	45-70
4.75	0-20
2.0	0-6
0.425	
0.075	0-2

The following weights (8) are suggested for the air-dry samples (1 kg = 2.2 lb):

Nominal Maximum Size of Particle (mm)	Minimum Weight of Sample (kg)
9.5	1
12.5	1
19.0	2
25.4	5
38.0	10

The samples are then tested according to AASHTO T11 and T27, and the results are compared with the specified gradation.

Selection of Emulsion Type

Asphalt emulsion grades CMS-2, CMS-2h, and CMS-2s are normally used for open-graded mixes by the Forest Service. Aggregate characteristics, particularly gradation, are the primary controlling influence on the selection of the type of emulsified asphalt. Grades CMS-2 and CMS-2h are used when aggregate passing the 2-mm (No. 10) sieve is less than 6 percent and that passing the 0.074-mm (No. 200) sieve is less than 2 percent. CMS-2s is used when the surface area increases because of an increase in the percentage of aggregate passing the 2-mm and 0.074-mm sieves.

Selection of Mix Proportion

The emulsion content is determined from the oil-ratio (K_c) test. The following formula is used to estimate the percentage starting content: Beginning emulsion content = (K_c x 1.5) + 3.5. If the oil-ratio equipment is not available, the following table can be used to determine the beginning emulsion content:

Aggregate Absorption (%)	Approximate Emulsion Content (percentage by weight of aggregate)
<1	5.0
1-2	6.0
>2	7.0

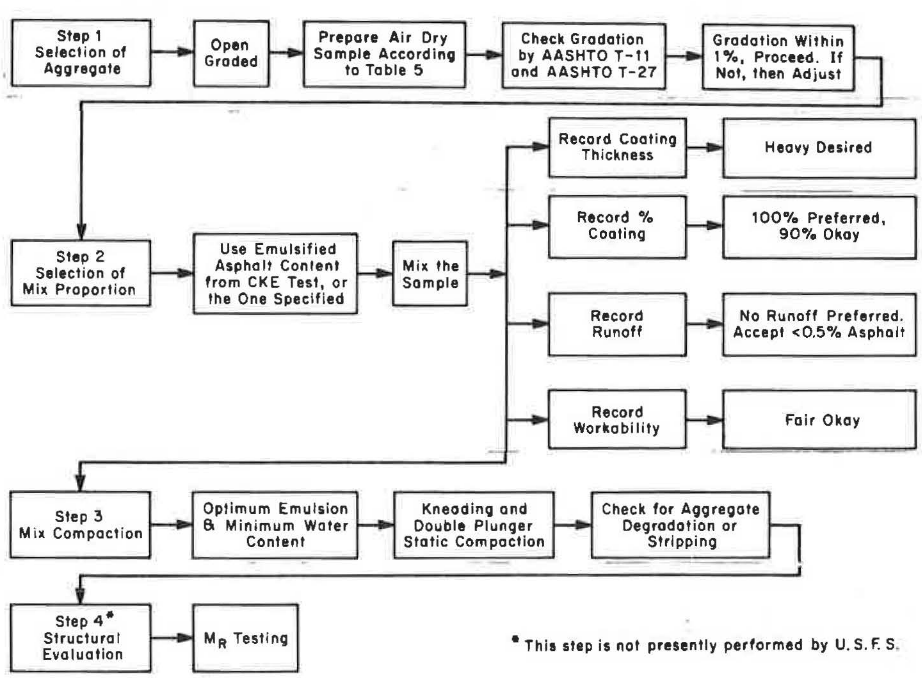
Once the beginning emulsion content is estimated, a number of trial mixes are prepared. The percentage of water and asphalt is varied in each case, and the coating thickness, percentage of coated area, excess fluids, and workability are recorded. The emulsion content and lower and upper limits of the water content are determined as follows:

1. For the minimum acceptable mix, 90 percent of the area is coated by emulsion and the workability is fair. The optimum emulsion content is reached when coating is heavy and the coated area is 100 percent. These evaluations are done visually.
2. The lower limit for moisture content is the hygroscopic moisture of the aggregate. The upper limit is the highest water content at which no appreciable excess fluids are present.

Specimen Fabrication

A 1200-g (2.65-lb) mixture is fabricated at the lower limit of moisture and optimum emulsion content in a mixing bowl. Half of the mix is then placed in a 101.6-mm (4-in) diameter compaction mold and rodded 20 times in the center and 20 times around the edge with a bullet-nosed steel rod. The second half is then added, rodded, and compacted by using a kneading compactor. Approximately 20 tamping blows are applied at 1.7 MPa (250 lbf/in^2) to accomplish preliminary compaction. Final compaction is done by applying 150 tamping blows at 3.4 MPa (500 lbf/in^2) and then applying a leveling load of 56 kN (12 600 lbf) by using the double-plunger method. In the case of unstable material, a static load of 178 kN (40 000 lbf) is applied by using the double-plunger method. Two specimens

Figure 2. Testing schedule for open-graded mixes: U.S. Forest Service procedure.



are prepared, and the dry density is determined after the samples have been oven cured for 24 h at 110° ± 5°C (230° ± 9°F). This value is used only for field compaction control.

Strength Test

No standard strength tests have been adopted by the Forest Service. However, some stable cores have been tested for resilient modulus, from which strength coefficients have been obtained by using the AASHTO Interim Guide (7).

FHWA PROCEDURE

Figure 3 shows the steps involved in the design procedure for open-graded asphalt emulsion mixes used by Region 10 of FHWA. Each of these steps is described below.

Steps Currently in Use

The typical gradations used by FHWA are given in Table 2. Gradings A and B are normally recommended for base courses, whereas grading C is recommended for surface courses. All aggregates should be free of clay, loam, and vegetable matter. The aggregate selected should also meet the quality requirements given. The gradation is checked by carrying out AASHTO tests T27 and T11.

Selection of Emulsified Asphalt

Only cationic asphalt emulsions, grade CMS-2 or CMS-2h, are recommended.

Selection of Mix Proportion

Once it has been determined that the aggregate meets the requirements given above, an oil-ratio test is carried out to determine the beginning emulsion content. The relation used to estimate beginning emulsion content is identical to that used by the U.S. Forest Service.

About 15-20 samples, weighing 500 g (1.10 lb) each, are prepared by thoroughly mixing the emulsion and aggregate with a putty knife. The mixing process begins by adding the beginning emulsion content and testing for harshness. A mix that shows stiffness in the first 15-20 s of mixing is harsh.

Figure 3. Testing schedule for emulsified-asphalt mixes: FHWA procedure.

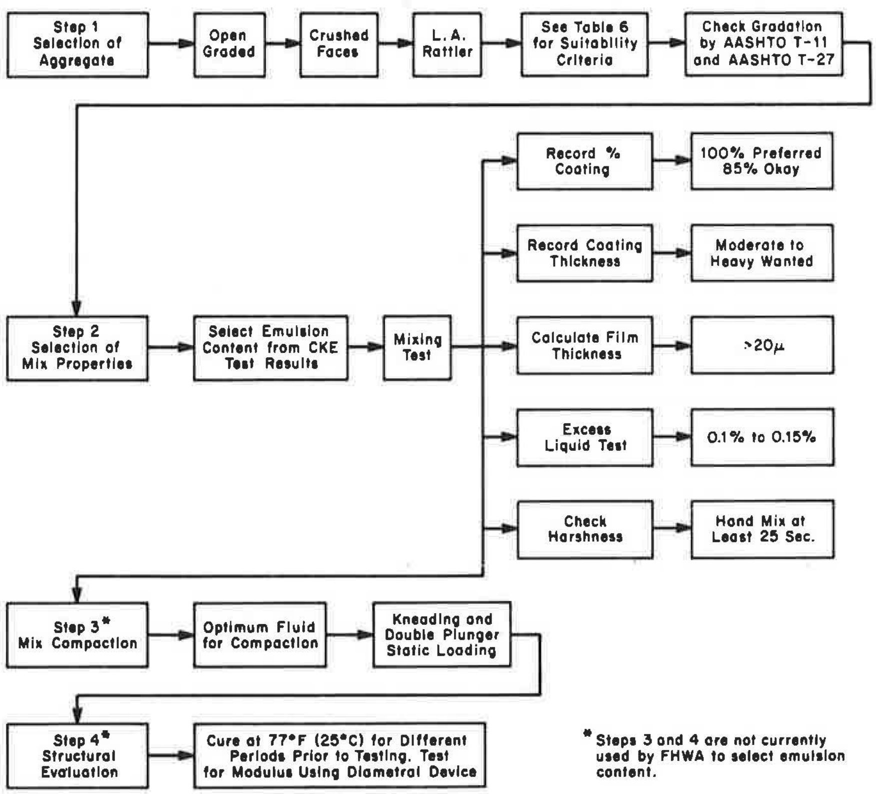


Table 2. Aggregates suitable for emulsified-asphalt mixes: FHWA procedure.

AASHTO Designation	Property	Grading A	Grading B	Grading C
M-92	Gradation (percentage passing)			
	38.0 mm	100		
	24.4 mm		100	
	19.0 mm			100
	2.0 mm	0-7	0-7	0-7
	0.075 mm	0-2	0-2	0-2
T-176	Minimum sand equivalent (%)	45	45	45
T-96	Maximum loss (Los Angeles rattler at 500 revolutions)	35	35	35
California 205-E	Minimum crushed faces (%)	70	70	70
T-104	Sodium sulfate soundness loss on portion retained on 4.75-mm sieve (%)	12	12	12

Acceptable mixes do not become stiff until 30-45 s of mixing.

An acceptable emulsion content is determined by evaluating mix characteristics that must fall within an acceptable range, as follows:

1. Thickness of coating—The coating, which is evaluated visually, must be moderate to heavy.
2. Percentage of coating--The percentage of coating is also evaluated visually and should be within 90-100 percent. The absolute lower limit is 85 percent.
3. Film thickness—Film thickness (in micrometers) is calculated by using the following formula: Film thickness = (48.7 x percentage effective asphalt)/surface area (from centrifuge kerosene equivalent). This should be 20 µm or more where the effective asphalt content is the percentage residual asphalt in the emulsion minus the percentage asphalt retained in the tared pans.
4. Excess liquids—Water is added before emulsion, starting with 1.0 percent and increasing by 1.0 percent increments. The process is continued until a measurable amount of excess liquid can be poured out of the mixture when the beginning emulsion content is used. The amount of excess liquid should be slight: 0.1-0.15 percent.
5. Harshness—The mix should be easy to mix by hand for at least 25 s.

Proposed Steps

The steps described below are proposed, but not currently used, by FHWA to select emulsion or water content.

Specimen Fabrication

The procedure used to fabricate a specimen is similar to that used by the Forest Service; that is, specimens 63.5 mm (2.5 in) in height by 101.6 mm (4 in) in diameter are compacted by using the kneading compactor and double-plunger static compaction. Dry density and free fluids (if any) are recorded.

Mix Cure

The rate at which open-graded emulsions develop strength is determined by testing the samples at 25°C (77°F) for various periods of cure.

Strength or Stiffness Test

A diametral test (5) is being considered for use in evaluating open-graded emulsified-asphalt mixes, but no strength test is actually included in the FHWA procedure.

DIFFERENCES IN MIX PROCEDURES

Table 3 summarizes the three mix-design procedures described above. Differences in the procedures are discussed below.

Mix Evaluation

Coating is determined by observing the emulsion mix after thorough mixing and drying. This is a subjective evaluation, and the results are recorded as a numerical percentage. Each of the agencies discussed above has various recommended coating requirements, ranging from 75 to 90 percent minimum. Factors that affect the degree of coating include the quantity of fines in the aggregate, the mixing effort, the charge on the aggregate surface, moisture, mixing time, emulsion type, and emulsion and water contents.

Curing

Three methods have been used to cure emulsion mixes: air, oven, and vacuum curing.

Air curing has been used most extensively, but its effectiveness is directly dependent on the height of the sample. As the height increases, the time required to reach final curing increases. This can create considerable delay. Currently, two methods are used to achieve curing in the

Table 3. Differences between mix-design procedures for open-graded emulsion mixes.

Design Step	Chevron and Asphalt Institute	U.S. Forest Service	FHWA
Evaluation of aggregate			
Gradation	Three proposed gradations	One gradation	Three possible gradations
Quality	Acid resistance, surface only[a]; Los Angeles rattler; crushed faces	Covered in specifications	Sand equivalent, Los Angeles rattler, sodium sulfate soundness
Type of emulsion	CMS or MS; Chevron selection based on aggregate, rain, and construction conditions	CMS-2 and CMS-2h or CMS-2s, depending on gradation	CMS-2 and CMS-2h
Mix proportion			
Beginning asphalt content	From table relating emulsion content and gradation	CKE test: 1.5 K_c + 3.5 or from table content and absorption	CKE test: 1.5 K_c + 3.5
Mixing-moisture content	Minimum to achieve coating or in situ moisture content	When aggregate darkens	Natural aggregate moisture
Criteria for optimum fluid content	Coating, thickness, workability, percentage runoff	Coating, workability, thickness, percentage coated area, little or no excess fluids	Workability, coating thickness, percentage coated area
Mixing time	2 min hand mixing or 30 s by machine	30 ± 5 s hand mixing	Effective asphalt content at 30-45 s hand mixing
Specimen fabrication			
Compaction	Kneading and double-plunger static loading compaction	Kneading and double-plunger static loading compaction	-
Curing	In mold 24 h at 22°C for washoff test; in mold 72 h at 22° ± 3°C; in vacuum of 10-20 mm Hg four days for M_R test	In oven at 110° ± 5°C for 24 h	
Measurements and calculations	Dry density	Dry density	-
	Mixing-fluids content must be adjusted to minimize fluid exudation	Effective emulsion content	
Mixture testing	Washoff test on air-cured samples Resilient modulus test on air- and vacuum-cured samples	-	-
Evaluation	75-100 percent coating, less than 0.5 percent runoff, good workability, less than 0.5 percent washoff, resilient modulus	Moderate to heavy coating, 90-100 percent coated area, no excess fluids, fair workability	90-100 percent coating, moderate to heavy coating, 20-µm minimum film thickness, 0.1-0.15 percent excess liquids, good workability

Note: t°C = (t°F - 32)/1.8.
[a] Chevron only.

air: (a) leaving the sample to cure in the mold and (b) removing the sample from the mold and placing it in a rubber membrane to cure. Open-graded emulsion mixes may slump unconfined without any preliminary cure.

Oven curing is used by some agencies, but additional research is needed to obtain a suitable oven temperature and duration period. Temperatures above 38°C (100°F) can result in loss and/or redistribution of the residual asphalt, and the sample may slump and fall apart.

Vacuum curing is used by Chevron USA, Inc., for dense mixes and open mixes. A sample fabricated to 63.5 mm (2.5 in) in height by 101.6 mm (4 in) in diameter is initially cured by placing the mold in a horizontal position for 72 h at a temperature of 22° ± 3°C (73° ± 5°F). The specimen is then removed from the mold and vacuum desiccated for four days to achieve the ultimate cured condition.

Compaction

Several methods have been used to compact emulsion mixes.

The most widely used is the kneading compactor. The compaction equipment and the procedure are described in detail in ASTM D1561-65. Test specimens 63.5 mm (2.5 in) in height by 101.6 mm (4 in) in diameter are prepared. To prevent degradation from occurring during compaction, a protective rubber pad is often used (7,9,10).

The Marshall hammer has been used in research at Oregon State University (OSU). The results of the OSU investigations indicate that, in good-quality aggregates, degradation will not take place. The vibratory compactor has also been used at OSU. A preliminary evaluation of the various techniques would suggest that the vibratory hammer produces a sample with the least amount of degradation. Studies completed at OSU (1) also indicate that there are differences in the rate of stiffness development for mixes prepared with Marshall and vibratory techniques.

Design Emulsion Contents

A limited round-robin study has been performed by using the three mix-design procedures discussed in this paper. Table 4 summarizes the results for three crushed basaltic aggregates (Forest Service gradation as given on page 28). The recommended amounts of emulsion are quite consistent, but the water content tends to vary from one agency to another. This could possibly be caused by differences in absorbed moisture at the time of testing or differences in the mix-design procedures.

DISCUSSION OF OPEN-GRADED EMULSION MIXES

Open-graded emulsion mixes have been and will continue to be used. They offer considerable advantages and yet, because of the newness of the materials, their use has also posed some problems. Some of their benefits and limitations are discussed briefly below.

Table 4. Results of round-robin study of mix-design procedures.

Aggregate	Agency	Emulsion Type	Emulsion Content (%)	Water Content (%)
Rivergate basalt	Forest Service	CMS-2	6.7	2.5
	FHWA	CMS-2	7.0	<2.0
	Chevron	CMS-2	5.0-7.0	<2.0
Berry Creek	Forest Service	CMS-2	7.0-7.7	<3.0
	FHWA	CMS-2	6.0	<3.5
	Chevron	CMS-2	5.0	2.0
	OSU (Forest Service method)	CMS-2	6.0	<4.0
Eckman Creek	Forest Service	CMS-2	5.5-6.0	5.5-6.0
	FHWA	CMS-2	7.0	<8.0
	Chevron	CMS-2	6.0	2.0
	OSU (Forest Service method)	CMS-2	6.0	4.0

Benefits

Some of the benefits of open-graded emulsified-asphalt pavements are as follows:

1. Resistance to cracking—Experience has proved these pavements to be highly resistant to cracking even under heavy loads. These pavements have successfully carried logging trucks with gross loads as heavy as 890 kN (200 000 lbf) without distress.
2. Reduced pollution—Dust pollution at the mixing plant is minimized, and air pollution associated with aggregate drying is eliminated.
3. Reduced asphalt oxidation—Because the aggregate and emulsion are mixed cold, severe asphalt oxidation in the mixing process does not occur. The thicker asphalt films also tend to retard oxidation of the asphalt in the pavement.
4. Lower costs—Construction costs tend to be lower because fewer pieces of construction equipment are needed. Because the mixtures are prepared cold, no dryer is needed and there are savings in fuel costs.
5. Energy—With today's awareness of the need to save and conserve energy in all of its forms and the need for more efficient use of the energy we must consume, this construction procedure offers many benefits. In addition to the monetary savings that can be expected, there is also the important consideration of the potential total savings of energy. Substantial amounts of energy can be saved in heating and drying aggregates and heating and maintaining the temperature of liquid asphalt by using open-graded emulsified-asphalt mixtures.

Limitations

The many limitations on the wide use of emulsion mixes can be reduced to three essential points:

1. Emulsion mixes may never have the same versatility with respect to climatic conditions that hot mixes have. However, this should not in itself be a reason for avoiding emulsion mixes.
2. There is no nationally accepted standard laboratory procedure for the design of emulsion mixes. Open-graded emulsion-mix design is based mainly on the spoon and bowl mixing test, and each agency has its own standards that the mix must meet to be acceptable from the point of view of workability, coating thickness, and percentage of aggregate coated. Even if runoff, washoff, and compaction tests are specified to minimize loss of emulsion and to maximize density, no standard strength test is available to the design engineer who faces problems with pavement thickness design. More data on the structural performance of emulsion-mix pavements are needed to determine a standard strength test that reflects the actual behavior of emulsion-mix pavements.
3. Design and construction experience with emulsion mixes is lacking. To overcome this problem, we suggest a preconstruction conference among contractors, agencies, and materials suppliers and the development of a manual of construction practices.

SUMMARY

Although there is no standard mix-design procedure for open-graded emulsion mixes, the methods described in this paper are encouraging. Open-graded emulsified-asphalt pavements designed by these methods have provided enough initial strength to support heavy vehicle loads immediately after construction and are durable enough to perform as well as a hot mix.

The following points have been noted in this study:

1. Mix designs adopted by different agencies are

essentially a trial-and-error process, since a universally acceptable design procedure is still not available.

2. Curing is not as important a consideration in open-graded mixes as in dense mixes, although it will be slower in the cooler climates.

3. Aggregates used in open-graded mixes must be clean, of good quality, uniform in size, and rough in texture. Dirty aggregate causes coating problems, and unsound aggregate causes performance problems.

4. Open-graded emulsion mixes, though they possess little if any unconfined strength, can support gross loads as heavy as 890 kN (200 000 lbf) without significant rutting.

5. Open-graded mixes should not be placed in heavy rain, for this may result in washoff of emulsion from the aggregate. The emulsion must break to be safe from washoff.

Although a number of designs for open-graded emulsion mixes are available, the results in terms of design emulsion and water content are similar. It would be desirable to establish one of the methods discussed in this paper as a standard for others to use.

However, design strength criteria are badly needed. Values used to date have been chosen based on limited experience and engineering judgment. A means of better predicting the effects of curing is needed in the design process. Whatever is done should ensure that laboratory curing conditions compare as much as possible with curing conditions in the field.

REFERENCES

1. R. G. Hicks and others. A Test Procedure to Characterize the Elastic Behavior of Open-Graded Emulsion Mixes. Department of Civil Engineering, Oregon State Univ., June 1977.

2. R. G. Hicks, D. Hatch, and J. Walter. Evaluation of Open-Graded Emulsion Mixes as Road Surfaces. Department of Civil Engineering, Oregon State Univ., March 1978.

3. E. S. Richardson and W. A. Liddle. Experience in the Pacific Northwest with Open-Graded Emulsified Asphalt Pavements. Federal Highway Administration, U.S. Department of Transportation, Implementation Package 74-3, July 1974.

4. E. W. Merten and M. J. Borgfeldt. Cationic Asphalt Emulsions. In Bituminous Materials: Asphalt, Tars, and Pitches (A. J. Holberg, ed.), Vol. 2, Part 1, Interscience Publishers, New York, 1965.

5. R. J. Schmidt. A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes. HRB, Highway Research Record 404, 1972, pp. 22-32.

6. Bitumuls Mix Manual. Chevron USA, Inc., San Francisco, Jan. 1977.

7. R. Williamson. Status Report of Emulsified-Asphalt Pavements in Region 6. Region 6, U.S. Forest Service, Portland, OR, Feb. 1976.

8. Mix Design Procedure for Open-Graded Emulsified-Asphalt Pavement. Region 6, U.S. Forest Service, Portland, OR, 1974.

9. Mix Design Procedure for Open-Graded Emulsified-Asphalt Pavements. Region 10, Federal Highway Administration, U.S. Department of Transportation, June 1976.

10. L. D. Coyne. Design and Construction of Emulsified-Asphalt Open-Graded Mixes and Overlays. Chevron Asphalt Co., San Francisco, Tech. Paper 163, March 1972.

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

Mechanistic Thickness-Design Procedure for Soil-Lime Layers

MARSHALL R. THOMPSON AND JOSE L. FIGUEROA

A mechanistic thickness-design procedure for soil-lime pavement layers is presented. The procedure, which is based on a stress-dependent finite-element computer model called ILLI-PAVE, is limited to pavements constructed of a cured soil-lime layer and a nonstructural surface course (surface treatment or thin asphalt concrete). Design input data are soil-lime strength and modulus, subgrade resilient modulus, and estimated traffic. The procedure assumes that the soil-lime mixture is capable of developing significant increase in strength (relative to the strength of the natural soil) and that quality field construction and control are achieved.

Thompson (1) has considered the use of soil-lime mixtures for the construction of low-volume roads. The topics reviewed by Thompson include mixture properties and characteristics, soil-lime pavement layers (load-deflection behavior and field performance) and thickness-design concepts. Thompson concluded that "a more mechanistic and rational design procedure would be appropriate for designing pavements containing lime-treated soils" (1).

A repeated-loading study of soil-lime layers by Suddath and Thompson (2) indicated that a stress-dependent finite-element computer model called ILLI-PAVE adequately predicted load-deflection behavior. The study demonstrated that high load-carrying capacities can be developed by a soil-lime structural paving layer.

A simple thickness-design procedure for soil-lime layers has been developed based on the ILLI-PAVE model. The procedure is limited to pavements constructed of a cured soil-lime layer and a nonstructural surface course (surface treatment or thin asphalt concrete).

DEVELOPMENT OF DESIGN PROCEDURE

General Observations

Normally, only soil-lime mixtures that develop significant strength increases—mixtures that Thompson has called "lime reactive" (3)—are used in constructing structural paving layers. These mixtures have compressive and shear strength, and the factor that controls layer thickness is the flexural stress at the bottom of the soil-lime layer. The design procedure is based on the concept of a limiting stress ratio (S = flexural stress/flexural strength), which accounts for mixture fatigue behavior.

Description of ILLI-PAVE

ILLI-PAVE, a stress-dependent finite-element computer program, is described elsewhere (4). The program was developed based on the early work of Duncan, Monismith,