Emulsion Mix Design Methods: An Overview

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A general overview is presented of several methods of emulsion mix design currently being used either experimentally or on an operating basis. Most of the methods make use of either Hveem or Marshall equipment for molding and testing specimens of the mixture. In most cases, modifications have been made to standard procedures to accommodate the special requirements of emulsified-asphalt mixes. Although laboratory procedures may differ in each case, the test methods must generally address the following problems: (a) the amount of mixing water required as an aid to proper coating and workability, (b) the type and grade of emulsified asphalt to be used, (c) the amount of emulsified asphalt required for optimum results, (d) the curing rate of specific mixes, (e) the water sensitivity of the mixture, (f) some measure of strength or load-carrying capability, (g) the tendency of the emulsified asphalt to drain off the aggregate (in open-graded mixes) before a sufficient thickness has adhered to the aggregate surface, (h) the optimum mixing time to ensure proper coating but not to the extent that the emulsified asphalt is stripped from the aggregate, and (i) a laboratory compactive effort that will produce a density comparable to that obtained in the field. Some of the problems associated with emulsified-asphalt mix design are examined, and the known test procedures used to achieve the objectives of an acceptable mix-design system are summarized.

In recent years, the use of emulsified-asphalt mixes in road construction has gained wide acceptance. Engineers have learned that mixes of this type can be designed and constructed so as to offer performance characteristics comparable to those of hot plant mixes. In addition to the obvious energy savings, the use of emulsified asphalt provides significant economic advantages because it permits a wide latitude in the selection of aggregate gradations and quality standards (1).

Because of environmental and energy considerations, the U.S. Environmental Protection Agency, the Federal Energy Administration, and the Federal Highway Administration (FHWA) have encouraged greater use of emulsified asphalt. Such federal action has been partly responsible for a gradual increase in the use of emulsion. In 1978, for the first year in history, the consumption of emulsions exceeded that of cutback asphalt. Of the 32 million Mg (35 million tons) of asphalt used in 1978, about 8.4 percent was asphalt emulsion and 7.3 percent was cutback asphalt.

Much of the early history of emulsion-aggregate mixes involved the in situ stabilization of sands and local fine aggregates. But the development of mobile, highly efficient mixing plants for emulsified-asphalt mixes (EAMs) now permits a much broader range of mixture types. Furthermore, these plants can be set up in remote areas where the cost of hot plant mixes would be economically prohibitive. Experience with EAMs in logging operations conducted by the U.S. Forest Service has shown that these mixes can support loads of approximately 889 kN (200 000 lbf) without undue distress (2).

In 1978, the Asphalt Institute, under contract to the Asphalt Emulsion Manufacturers Association and FHWA, produced a publication entitled A Basic Asphalt Emulsion Manual (1). As an adjunct to the main objective of this effort, data on various EAM design methods were also assembled. Eleven different methods were discovered during the collection of material for the manual. FHWA published all 11 procedures as Volume 2 of their version of the manual (3). The Asphalt Institute included only 2 procedures as part of its basic manual, one based on the Hveem procedure and the other on the Marshall procedure (1).

In the latter part of 1979, the Asphalt Institute began two comprehensive studies of EAM design procedures. The first is an in-house project funded by the Asphalt Institute. The following specific tasks are included:

1. Investigate the use of a range of emulsion contents for preparing trial mix specimens based on residual asphalt in the emulsion for various gradings.
2. Investigate the use of existing coating tests or modifications of these tests for selecting the type of emulsified asphalt and for determining water content for mixing.
3. Investigate determinations of air-void contents and voids in mineral aggregate of compacted EAMs and possible use of these properties as criteria for mix design.
4. Investigate retained Marshall stability of EAMs after various conditions of exposure to water or moisture vapor.
5. Prepare a draft of the Marshall mix-design procedures for EAMs.

The primary objective of the second study, which is being funded by the National Cooperative Highway Research Program, is to verify and/or modify the EAM design methods of the Asphalt Institute and the University of Illinois. The applicability of these mix-design procedures and criteria to prediction of the field performance of base- and surface-course mixtures will be determined. The base- and surface-course mixtures studied will involve both slow- and medium-setting emulsions as well as various types, gradings, and qualities of aggregate. The evaluation will also consider the relations between the properties of the mixtures as determined in the laboratory and the rate of attainment of these properties in the field under different environmental conditions.

Reports on both studies will be published when the research is completed.

GENERAL CONSIDERATIONS OF EAM DESIGN

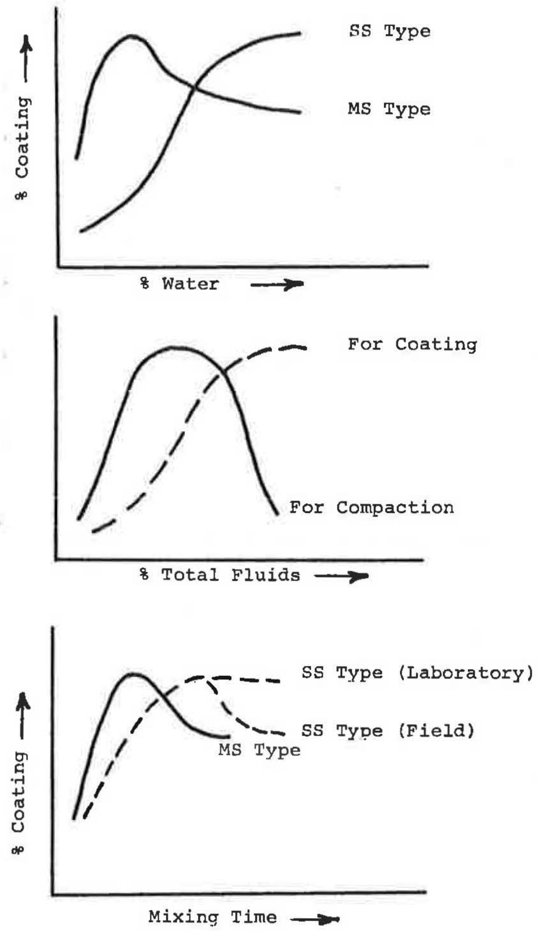
The development of a standardized procedure for the design of mixtures containing emulsified asphalt and aggregate presents a significant challenge to the highway industry. Although considerable research has been done in this area, unanimous agreement has not been reached and much research remains to be done (4).

Standard design methods for hot plant mixes are readily available, and technologists are in good agreement as to the validity of test results obtained and their specific application. The design of emulsion mixes is considerably more complex because of the difficulty of duplicating the field curing of EAMs in the laboratory. In mix-design procedures for hot plant mixes, ultimate stability and related mix properties are reached at or near the time when the test specimens are formed. In emulsion mixes, ultimate stability and related properties are not reached until virtually all water in the mixture has evaporated. Under field conditions, this evaporation may require several months, even as much as two years.

To measure the test properties of EAMs, it is necessary to devise some type of laboratory curing procedure. The degree and rate of curing should bear a known relationship to the curing of the mixture in the field. Laboratory methods used to remove the water and the rate of water removal can have a significant effect on the test values obtained. Too-rapid evaporation of water by oven drying may be unrealistic and diminish the value of the test properties (5).

Some of the test procedures involve air drying, whereas others involve oven drying (curing). In some cases, mixtures are left in the forming mold for curing so that air does not penetrate the interior of the specimen. Whether the mixture is open graded or dense graded will also affect the specific approach used and the type of data needed. Thus, the interpretation of laboratory test results and their correlation with field performance is not always clear and direct.

Figure 1. EAM characteristics.



Some of the general aspects of the coating and mixing of EAMs are shown in Figure 1. The figure is conceptual in nature; i.e., it is not based on specific laboratory test data. It can be seen that the percentage of water, percentage of total fluids, and mixing time are critical considerations with respect to coating and compaction (6).

Irrespective of the approach or the type of test equipment used in emulsion mix design, certain basic questions must be answered by the procedure:

1. What type and grade of asphalt emulsion will be most compatible with the aggregate in question?
2. What aggregate type and gradation will best fit the traffic and environmental requirements?
3. How much mixing water must be added to achieve the desired degree of coating and workability in the mixture?
4. What percentage of emulsion must be used to achieve optimum mixing conditions and provide a sufficient coating of residual asphalt on the aggregate particles?
5. What strength level or load-carrying capacity will the mixture produce under optimum conditions?
6. Will the mixture be water sensitive (subject to stripping) if adverse moisture conditions are present?
7. Will the addition of a small quantity of mineral filler or portland cement be necessary to develop early strength or to prevent runoff of the emulsion, particularly with open-graded mixes?
8. How should the mixture be "laboratory cured" in order to duplicate field curing conditions?
9. What relationship will the laboratory test data have to the field performance of the mixture? Can probable success be predicted with a reasonable degree of assurance, based on the test data?

Standards of the American Society for Testing and Materials describe 16 different types of emulsified asphalt. Each is designed for a specific function, although some grades can be used for multiple purposes. For emulsion-aggregate mixes, it is probable that a medium-setting emulsion would be selected for an open-graded mix and either a medium- or slow-setting emulsion for dense-graded mixes. It is unlikely that a rapid-setting emulsion would be used because it tends to break before the aggregate is properly coated and the mixture spread. The choice between anionic and cationic emulsion depends largely on the type of aggregate involved. The specific grade is determined by laboratory tests that include a visual inspection of the coating achieved by one or more different grades of emulsion. The aggregate gradation has a significant effect on the selection of the grade of emulsion to be used.

Emulsion-aggregate mixes offer a wider choice of aggregate gradations than do hot plant mixes with asphalt cement. Although the use of "dirty" aggregate is not recommended, certain types of emulsified asphalts are able to provide a reasonably good coating on aggregates that would not be used in hot-plant-mix operations. Emulsion used for this purpose normally contains a small percentage of solvent. As a general rule, an aggregate could be considered for EAMs if (a) it has less than 20 percent passing the 0.074-mm (No. 200) sieve, (b) it has a sand equivalent of 25 or more, and (c) it has a plasticity index that, multiplied by the percentage passing the 0.074-mm sieve, does not exceed 72. Very dense-graded aggregates may present a special problem in that a sufficient amount of fluids (emulsion plus mixing water) cannot be incorporated because of limited void space (6).

In virtually all EAMs, it is necessary that some percentage of mixing water be added to the aggregate to facilitate coating and workability of the mixture. This is largely a trial-and-error proposition. The amount of mixing water must be sufficient to aid in good distribution of the emulsion over the aggregate surface, yet water should not be used to the extent that the emulsion will drain from the aggregate particles (7). Complete asphalt coating is not necessarily required in order to produce a satisfactory mix. In a condition known as "graybacks", part of the aggregate surface may appear to be uncoated and yet the mix will be satisfactory in the field.

The desired percentage of residual asphalt is the major factor in determining the amount of emulsion to use. It must be remembered that the emulsion contains about one-third water, which is lost in the curing process. The required amount of residual asphalt will be about the same as the amount of asphalt cement required for a hot plant mix. Factors such as void content, voids filled with asphalt, degree of aggregate coating, stability, and stiffness modulus must be taken into account in arriving at the optimum emulsion content.

The asphalt mixture must possess sufficient stability or resistance to deformation to support anticipated traffic loads without cracking, rutting, or distorting. In many EAMs, stability continues to increase over time as water evaporates. The mix-design procedure must be able to measure initial and long-range stability. Furthermore, a correlation must be made between laboratory design and field performance requirements.

The test procedure must provide some indication of the water sensitivity of the EAM. If there is an indication of stripping or hydrophilic tendencies, it may be desirable to incorporate an antistrip additive to the emulsion. An unrealistic laboratory curing procedure could greatly distort the measurement of stripping.

It has been found that the addition of a small quantity of mineral filler or portland cement may improve early strength and make the mixture more resistant to freeze-thaw cycles. The addition of cement may also aid in preventing excessive runoff in certain types of EAMs. As a general rule, the maximum amount of cement or filler should not exceed a ratio of about one part to five parts of emulsion by weight (7).

SUMMARY OF KNOWN MIX-DESIGN METHODS

For any test measurement to have full value, it must bear a known relationship to the same value of the mixture in the field. This means that the mixing, compaction, and curing methods used in the laboratory must provide test specimens that are very similar to the same mixture in the field and there must be a predictable relationship between the properties in the laboratory and those in the field. Several different approaches are currently being used to provide some of these answers.

The following summaries of emulsion-mix-design procedures are based on Volume 2 of A Basic Asphalt Emulsion Manual (3) as published by FHWA. Complete details of each procedure are provided in that publication.

Asphalt Institute Method

The Asphalt Institute method covers the selection, proportioning, and testing of aggregates, additives, and emulsified asphalt for mixes to be used in pavement construction. The procedure is a combination of test methods of the California Division of Highways as well as procedures developed within the Asphalt Institute. The major steps involved in the Asphalt Institute procedure are shown in Figure 2. The centrifuge kerosene equivalent (CKE) test is used in estimating the emulsified-asphalt contents for trial mixes of aggregates (other than open graded).

The percentage of emulsified asphalt by weight will generally be in the range of 5-10 percent for dense-graded mixes, 4.5-8 percent for fine-aggregate mixes, 4.5-6.5 percent for open-graded coarse mixes, 5.0-7.0 percent for open-graded medium mixes, and 6.0-8.0 percent for open-graded fine mixes. Mixing by either spoon and bowl or mechanical means is done to determine the coating, workability, and runoff (open-graded mixes only) of the trial mixture. The optimum fluid content (mixing water plus emulsified asphalt) for compaction and test-specimen fabrication is determined by a light kneading compaction followed by application of a double-plunger static load.

The strength of emulsified-asphalt mixes is measured by running a final modulus at a temperature of 23° ± 1.7°C (73° ± 3°F) after a total of three days of cure in the mold plus four days of vacuum desiccation. These data are used in conjunction with certain project variables (traffic, regional temperature, and curing conditions) and other mix properties (volume percentage of asphalt residue and air voids) in determining the pavement thickness requirements.

The strength of base and temporary surface mixes (other than open graded) is evaluated before and after vacuum saturation. Base and temporary surface mixes are tested at 23° ± 3°C (73° ± 5°F) for resistance (R-value) and cohesion (C-value). Surface mixes are tested at 60° ± 3°C (140° ± 5°F) for their stabilometer S-value and cohesiometer C-value.

If rain is a possibility on a project within a short period after laydown, open-graded mixes are evaluated for damage by surface water. Under favorable curing conditions, after 24 h, damage from washoff as a result of rainfall is generally not a problem. Non-open-graded mixes that are used in the base course or as a temporary wearing surface are evaluated for early strength and fully cured strength after vacuum saturation.

The items of test data recommended for inclusion in a report on EAM design are given in Table 1.

U.S. Forest Service Method

Dense-Graded Mix

The method used by the U.S. Forest Service to determine the proportions of dense-graded aggregate, emulsified asphalt, and water that will yield a workable paving mixture uses the CKE test, mixing tests, and split-tension tests on specimens compacted with a kneading compactor. The method, including preparation and preliminary tests, normally requires about 48 person-h over a period of 13-15 workdays.

The amount of added water for mixing is determined by adding to the first 500-g aggregate sample the minimum amount of water required to uniformly darken the aggregate. The aggregate is stirred until the water is evenly distributed. The emulsified asphalt is then added and mixed by hand for 30 ± 5 s. The workability of the mixture is then recorded as good, fair, or poor. After curing overnight, the asphalt coating is recorded as thin, moderate, or heavy, and an estimate is made of the percentage of aggregate area coated. Several 500-g batches are made in this way by using a constant emulsion content and varying the water content by 1 percent for each batch. These mixing tests are continued until the minimum moisture content at which the mix has at least fair workability, 90 percent coated area, and a moderately heavy to heavy coating is found. A total of eight specimens are prepared with the optimum fluid content. The specimens are cured by drying in an oven for 24 h at 49° ± 1°C (120° ± 1.8°F).

Half of the specimens are tested in a dry condition and half after 24-h water immersion by using the split tension test. The test data are plotted on four graphs: (a) dry tensile strength versus emulsion content, (b) wet tensile strength versus emulsion content, (c) index of retained strength versus emulsion content, and (d) dry density versus emulsion content.

The report of the laboratory test results includes the following information: gradation, aggregate specific gravity, emulsion type, percentage emulsion content by dry weight of aggregate, lower-limit percentage moisture content, upper-limit percentage moisture content, maximum dry density, and minimum temperature for 90 percent coating.

Open-Graded Mix

The method used by the U.S. Forest Service to determine the proportions of open-graded aggregate, emulsified asphalt, and water that will yield a workable paving mixture involves making several trial mixes with varying water and emulsion contents and comparing the characteristics of the mixes. Several trial batches are made for visual inspection. The starting emulsion content may be determined from the CKE test. If the equipment for this procedure is not available, the starting emulsion content can be determined as follows: If the absorption of the aggregate is 1 percent or less, mix the first batch with 5 percent emulsion. If the absorption is 1-2 percent, start with 6 percent emulsion. Start with 7 percent emulsion when the absorption is greater than 2 percent. The starting point for mixing water is determined by adding the minimum amount of water required to darken the oven-dry aggregate. Several batches will be made by holding the emulsion content constant and varying the water content by 1 percent intervals.

The optimum emulsion content and upper and lower limits for moisture content are determined as follows: The minimum acceptable mix must have a moderately thick coating, 90 percent coated area, and fair workability over a range of at least 1 percent moisture. The optimum emulsion content is reached when the coating is heavy, the coated area is 100 percent, and little or no excess fluid is present.

The density of the emulsion-aggregate mixture is determined by preparing a test specimen 102 mm (4 in) in diameter and 64 mm (2.5 in) high by using the kneading compactor.

The report of the laboratory test results includes the same items of information reported for Forest Service dense-graded mixes.

Chevron Method

The Chevron method covers the selection, proportioning, and testing of aggregate, additive, and emulsified asphalt in emulsion mixes. This design procedure is broken into the following parts:

1. Selection of aggregate;
2. Selection of type of emulsified asphalt;
3. Selection of mix proportions;
4. Specimen fabrication;
5. Mix curing;
6. Moisture exposure, including (a) washoff and (b) vacuum saturation;
7. Strength tests, including (a) resilient modulus, (b) resistance R-value, (c) stabilometer S-value, and (d) cohesiometer test;
8. Design criteria; and;
9. Testing schedule.

Figure 2. Testing schedule for EAMs.

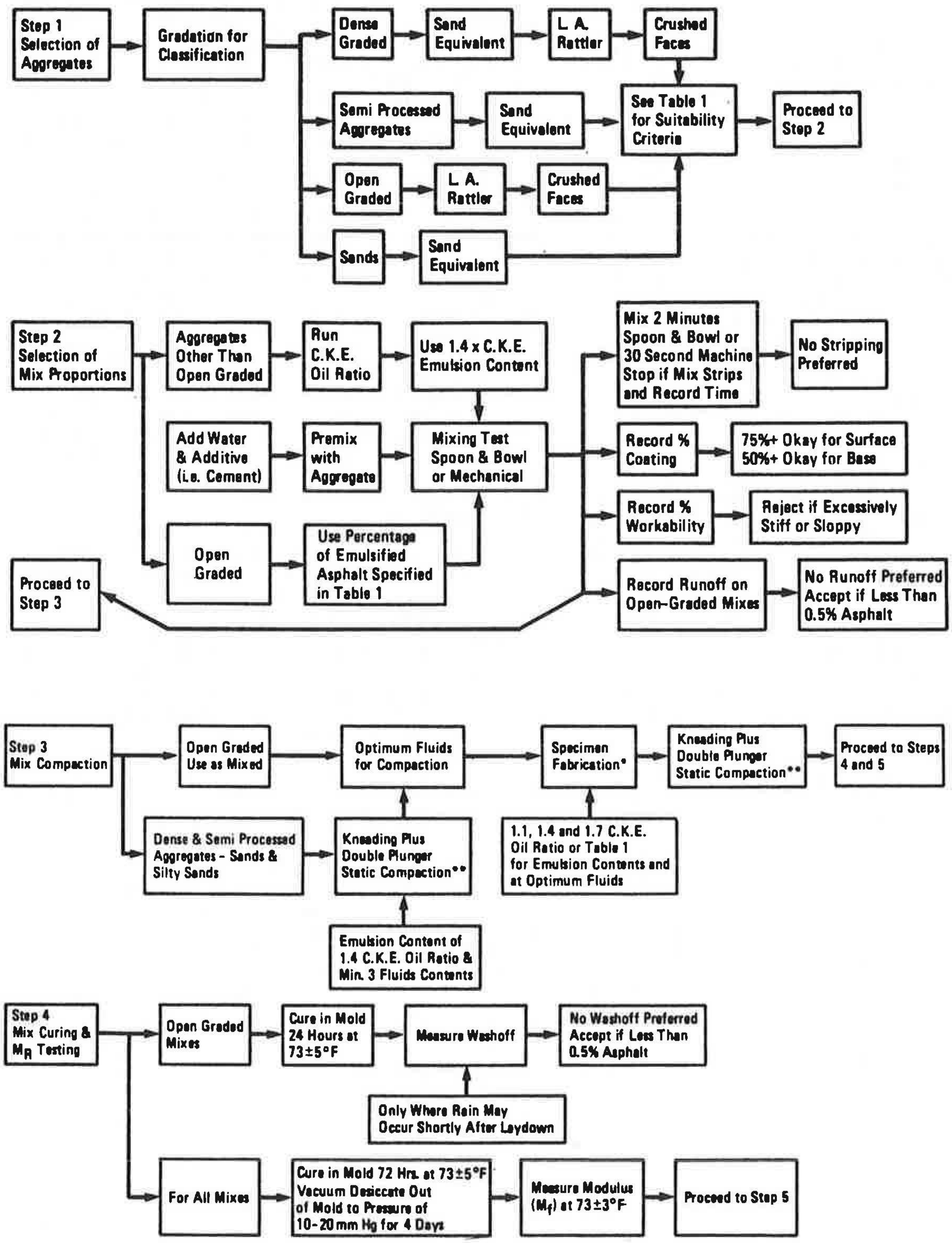
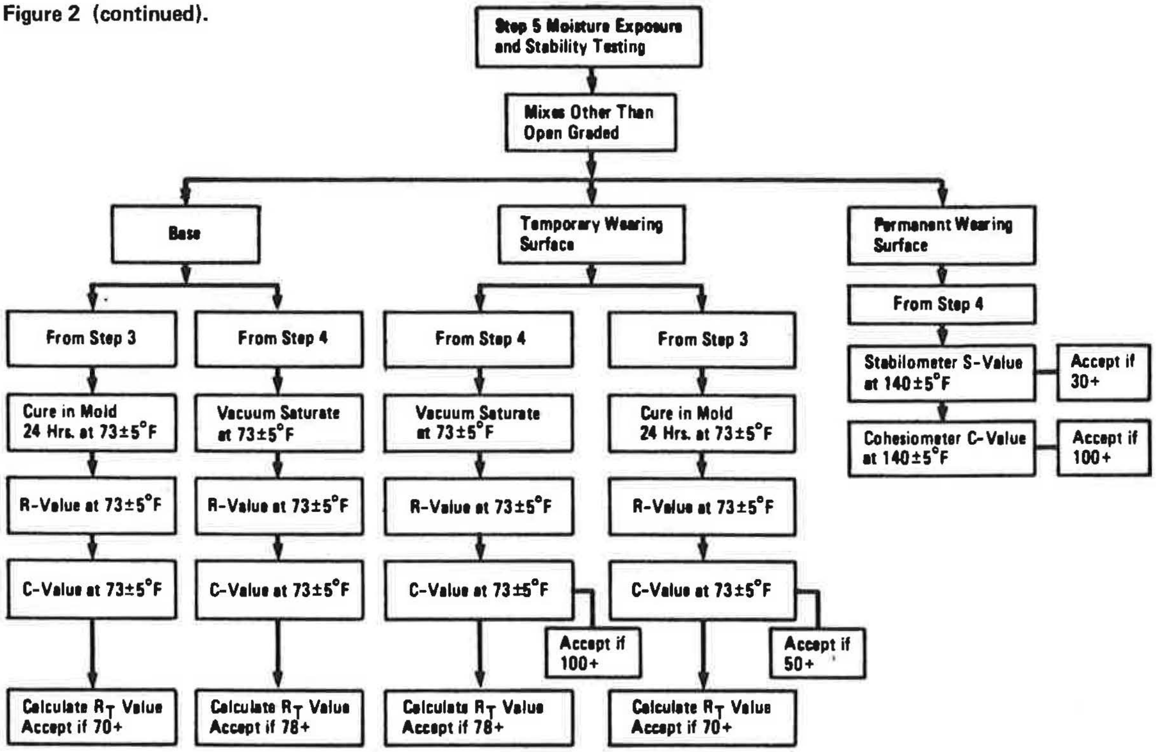


Figure 2 (continued).



*Two specimens prepared at each emulsified asphalt content for all mixes.
**Includes 10-50 blows (250psi) kneading and up to 40,000 lb. double plunger.

Note: t°F = (t°C ÷ 0.55) + 32.

Table 1. Test data recommended for inclusion in Asphalt Institute report on an EAM design.

Category	Data Item to Be Recorded: All Mixes	Open-Graded Mixes Only	Not Applicable to Open-Graded Mixes
Aggregate	Gradation Sand equivalent (%) Los Angeles abrasion loss (%) Percentage crushed particles As-received moisture content (%)		CKE oil ratio (%)
Mixture[a]	Compacted mix density[b] (kg/m³) Asphalt coating (%) Resilient modulus M_R (kPa) Moisture pickup by vacuum soak (%)	Asphalt runoff (%) Asphalt washoff (%)	Resistance R-value Cohesiometer C-value R_t-value Stabilometer S-value Volume of air V_a Volume of asphalt V_b
Mix design	Emulsified asphalt Type Content (%) Residual asphalt content (%) Minimum aggregate pre-mix water content (%) Optimum fluid content for compaction (%)		

[a]Test values by type of mix (dense or open graded) and paving use (base or surface) are reported for each type and content of emulsified asphalt selected for mix design.
[b]Dry vacuum desiccated.

For dense-graded mixes, the starting emulsified-asphalt content is based on the CKE test; for open-graded mixes, the starting emulsion content is selected from a table that is provided with the outline of the test procedure.

Specimens are fabricated at optimum moisture by using a compactive effort similar to that obtainable under field compaction—a light kneading compaction that is followed by a double-plunger static load of 178 kN (40 000 lbf). The mixing fluids for open-graded mixes are assumed to be at optimum for compaction.

The rate at which emulsified-asphalt mixes cure or develop tensile strength is important. A number of factors, including aggregate gradation, type and amount of emulsion, type and amount of additive, and construction and climatic conditions, must be assessed by the engineer in determining the rate of development of tensile strength. To assist the design engineer, strength measurements are made at two curing conditions. The emulsified-asphalt mix is also tested after vacuum saturation.

One of the two specimens fabricated at each asphalt content is cured by placing the mold in a horizontal position

Table 2. Recommended test results and design criteria for Chevron method.

Test Method	Base or Temporary Surface		Wearing Surface	
	Dense-Graded	Open-Graded	Dense-Graded	Open-Graded
Minimum coating (%)	50	50	75	75
Maximum runoff (percentage residual asphalt)	NA	0.5	NA	0.5
Maximum washoff (percentage residual asphalt)	NA	0.5	NA	0.5
Maximum combined runoff and washoff (%)	NA	0.5	NA	0.5
Minimum resistance R-value at 23° ± 3°C				
Initial cure[a]	70	NA	NA	NA
Final cure[b] plus water soak[c]	78	NA	NA	NA
Minimum stabilometer S-value at 60° ± 3°C, final cure[b]	NA	NA	30	NA
Minimum cohesiometer C-value at 23° ± 3°C				
Initial cure[a]	50[d]	NA	NA	NA
Final cure[b] plus water soak[c]	100[d]	NA	NA	NA
At 60° ± 3°C, final cure[b]	NA	NA	100	NA

Note: t°C = (t°F - 32)/1.8.
NA = not applicable.
[a]Cured in the mold for 24 h at 23° ± 3°C.
[b]Cured in the mold for 72 h at 23° ± 3°C plus four days vacuum desiccation at 10-20 mm Hg.
[c]Vacuum saturation at 100 mm Hg.
[d]Applicable to temporary wearing surface only.

for a total of 24 h at a temperature of 23° ± 3°C (73° ± 5°F).

The other specimen is removed from the mold and vacuum saturated for 1 h. This simulates the effect of prolonged exposure to subsurface water on other than open-graded base and permanent wearing surfaces. The ability of the open-graded mix to withstand rain damage is measured by a washoff test.

Resilient modulus (M_R), resistance R-value, and stabilometer S-value are determined on the compacted mixture. M_R is used to measure elastic response and to determine the structural contribution of the mix in the pavement section. The R-value is used to measure the stability or bearing capacity of other than open-graded mixes at a test temperature of 23° ± 3°C (73° ± 5°F). The test is also performed on vacuum-saturated specimens. The S-value is used to measure the stability or bearing capacity of compacted, fully cured, permanent surface mixes other than open-graded. The cohesiometer is used to measure the cohesive resistance or tensile stength of the compacted mixture.

Table 2 provides a summary of recommended test results and design criteria.

FHWA Region 10 Method

Dense-Graded Mix

The FHWA Region 10 procedure for dense-graded mix describes a method of determining the amount of emulsified asphalt to be combined with dense-graded aggregate to produce emulsified-asphalt pavement.

The CKE test is used to determine the "oil ratio", which is multiplied by 1.6 to establish the value for beginning emulsion content. Trial batches of 500 g each are made by holding the emulsion content constant and varying the water content by increments of 1 percent. About 3 percent water is normally used as a starting point. Test specimens are prepared by using a kneading compactor.

Any one of three curing methods can be used, but all involve an air environment at 23°C (73°F). Each method involves a different time period for curing the specimens. The cured specimens are tested for resilient modulus. One of the curing procedures also includes stabilometer and cohesiometer testing. Experimental work is under way to broaden the scope of this test to include M_R measurements after some form of freeze-thaw cycles.

Open-Graded Mix

The FHWA mix-design procedure for open-graded emulsified-asphalt paving mixes was developed for use on projects in Region 10 (Idaho, Oregon, and Washington) and has been used extensively on projects in that area. The procedure describes a method of determining the amount of emulsified asphalt to be used in producing an open-graded mixture by using CMS-2. The beginning emulsion content is determined by the CKE test with appropriate correction for aggregate specific gravity. A determination is then made of the percentage moisture contained in the aggregate. The calculated beginning emulsion content is used with a 500-g aggregate sample. The emulsion and aggregate are mixed for 30-45 s, and the harshness of the mix is observed. A harsh mix will become stiff in the first 15-20 s of mixing, whereas acceptable mixes will not become harsh until they have been mixed for 30-45 s. Any excess liquids that drain from the aggregate must be retained and the weight recorded for later evaluation. The mix should be surface dried, usually with the aid of a fan, after which it is spread in a thin layer and evaluated for the following factors:

1. Thickness of coating, which is evaluated visually and recorded as either thin, moderate, or heavy (T, M, or H);
2. Percentage of particle surface coated, also evaluated visually and recorded; and
3. Any observation that might later be of interest (e.g., an odd smell).

More trial batches are then made by holding the emulsion content constant and increasing the water content by increments of 1 percent. This procedure is continued until a measurable amount of excess liquids can be poured from the mixture into a tared pan. More batches are then mixed at 1 percent above and below the beginning emulsion content. Effective asphalt content is the percentage of residual asphalt in the emulsion minus the percentage of asphalt retained in the tared pans. The film thickness of the asphalt coating (in micrometers) is calculated by using the following formula:

$$\text{Film thickness} = (48.7 \times \text{percentage effective asphalt}) \div \text{surface area (from CKE)} \quad (1)$$

Evaluation of recorded data from the mixing trials will include the following values:

Property	Value
Coating	
Percentage	90-100 percent, absolute lower limit of 85 percent
Thickness	Moderate to heavy
Film thickness	> 20 μm
Excess liquids	Slight amount, 0.1-0.15 percent
Harshness	25 s hand mixing before mix becomes stiff

Armak Method

The Armak Company method of emulsified mix design is a modification of the standard Marshall test procedure, ASTM D1559. Aggregates used in this procedure are dried at room temperature to approximately 1 percent of natural moisture. All aggregate must pass the 12.5-mm (0.5-in) sieve. Mixing and compacting are performed at room temperature. The required amount of additional mixing water is determined by AASHTO method T99. Mixes are usually made from +3 percent to -1 percent of optimum moisture with varying emulsion contents. Normally, five sets of specimens are made and are treated as follows:

1. One set of specimens is tested at room temperature immediately after compaction.
2. A second set of specimens is cured for 24 h at room temperature and then tested at 38°C (100°F).
3. A third set of specimens is cured for 24 h at room temperature and then immersed in a water bath at 38°C for 2 h. These specimens are surface dried with an absorbent material and tested at 38°C for base course and 60°C (140°F) for surface course.
4. A fourth set of specimens is cured for 72 h at room temperature and then tested at 38°C for base course and 60°C for surface course.
5. A fifth set of specimens is cured for 72 h and then immersed in a water bath at 38°C for 2 h. The specimens are surface dried with an absorbent material and tested at 38°C for base course and 60°C for surface course.

McConnaughay Method

K.E. McConnaughay, Inc., of Lafayette, Indiana, has two mix-design procedures for emulsified-asphalt mixes, one for hot mixes and one for cold mixes. With each of these, either the Hveem procedure (ASTM D1560 and D1561) or the Marshall procedure (ASTM D1559) can be used, with the following modifications:

1. Hot mixes--(a) Use ASTM D244, residue by distillation, to determine residue content of the emulsion to be used; (b) weigh the required amount of emulsion on the cold aggregate; (c) mix the emulsion and aggregate and heat on a hot plate with periodic hand mixing at 121°C (250°F); (d) compact the bituminous mixture at 110°C (230°F) in accordance with the design procedure used; and (e) test as prescribed in method used.
2. Cold mixes--(a) Determine the proper emulsion that will provide for satisfactory coating and water resistance by using ASTM D244 coating ability and water resistance and following the alternative provided by note 22 (jobsite aggregate shall be used); (b) determine the residue content of the emulsion to be used by ASTM D244, residue by distillation; (c) determine moisture content of the jobsite aggregate; (d) weigh the required amount of emulsion into the cold, wet aggregate and mix thoroughly; (e) compact the cold emulsion-aggregate mixture in accordance with the design procedure selected, except that compaction is done cold (note that, if the moisture is excessive, it may be necessary to aerate the mixture before compaction); (f) remove the base plate and paper discs and place the mold that contains the compacted specimen on a perforated shelf in a forced-draft oven at 60°C (140°F) for 48 h of curing; (g) after removal from the oven and while the specimen is still at 60°C, apply a static load of 178 kN (40 000 lbf); and (h) test as prescribed in the method used.

Arizona Method

The Arizona Department of Transportation procedure is designed for the testing of specimens made from asphalt emulsions mixed with granular soils. The granular soils to be evaluated are essentially noncohesive, have less than 15 percent passing the 0.074-mm (No. 200) sieve, and have a sand-equivalent value greater than 25. The evaluation is made from test results obtained from specimens formed by use of the Texas Transportation Institute (TTI) compactor and tested by using the Hveem stabilometer and cohesiometer.

The amount of mixing water used should be just sufficient to darken the aggregate. The CKE procedure is used to determine the beginning amount of emulsion. At least three emulsion contents should be used in making test specimens. The emulsion content should be 1.1, 1.3, and 1.5 times the oil ratio obtained in the CKE test. Both the quantity of prewetting water and emulsion content are expressed as a percentage of the dry aggregate weight. Each batch of mixed material should provide a sufficient quantity for three specimens of about 1100 g each plus at least 100 g for determination of total moisture content at the time of compaction.

The TTI compactor is used for molding test specimens. Specimens are molded at ambient temperature. The compaction procedure involves rodding the specimen with a 9.5-mm (0.375-in) diameter bar (mold charged in two layers) followed by compaction with an initial starting foot pressure of 1724 kPa (250 lbf/in²). Initial compaction is continued until the foot penetrates the sample to about 3 mm (0.125 in), which usually requires 10-50 tamps. After initial compaction at 1724 kPa, the foot pressure is changed to 3447 kPa (500 lbf/in²) for 150 tamps. If the material cannot withstand the initial compaction stresses, a double-plunger compaction procedure is used with a load of 178 kN (40 000 lbf) held for 2 min. The specimens are cured in the mold at 25°C (77°F) for three days, after which a set of three specimens can be tested directly by using the stabilometer or, in some cases, undergo a saturation procedure before testing. Vacuum saturation may be used for the soak test. Stabilometer and cohesiometer tests are performed at ambient temperature. Standard calculating procedures are used to obtain (a) compaction density, (b) "cured" and "soaked" test density, (c) cured and soaked moisture content, and (d) cured and soaked values for R, S, and C.

Illinois Method

The Illinois method for design of cold mixtures containing emulsified asphalt and aggregate was developed at the University of Illinois under the sponsorship of the Illinois Department of Transportation and FHWA. Complete details of the method are available elsewhere (8).

The procedure uses a modified Marshall method of mix design and a moisture durability test. The method and recommended test criteria are applicable to base-course mixtures for low-traffic-volume pavements that contain any grade of emulsified asphalt and dense-graded aggregates ≤25 mm (1 in) maximum size. This procedure is recommended for road mixes or plant mixes that are prepared at ambient temperature. The procedure attempts to simulate actual field conditions as nearly as possible.

The design procedure involves the following major steps:

1. Tests are conducted to determine the properties of aggregates and their suitability for use in emulsified-asphalt mixtures.
2. Tests are conducted to determine the properties and quality of emulsions.
3. A simplified procedure is used to estimate a trial residual asphalt content for a given aggregate. This trial

asphalt content is then used in coating tests to determine the suitable type(s) of asphalt emulsion(s) and amount(s) of premixing water required.

4. Mixtures are prepared and aerated to varying moisture contents by using the trial residual asphalt content and the required mixing water. The mixture is then compacted into Marshall specimens, which are dry cured one day and then tested for modified Marshall stability.

5. By using the required mixing water and optimum compaction water content, mixtures are prepared at varying residual asphalt contents. If the optimum compaction water content is lower than the minimum required mixing-water content, aeration is required before compaction. The mixtures are then compacted into Marshall specimens and air cured for three days. The specimens are tested for bulk density, modified Marshall stability, and flow. The moisture susceptibility of the mixture is evaluated by subjecting a series of specimens to a special capillary-water-soak test for four days.

6. The optimum asphalt content is chosen as the percentage of emulsified asphalt at which the paving mixture best satisfies all of the design criteria. The method for calculating the trial residual asphalt content is as follows:

$$R = 0.001\,38\,AB + 6.358\log_{10}C - 4.655 \quad (2)$$

where

R = trial residual asphalt content by weight of dry aggregate (%),
A = percentage of aggregate retained on the 4.75-mm (No. 4) sieve,
B = percentage of aggregate passing the 4.75-mm sieve and retained on the 0.074-mm (No. 200) sieve, and
C = percentage of aggregate passing the 0.074-mm sieve.

Note that gradation is based only on washed-sieve gradations. The R is rounded off to the nearest half percent to yield the trial residual asphalt content.

The initial water content is determined by using the following criteria:

1. For anionic emulsion, the initial trial batch may be mixed without the addition of any water (i.e., in the air-dry condition).
2. For cationic emulsion, a higher water content is often required to produce satisfactory mixes. The coating test should start at about 3 percent water.

Before compaction, the mix is placed no deeper than 25 mm (1 in) in an aeration pan. The pan with the mixture is placed in a curing oven at 93° ± 3°C (200° ± 5°F). The mixture is stirred and weighed every 15 min until the weight is within 20 g of the required weight loss. The mixture is then cooled to 22° ± 1.7°C (72° ± 3°F). The mixture is stirred every 10 min until the calculated required water loss is complete. It is then ready for compaction. The mixture is compacted in the Marshall mold by using 75 blows on each side of the specimen. The specimens are cured at 22° ± 1.7°C in the forming mold for a specified curing period of 24-72 h. The specimens must be set on their edges for equal ventilation on both sides. The specimens are removed from the mold approximatey 2 h before the intended testing time and brought to a temperature of 22° ± 1.7°C. The testing load is applied at a constant rate of deformation of 51 mm/min (2 in/min) until failure. Three companion samples are placed in a capillary soak test: The specimens are placed in a modified mold in water at 22°C (72°F) to a depth of 25 mm for 48 h and are then removed and extruded from the modified molds and tested in the same way as the unsoaked specimens.

The test results are plotted on graphs, and the following properties are reported:

1. Dry stability at one day versus compaction moisture,
2. Dry and soaked stability versus residual asphalt content,
3. Dry bulk density (corrected for moisture) versus residual asphalt content,
4. Percentage total voids versus residual asphalt content,
5. Percentage moisture absorbed versus residual asphalt content, and
6. Percentage stability loss versus residual asphalt content [(dry stability - wet stability) 100/dry stability].

Purdue Method

An investigation conducted by the Joint Highway Research Project at Purdue University, in cooperation with the Indiana State Highway Commission and FHWA, deals with the establishment of a method for preparing and testing asphalt-emulsion-treated mixtures (AETMs) by using Marshall equipment (9). The AETMs were evaluated with emphasis on coating, workability, ease of handling, curing rate, and amount of moisture retained in the mixture before and after compaction. Based on these factors, a method for preparing standard Marshall specimens was developed. In addition, a limited study was conducted to evaluate three different methods for water-sensitivity tests in order to select a satisfactory method for AETMs.

A laboratory investigation to determine the effect of asphalt emulsion content and initial added-moisture content on the design parameters and properties of AETMs by use of Marshall equipment was initiated. The evaluation was conducted at different curing stages of the mix; the early curing condition (one-day air-dry curing) was emphasized. The standard 50-blow Marshall procedure was used.

In addition to the usual Marshall criteria for asphalt mixes, this procedure incorporated two new concepts: (a) Marshall stiffness (S_M), determined as the ratio of Marshall stability to flow, and (b) Marshall Index (I_M), represented by the slope of the linear portion of the load-deformation trace obtained from the autographic Marshall equipment. The autographic equipment provides a continuous recording chart for load versus deformation throughout the testing range.

The initial water content was added to the aggregate, and the mixture was left to stand for 10-15 min before the emulsion was added. Then the materials were mixed with a combination of hand and mechanical mixing. The mixture was then cured in a 60°C (140°F) forced-draft oven for 1 h before remixing and compaction. The AETM was compacted at room temperature by using 50 blows on each side of the specimen. The compacted specimens were left in the mold for about 30 min before extrusion. The samples were then left to cure at room temperature [22°C (72°F)] for the required curing time before testing.

In one phase of the test program, some specimens were oven cured for three days in a forced-draft oven at 49°C (120°F) and then brought to 22°C before testing. The test program also involved soaking specimens for four days in a 22°C water bath before testing in order to measure water sensitivity.

Perhaps the most significant finding of this research is that two different curing periods will provide better understanding and control of mix performance. The two curing periods must be selected to represent the early curing condition and curing for relatively long periods, and emphasis must be placed on the AETM properties in the early curing condition. Furthermore, more reliance on the use of water-sensitivity test results (soaked specimens) as opposed to dry test results are beneficial in providing realistic results and better control of AETM properties. This research also verified some of the effects on AETM properties of asphalt emulsion content, percentage of added water, and curing time.

The test results show that a high degree of stability is attained at the expense of lowered durability (measured as the resistance to water damage). The research indicates that the final design must provide a balance between stability and durability requirements. This can be achieved by controlling and evaluating both the dry and soaked properties of the mix and putting greater emphasis on the soaked specimens.

SUMMARY AND CONCLUSIONS

The available literature on the development of mix-design procedures for emulsion-aggregate mixtures indicates a multiplicity of approaches. There appears to be no consensus concerning the determination of mixing-water requirements, optimum emulsion content, degree and method of curing, specimen formulation, or stability (strength) criteria. However, the following general conclusions can be drawn from test procedures currently in use:

1. Most of the known methods for the design of emulsion-aggregate mixtures use Hveem or Marshall test equipment and include some type of modification(s) to the procedure in relation to specimen preparation, curing, and test temperature.
2. It is usually necessary to add additional water to an emulsion-aggregate mixture to aid in mixing and coating. The amount of water is often determined by trial and error, based on visual inspection of the degree of coating and the amount of runoff.
3. Most procedures use the CKE test to determine the starting percentage of emulsified asphalt. Then mixes that use emulsion percentages above and below the starting percentage can be made for evaluation.
4. The method of curing has a significant effect on the results obtained. In some procedures, a curing or aeration period precedes the molding of the specimen; in others, curing of the molded specimen is required.
5. There are no standard acceptance criteria for EAMs. Acceptance criteria are based on the specific design method used. Different procedures may produce different test values for the same mixture.
6. Complete coating of all aggregate particles is not necessary for an EAM to perform satisfactorily.
7. The evaluation of open-graded EAMs is based primarily on coating, film thickness, workability, and runoff.
8. Considerably more work needs to be done to correlate laboratory test values with field performance characteristics, particularly with respect to the curing of the mixture.

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Use of Marshall Equipment in Development of Asphalt Emulsion Mixture Design Methods and Criteria

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Design procedures for emulsified-asphalt mixtures have been developed by using Marshall equipment. The procedures are intended for use with dense-graded aggregates in base courses on low-volume roads in Illinois. Laboratory and field tests conducted to provide a basis for selecting strength tests and criteria, curing times and temperatures, moisture absorption, and durability tests and criteria are described.

A mix-design method for dense-graded asphalt emulsion cold mixes that uses Marshall equipment has been developed. Details on the design procedure are available elsewhere (1-3). This paper describes why certain tests, curing times, mixing procedures, and stability criteria were selected.

The design procedure was developed specifically for base courses for low-volume roads in Illinois. The mixtures typically use local dense-graded gravel-sand or crushed-limestone aggregates. Several cities and counties in Illinois have used such asphalt emulsion bases on low-volume roads with generally good success. For example, Clark County has constructed more than 322 km (200 miles) of such bases in the past 15 years. Only a small amount of localized repair has been necessary on these pavements, where (a) the base thickness or subgrade stability or both were deficient and (b) construction