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.

REFERENCES

1. A Basic Asphalt Emulsion Manual. Asphalt Institute, College Park, MD, Manual Series 19, March 1979.
2. 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.
3. A Basic Asphalt Emulsion Manual: Volume 2—Mix Design Methods. Federal Highway Administration, U.S. Department of Transportation, Implementation Package 79-1, Jan. 1979.
4. G.K. Fong. Mix Design Methods for Base and Surface Course Using Emulsified Asphalt: A State-of-the-Art Report. Federal Highway Administration, U.S. Department of Transportation, Rept. FHWA-RD-78-113, Oct. 1978.
5. J.A.N. Scott, R.J.M. Tausk, and W.C. Vonk. Breaking and Curing Behavior of Asphalt Emulsions in Highway Applications. Presented at 6th Annual Meeting, Asphalt Emulsion Manufacturers Assn., San Francisco, March 14-16, 1979.
6. J.E. Huffman. Emulsified Asphalts in Paving and Maintenance. Canadian Technical Asphalt Assn., Toronto, Nov. 1975.
7. L.D. Coyne and R.M. Ripple. Emulsified-Asphalt Mix Design and Construction. Presented at AAPT Annual Meeting, Phoenix, AZ, Feb. 1975.
8. M.I. Darter and others. Development of Emulsified-Asphalt-Aggregate Cold Mixture Design Procedures. Illinois Cooperative Highway Research Program, Univ. of Illinois, Urbana, Project IHR-505, Res. Rept. 505-5, Feb. 1978.
9. A.A. Gadallah, L.E. Wood, and E.J. Yoder. A Suggested Method for the Preparation and Testing of Asphalt-Emulsion-Treated Mixtures Using Marshall Equipment. Presented at AAPT Annual Meeting, San Antonio, TX, Feb. 1977.

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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

problems, such as compaction before adequate aeration, were encountered.

This paper outlines mix-design requirements, describes structural and durability criteria, and finally gives some mix-design applications.

MIX-DESIGN REQUIREMENTS

A design procedure for an emulsified-asphalt mixture (EAM) must determine the following:

1. The suitability of aggregates and emulsified asphalt,
2. The compatibility of emulsified asphalt and aggregate,
3. The optimal moisture content for compaction,
4. The optimal residual asphalt content, and
5. The adequacy of structural and durability properties.

Based on results from field and laboratory studies in Illinois (4-6) and other studies (7-16), the following design criteria are considered important in selecting the optimal residual asphalt content:

1. An EAM must provide adequate stability when tested in a "soaked" condition to provide adequate resistance to traffic load during wet seasons. Considerable free moisture is available in Illinois. Most subgrade soils drain poorly, and most low-volume roads are constructed with poor drainage characteristics (i.e., shallow side ditches and a high water table).
2. The percentage loss of stability of the EAM when tested soaked as opposed to dry should not be excessive. A high rate of loss indicates that the EAM has a high susceptibility to moisture and that softening and disintegration may occur during wet seasons.
3. The total voids in the EAM should be within a specified range to prevent either excessive permanent deformation and moisture absorption (for too high a void content) or bleeding and excessive cost of the residual asphalt from the EAM (for a low void content).
4. Moisture absorption into the EAM should not be excessive so that the potential of stripping or weakening of the bond between the residual asphalt and the aggregate is minimized.
5. Residual asphalt should provide adequate coating of the aggregate and should be resistant to stripping.

The basic design philosophy is that the residual asphalt content selected should meet all of these criteria and maximize the soaked stability of the mixture.

STRUCTURAL AND DURABILITY CRITERIA

A dense-graded EAM exhibits a wide range of structural and durability properties. This is generally attributable to the wide range of aggregates used for EAM bases but may also be attributable to the variety of types and grades of asphalt emulsion that are available. EAM material proportions can be optimized for proportioning, mixing, and compaction by using the mix-design procedure. However, even such an optimized mix may still not be structurally adequate or have sufficient durability. Criteria and tests are needed to determine the adequacy of an EAM for use in pavement bases.

A structural analysis of cold asphalt mixtures used in pavement bases was conducted as part of this study (7). The primary types of distress that occur in cold EAM pavements include alligator cracking (or repeated-load fatigue), rutting, and mix disintegration. Many of the problems are associated with a loss of subgrade support caused by the poor drainage conditions typical of low-volume roads. In the relatively wet climate of Illinois, there is an excess of soil moisture throughout most of the year. Thus, there is ample opportunity for free moisture to collect in the EAM base course, and the effect of moisture on the durability of EAMs must be considered.

The objective of the structural analysis was to develop procedures that relate cold EAM structural properties—specifically, the structural coefficient—to pavement performance. The major structural property of the cold-mix material that was correlated with performance was the resilient modulus M_R. Other structural properties, such as fatigue and permanent deformation (rutting) under repeated load, are strongly related to M_R. In base courses, the stiffer the EAM, the less potential there is for fatigue or alligator cracking and rutting distress to occur (8). A stress-dependent finite-element model of pavement analysis was used to analyze critical deflections, stresses, and strains over a range of material types and properties (nonstabilized granular, cold asphalt mixtures, and hot asphalt mixtures). The validity of the approach and the correlations was established by using data and results from the AASHO Road Test and other studies. Curing of the cold-mix base after compaction was found to be a critical factor. The better the curing environment (i.e., high temperature, dry weather, nonsealing of the base), the greater is the potential for improved performance.

These results were used to establish a correlation between M_R and the structural coefficient of the EAM base. By using data from the laboratory study, a correlation was also established between the M_R and Marshall stability at ambient temperature. Thus, the Marshall stability of the EAM could be used to determine the structural coefficient for design. By using the Illinois Department of Transportation (DOT) design procedure, a thickness of EAM base can be determined that provides a pavement that has a specified design life. As long as the structural properties of the EAM are retained, the pavement should provide the required service. If, however, the EAM base softens or distintegrates as a result of durability problems, the pavement will experience premature distress. To avoid this possibility, structural and durability criteria have been established.

The durability of EAM in relation to moisture and temperature effects was studied. Data for Marshall stability and M_R versus curing time were developed for air curing, capillary soaking, vacuum soaking, delayed capillary soaking, and delayed vacuum soaking. The effects of high-temperature soaking and freeze-thaw were also investigated.

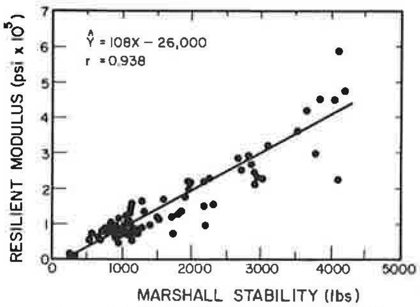
Materials and Testing

The aggregate used consisted of pit-run gravel from Clark County, Illinois, which has been successfully used in many kilometers of EAM. The emulsion used in the experiment was a CMS-2. The mix-design procedure and material properties are described elsewhere (1). Liquid content for mixing was 5.8 percent (4 percent residual asphalt by weight of dry aggregate). The total liquid content was satisfactory for immediate compaction.

Marshall-sized specimens were prepared. All specimens remained in the compaction molds until just before testing. This not only made handling of the specimens easier but also provided confinement (similar to the field condition) to eliminate possible damage from unconfined swell. A total of 74 specimens were prepared in this way. This established the four basic groups of the experiment: air cure, capillary soak, vacuum soak, and delayed capillary and vacuum soaks. Two structural measurements were selected for the study: diametral resilient modulus and Marshall stability (6).

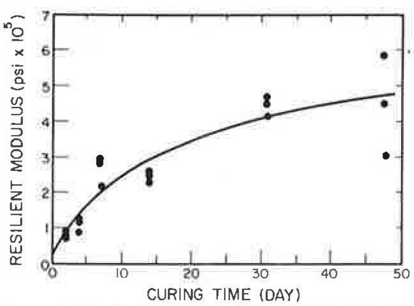
At the designated time, each set of specimens was ejected from the molds, a bulk (wet) density determination was made, and then diametral resilient modulus and Marshall tests for stability and flow were conducted at 22.2°C (72°F). After each set was tested, the samples were pulverized and mixed together to obtain the average moisture content of each set at the time of test. To determine moisture content, the samples were dried in a forced-draft oven at 127°C (260°F) for a minimum of 24 h. The moisture contents were used to calculate dry density, percentage saturation, voidless mix density, and percentage

Figure 1. Correlation between diametral resilient modulus and Marshall stability for EAM.



Note: 1 lbf/in² = 6.896 kPa; 1 lbf = 4.45 N.

Figure 2. Effect of air curing on resilient modulus of EAM.



Note: 1 lbf/in² = 6.896 kPa; t°F = (t°C ÷ 0.55) + 32.

air voids for each sample. Percentage voids was calculated as specified by Darter and others (1).

Soaking Procedures

The capillary soaking procedure used in the experiment is described elsewhere (6). Vacuum saturation of the samples was accomplished by using the equipment and procedures described in ASTM C593. After vacuum saturation, the samples were kept immersed in the same room-temperature water bath as the capillary samples until time for testing.

Strength Correlations

In a previous study (6), correlations between diametral resilient modulus, indirect tensile test, and Marshall stability test were established. The relation between the resilient modulus and Marshall stability takes on important significance where Marshall equipment is used in the mix design, since it can provide direct input to thickness design by means of relatively simple and inexpensive equipment. In this experiment, all strength determinations (diametral resilient modulus and Marshall stability) were conducted at room temperature [22.2°C (72°F)]. Figure 1 shows the correlation results of resilient modulus versus Marshall stability. The correlation coefficient for all 74 samples in this experiment was 0.938. For practical use, a resilient modulus approximately 100 times the Marshall stability value, measured at 22.2°C, would provide a reasonable estimate.

Air Cure

The air-cure group of specimens was tested at various times: from immediately after compaction to 48 days of air curing at room temperature. The moisture content ranged from an initial 5.8 percent to approximately 0.6 percent, and the release of moisture occurred rapidly during the initial days of curing. Figure 2 shows the plotted results of the air-cured resilient modulus, tested at 22.2°C (72°F), which indicate a rapid initial increase in strength, from approximately 96.5 MPa (14 000 lbf/in²) to more than 2757.6 MPa (400 000 lbf/in²). The rapid initial increase in strength is considered to be directly related to the rate of moisture reduction in the EAM. Under extended air curing, beyond that shown, the strength is expected to continually increase because of the "hardening" of the residual asphalt with time. In general, laboratory air curing at constant temperature from the top and bottom surfaces of a 63.5-mm (2.5-in) thick specimen would be expected to be more rapid than curing under field conditions at the same temperature.

Strength gains have been documented under actual field conditions and are illustrated in a figure later in this paper. A laboratory study by Schmidt and Graf (9) of the effects of moisture on asphalt-treated mixes has shown that the resilient modulus is reversible. There is significant loss in strength when the material is saturated and a corresponding increase in strength upon drying. The cyclic wetting and drying imposed on the samples produced corresponding cyclic strength properties, and successive cycles showed a trend toward continual strength increase at given moisture contents. It appears that the dry-wet cycles become less severe. In other words, the drying cycles result in a beneficial increase in strength that is greater than the damage done during the wetting cycles. Although the study by Schmidt and Graf (9) involved vacuum saturation and vacuum desiccation of laboratory samples, similar moisture behavior can be expected in the field during fluctuations in such factors as the groundwater table, rainfall, infiltration, capillary action, and temperature gradient. Moisture contents of EAM cores taken from 27 different projects in seven states (10)—projects that exhibit a wide variety of gradations, densities, and other mix characteristics—range from nil to as high as 10.1 percent. For EAMs that were similar in gradation and density to that used in this study, moisture contents between approximately 1 and 2 percent were common, even four years after construction.

In view of the above, one might ask the following questions: Isn't vacuum saturation too severe, since it does not represent field conditions? Is there a difference in structural response based on the soaking method? Is there a net benefit in the drying cycle over the wetting cycle?

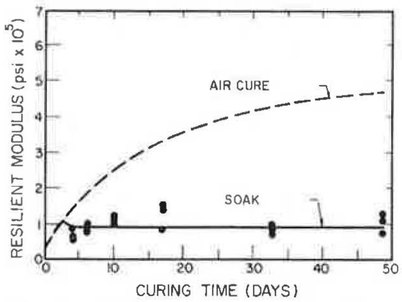
Capillary and Vacuum Soaking

Figures 3 and 4 show the results of resilient modulus versus time, tested at 22.2°C (72°F), for the two soaking methods used in this experiment. In both cases, the compacted specimens were allowed to air cure for three days before soaking was begun. It can be seen that the strength gain ceased in both cases and remained dormant during the soaking period. A statistical analysis that compares the data for the capillary-soaked versus the vacuum-soaked specimens shows no significant difference for the resilient moduli or for stability. It is inferred from this study, therefore, that the effect of capillary soaking may be as severe as that of vacuum soaking.

In an earlier study by Terrel and Monismith (11), a modified wet-sand apparatus was used to investigate the effects of moisture. These results show similar behavior; i.e., the gain in strength stopped or decreased slightly with time. It would appear, therefore, that each of the soaking procedures produces similar results. Even though the vacuum method resulted in higher moisture contents and higher degrees of saturation than the capillary method (see Figure 5), the effect on strength was the same.

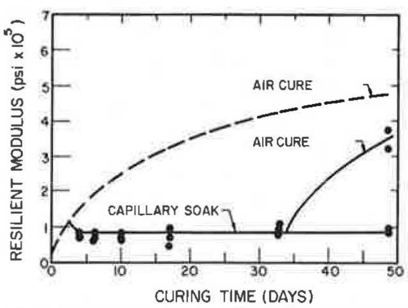
Figure 5 shows the rapid change in moisture content associated with either test method. Figure 5 also explains the rate of strength increase when a set of specimens was removed from capillary soaking and allowed to air cure. The strength increase as moisture is lost is similar to the original air-curing curve. Scrimsher and others (17) conducted a study in which they used four moisture tests:

Figure 3. Effects of vacuum soaking on resilient modulus of EAM.



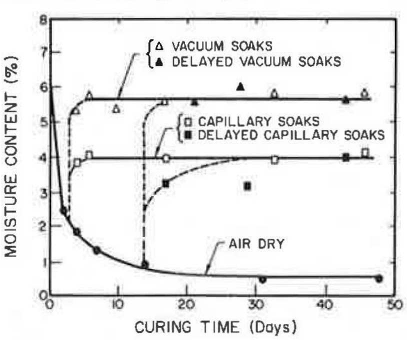
Note: 1 lbf/in² = 6.896 kPa; $t°F = (t°C \div 0.55) + 32$.

Figure 4. Effects of capillary soaking on resilient modulus of EAM.



Note: 1 lbf/in² = 6.896 kPa; $t°F = (t°C \div 0.55) + 32$.

Figure 5. Effects of EAM moisture contents for various curing methods.



moisture vapor saturation, immersion swell, sand bath assembly, and capillary absorption. That study showed clearly that the capillary absorption test has the following advantages over the other tests:

1. There is realistic representation of field conditions for a base course.
2. Samples are confined and thus do not "fall apart" during soaking.
3. Simple, inexpensive equipment is used.
4. Absorbed moisture content can be easily measured.

Delayed Capillary Soaking and Delayed Vacuum Soaking

In the delayed-soaking test groups, all sets were allowed to air cure for 14 days before the soaking procedure began. Figures 6 and 7 show the results [all tests at 22.2°C (72°F)]. In both cases, there was a rapid loss in strength that either leveled off or continued to decrease gradually. Once again, there was no significant difference in the strength values for the two soaking methods even though the moisture contents and degrees of saturation (see Figures 5 and 8) are different. Statistically comparing delayed-soak samples with soaked samples for similar "soaking times" showed significantly higher strength values in the delayed-soak samples. Thus, it is inferred that the detrimental effects of moisture are lessened as air curing is increased or the extent of breaking of the emulsion is increased. This points up the extreme importance of obtaining adequate early field curing.

One set in the delayed vacuum-soaked group was subjected to three days in a 60°C (140°F) water bath and then four additional days of soaking at 22.2°C (72°F). The results shown in Figure 7 indicate an increase in damage as a result of the elevated soaking temperature.

Another set from the delayed vacuum-soaked group was subjected to three freeze-thaw cycles, each of which consisted of 24 h in a -28.9°C (-20°F) freezer plus 24 h in a 22.2°C water bath. The six-day freeze-thaw sequence was preceded and followed by three days and four days, respectively, of immersion in a 22.2°C water bath. Once again, it should be noted that all samples remained in their molds until just before testing so that swell was restricted to two dimensions. As Figure 7 shows, the strength loss was substantial. Admittedly, this was an extreme test procedure. However, considering the similar damage caused by the different methods of soaking, plus the fact that the difference in total moisture content between vacuum saturation and capillary saturation was less than 2 percent (or approximately 20 percent less in degree of saturation), the possibility of field damage from freeze-thaw seems great. The fact that asphalt cement and emulsions "waterproof" the mixtures should not prevent further study into the effects of freeze-thaw, particularly in a system that incorporates water in its construction.

Figure 9 compares all of the results from the durability study.

SELECTION OF LIMITING CRITERIA FOR MIX DESIGN

Specific durability and structural tests and limiting criteria that relate realistically to field conditions and performance must be selected for mix design.

Structural Test

Significant correlations between the major structural tests of resilient modulus, Marshall stability, and indirect tensile strength (6) indicate that any one of these could be used to provide a structural evaluation of the EAM. Marshall stability is selected because it is the standard test used by the Illinois DOT for routine hot-asphalt mix design and the equipment is readily available.

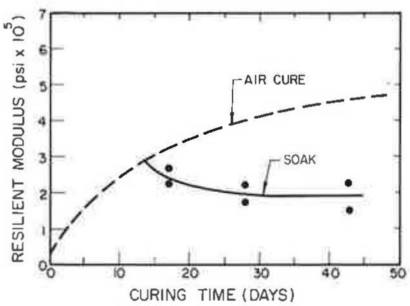
Durability Test

The capillary absorption (or soak) test is believed to be the most realistic test available that represents the field moisture conditions of an EAM base course. Extensive use and evaluation of the test have shown it to be very simple, convenient, and realistic (6, 17). The only disadvantage is the relatively long soaking time required. Based on experimental testing, a four- to five-day soak is believed to be adequate to provide a realistic indication of the moisture durability of the EAM.

Minimum Marshall Stability

An EAM must have at least minimal Marshall stability to prevent excessive permanent deformation of the base course. The results for field cores taken from Clark County, Illinois, are shown in Figure 10. The base EAM ranged in thickness from 102 to 203 mm (4-8 in). The 203-mm cores were cut in half and tested separately as top and bottom. The results show an increase in stability with

Figure 6. Effects of delayed capillary soaking on resilient modulus of EAM.



Note: 1 lbf/in^2 = 6.896 kPa; t°F = (t°C ÷ 0.55) + 32.

Figure 7. Effects of several curing conditions after delayed vacuum soaking on resilient modulus of EAM.

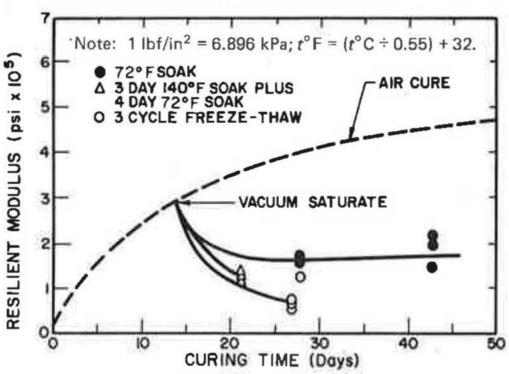


Figure 8. Resilient modulus versus degree of saturation for various curing methods.

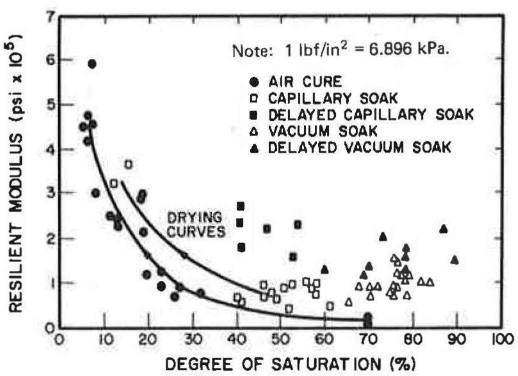
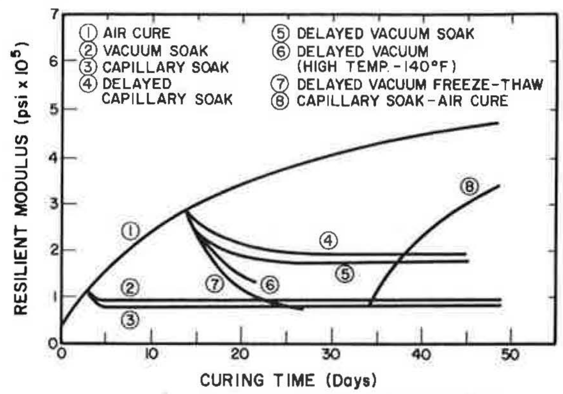
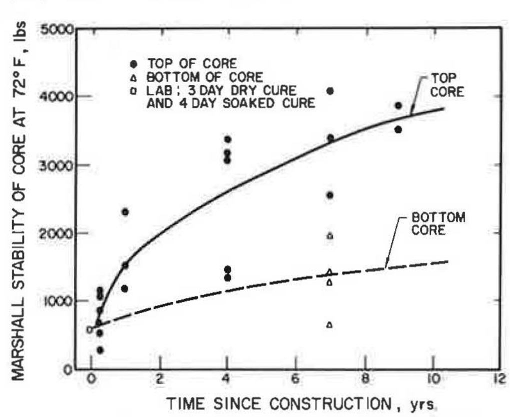


Figure 9. Resilient modulus of EAM as affected by various curing conditions.



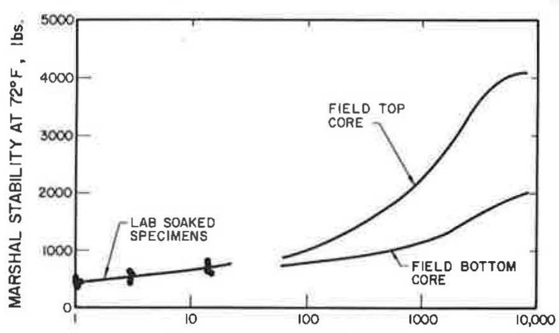
Note: 1 lbf/in^2 = 6.896 kPa; t°F = (t°C ÷ 0.55) + 32.

Figure 10. Marshall stability of cores cut from EAM projects in Clark County, Illinois.



Note: t°F = (t°C ÷ 0.55) + 32; 1 lbf = 4.45 kN.

Figure 11. Comparison of effects of field and laboratory curing on stability of EAM.



Note: t°F = (t°C ÷ 0.55) + 32; 1 lbf = 4.45 kN.

time after construction. The bottom of the cores shows significantly less stability than the top. This is the result of (a) moisture preventing the complete breaking of the emulsion, (b) moisture causing a stripping of the asphalt and weakening of the asphalt-aggregate bond, or (c) moisture never being fully released (cured) from the system and resulting in stagnation of strength gain. A comparison of the Clark County field curves (Figure 10) with the laboratory-prepared EAM specimens is shown in Figure 11. The field and laboratory curves appear to approximately meet. These EAM-base pavements have generally performed very well for 10 years.

The following rationale was used in selecting a minimum acceptable stability level:

1. A three-day laboratory dry cure at ambient temperature removes most of the moisture in the EAM specimens and represents a reasonably cured condition (Figure 5). Any heating of the EAM to accelerate the cure has been found to produce a very large increase in stability (i.e., two to five times). Since the EAM is not heated in the field, it is unrealistic to heat it for purposes of rapid curing.

2. A four-day soaking period after the three-day dry curing subjects the EAM to a realistic moisture environment. This gives an indication of the potential moisture durability of the EAM. Results given by Darter

and others (1) show that the loss in stability between the dry and soaked conditions is highly dependent on the content and character of the aggregate fines.

3. The minimal Marshall stability of the EAM after the three-day dry cure and four-day capillary soak should be at least 1.78-2.22 kN (400-500 lbf) for low-volume roads. This limiting criterion is based on both experimental results (such as the Clark County data and other data presented later in this paper for pavements that have performed satisfactorily) and stability correlations with the base structural coefficient. According to the correlations presented by Darter and Devos (7), a Marshall soaked stability of 1.78 kN would provide a structural coefficient for design of 0.14, which is equivalent to a crushed-stone base similar to that used at the AASHO Road Test. To provide some margin of design reliability, a minimum of 2.22 kN is desirable. The various EAMs described by Darter and others (1) have a soaked stability greater than 2.22 kN and have shown reasonably good field performance.

Loss of Stability

The extent of loss of stability resulting from the four-day capillary soak test is believed to be an indication of the potential durability of the EAM. A 50 percent loss is considered to be the maximum acceptable. EAM mixtures that had greater than 50 percent loss of stability had high clay contents, low sand equivalents, and low residual asphalt contents. As asphalt content is increased, loss of stability decreases significantly.

Compaction

Laboratory results showed that increasing the compactive effort from 50 to 75 blows increased stability, resilient modulus, and dry bulk density (6). The total voids and moisture absorbed were decreased. Field results are shown in Figure 12, where density of EAM base cores increases with time since construction. The mean data points for 50- and 75-blow laboratory compaction are also shown. The 75-blow density represents field density after about one to two years. It is believed that field compaction should be required to achieve at least 95 percent of 75-blow laboratory compaction.

Percentage Moisture Absorption

The more moisture that enters the EAM, the greater is the potential moisture damage. The California procedure that uses the capillary absorption test limited moisture absorption to 5 percent. After examination of the results from many mix designs, it is believed that a slightly lower value of 4 percent should be set as a limiting value.

Percentage Total Voids

The total voids (air plus water) affect the density, the amount of water that may be absorbed into the mix, and the potential for permanent deformation or rutting of the mix. A range of 2-8 percent for base course is recommended by the Asphalt Institute (18), but no information is available to support this range. It may not be necessary to place restrictions on voids, since absorbed water correlates well with void content (6).

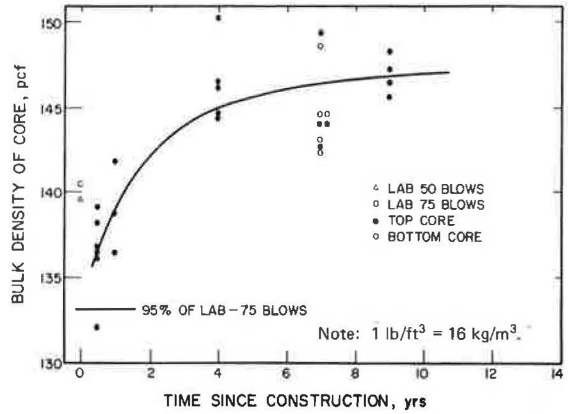
MIX-DESIGN APPLICATIONS

The aggregates used were obtained from pits and quarries in Illinois and are representative of typically used pit-run gravels and crushed-limestone aggregates.

Bond County Gravel

Bond County gravel comes from a pit located near the project and, if acceptable, would provide considerable economic advantage over other aggregate, which would have to be hauled in. The aggregate and emulsion properties are given by Darter and others (1). The washed gradation reveals a relatively high fines content, which was apparently caused by the failure to strip overburden at the pit. A relatively high amount of clay is indicated by the low sand-equivalent value of 22. Water absorption is excessive, and asphalt absorption may become a problem during later pavement life as asphalt is absorbed into the aggregate and film thickness is reduced. This aggregate would normally be rejected because of the gradation and low sand-equivalent value.

Figure 12. Increase of EAM base density over time from Clark County, Illinois.



The optimal residual asphalt content is estimated to be 5.4 percent, as computed by a prediction equation (1). Coating tests were conducted by preparing several laboratory bowl EAM mixtures over a range of premixing moisture contents (i.e., moisture contained in aggregate before adding emulsion) at the estimated optimal asphalt content. The best aggregate coating was obtained at premix moisture contents of 3-5 percent (excluding water contained in the emulsion). Marshall-sized specimens were prepared with 5.0 percent residual asphalt (actually, 5.4 percent should have been used, since that is the estimated optimal asphalt content) and compacted over a range of moisture contents. The specimens were air cured one day on a laboratory shelf, extruded from their molds, and tested in the Marshall stabilometer at 22.2°C (72°F). A curve that indicates maximum stability occurring at 3.5 percent total moisture content (by weight of dry aggregate) was obtained (see Figure 13). This optimal moisture content at compaction was used in the compaction of all other specimens.

Compacted EAM specimens were then prepared over a range of residual asphalt contents. Specimens were tested after three days of laboratory air curing—called dry curing—for Marshall stability at 22.2°C. Other specimens, after the three-day dry cure, were subjected to five days of the capillary soak test (2.5 days on each side of specimens)—called soaked curing—and then tested for Marshall stability. Dry bulk density and the moisture contained in the specimens were also determined. All results are plotted in Figure 13. Maximum soaked stability occurs at approximately 5.3 percent residual asphalt. There is a large loss of stability between the dry-cured specimens and the soaked specimens, but the amount of the difference decreases with increasing asphalt content. A large loss such as this has only occurred with aggregates that have a low sand equivalent (<25) and a large amount of fines [minus 0.074-mm (minus No. 200) sieve]—i.e., >15 percent.

The residual asphalt content at peak soaked stability is 5.3. The following values of other parameters are obtained from the graphs for this asphalt content:

Mix Parameter	Value at 5.3 Percent Asphalt	Limiting Criterion
Stability loss (%)	57	50 max
Total voids (%)	6.7	2-8
Moisture absorption (%)	3.6	4 max
Modified Marshall stability (kN)	2.4	2.2 min
Aggregate coating (%) (3-5 percent premix moisture)	60-70	50 min

All of the criteria except percentage loss stability are achieved at a residual asphalt content of 5.3 percent. A residual asphalt content of 5.6 percent is required to meet the 50 percent loss requirement. At 5.6 percent asphalt content, all other requirements are achieved. However, the values for soaked stability and absorbed moisture are very close to the acceptable values.

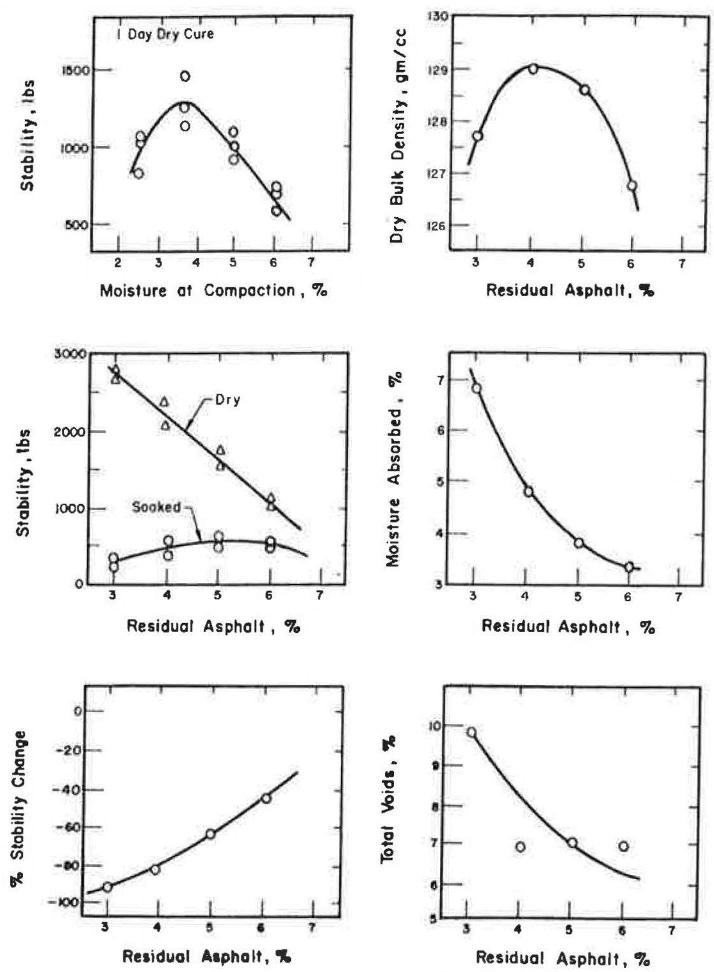
The following recommendations are made for mix design and construction:

1. Residual asphalt content = 5.6 percent by weight of dry aggregate,
2. Asphalt emulsion content (for an asphalt residue of 70 percent) = (5.6/0.70) = 8.0 percent by weight of dry aggregate, or approximately 81.4 L of emulsion per megagram of dry aggregate (19.4 gal/ton),
3. Premixing water content = 3-5 percent by weight of dry aggregate, and
4. Optimal water content at compaction = 3.5 percent by weight of dry aggregate (i.e., total water content in EAM).

The project was constructed in 1976 by using road-mix procedures. Three lift thicknesses were used: 64, 64, and 51.3 mm (2.5, 2.5, and 2.0 in), for a total of 178 mm (7 in). A residual asphalt content of about 4 percent was obtained, which is considerably less than that recommended. The water content of the gravel before mixing was 5.9 percent, which is greater than the optimal range for coating. The field mix observed just before compaction was estimated to have about 60 percent coating. Water content at the first pass of the roller was about 3.9 percent, which is near the recommended 3.5 percent. Field mix was obtained just before compaction and brought to the laboratory in sealed containers for compaction into Marshall-sized specimens and testing. Some of the results obtained are given below (1 kN = 224.8 lbf):

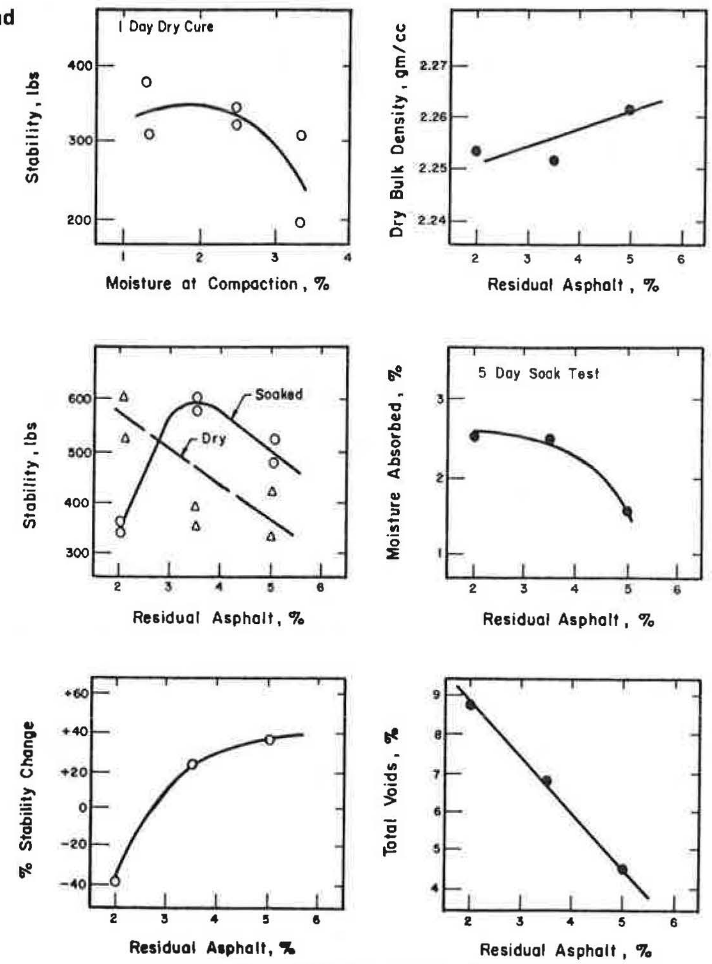
Item	Three-Day Dry Cure	Three-Day Dry Cure plus Five-Day Soaked
Laboratory mix design stability at 4 percent asphalt (kN)	9.78	2.00
Field mix stability at 4 percent asphalt (kN)	6.17	1.3
Moisture content at testing (%)		
Laboratory	2.2	2.6
Field	7.0	7.7

Figure 13. Mix design for Bond County pit-run gravel and HFE-300 emulsion.



Note: 1 lbf = 4.45 kN; 1 g/cm³ = 0.062 lb/ft³.

Figure 14. Mix design for Clark County pit-run gravel and HFE-300 emulsion.



Note: 1 lbf = 4.45 kN; 1 g/cm^3 = 0.062 lb/ft^3.

The percentage water absorption for laboratory and field mixes was 4.8 and 5.1 percent, respectively. These data indicate that the field mix has less stability and greater moisture content than the laboratory mixes. This, coupled with the low residual asphalt content, may cause serious problems for the EAM base. After one year of service, the pavement does not show any significant distress.

Clark County Gravel

Clark County gravel has been used in EAM low-volume pavement bases for many years with good success. The aggregate and emulsion properties are given elsewhere (1). The estimated trial residual asphalt content was computed to be 3.7 percent. Coating tests were conducted at 3.7 percent residual asphalt and varying premix moisture contents. Acceptable coatings were obtained over a range of 3-5 percent premix moisture. The total moisture content at compaction (as percentage of dry aggregate) that produces maximum stability is approximately 2.0 percent, as shown in Figure 14. A series of compacted Marshall-sized specimens were prepared and tested dry (after three-day curing on a laboratory shelf), and also after the three-day dry cure and a five-day soak (by using the capillary moisture soak test). Results show a peaked soaked curve with maximum stability occurring at about 3.5 percent residual emulsion. The dry-cure stability curve is greater than the soaked curve at 2-3 percent asphalt content but is less than the soaked curve for higher asphalt contents, as the curve for percentage change in stability reflects. Moisture content absorbed during the five-day soak test and total voids decrease with increased residual asphalt content.

The residual asphalt content at peak soaked stability is 3.5 percent. The following values of other parameters are obtained from the graphs for this asphalt content (1 kN = 224.8 lbf):

Mix Parameter	Value at 3.5 Percent Asphalt	Limiting Criterion
Stability change (%)	+25	-50 max
Total voids (%)	6.8	2-8
Moisture absorption (%)	2.5	4 max
Modified Marshall stability (kN)	2.6	2.2 min
Aggregate coating (%) (3-5 percent premix water)	60-75	50 min

Therefore, all of the criteria are achieved at a residual asphalt content of 3.5 percent. The mixture design used by Clark County uses a slightly coarser aggregate gradation and about 3.5-4.0 percent residual asphalt and has provided successful mixes for more than 10 years.

The following recommendations are made for mix design and construction:

1. Residual asphalt content = 3.5 percent by weight of dry aggregate,
2. Asphalt emulsion content (for an asphalt residue of 70 percent) = (3.5/0.70) = 5.0 percent by weight of dry aggregate, or approximately 50.4 L per megagram of dry aggregate (12 gal/ton),

3. Mixing water content = 3.5 percent by weight of dry aggregate, and
4. Optimal water content at compaction = 2.0 percent by weight of dry aggregate.

CONCLUSIONS

This paper describes the selection of various criteria for the EAM design procedure developed at the University of Illinois. A given mixture should meet the following selected criteria: (a) adequate stability when tested in a soaked condition, (b) no excessive loss of stability when tested soaked as opposed to dry, (c) limited moisture absorption into the mixture, and (d) adequate coating. The basic design philosophy is that a residual asphalt content should be selected that meets these criteria and maximizes soaked stability. Field and laboratory tests were conducted to establish a test series and procedures and tentative limiting criteria for mix design for low-volume bases. Much additional field verification is needed before the procedures and criteria can be used with confidence.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. M.I. Darter, S.R. Ahlfield, P.L. Wilkey, and R.G. Wasill. Development of Emulsified Asphalt-Aggregate Cold-Mix Design Procedures. Univ. of Illinois, Urbana-Champaign, Res. Rept. 901-5, 1978.
2. A Basic Asphalt Emulsion Manual. Asphalt Institute, College Park, MD, Manual Series 19, March 1979.
3. M.I. Darter, S.R. Ahlfield, P.L. Wilkey, A.J. Devos, and R.G. Wasill. Design of Emulsified Asphalt-Aggregate Bases for Low-Volume Roads. TRB, Transportation Research Record 702, pp. 164-172.
4. I. Ishai, M. Herrin, and D.G. Leverenz. Failure Modes and Required Properties in Asphalt-Aggregate Cold Mix Bases. Department of Civil Engineering, Univ. of Illinois, Urbana-Champaign, Res. Rept. 505-1, 1974.
5. M. Herrin, M.I. Darter, and I. Ishai. Determination of Feasible Testing Methods for Asphalt-Aggregate Cold-Mix Bases. Department of Civil Engineering, Univ. of Illinois, Urbana-Champaign, Res. Rept. 505-1, 1974.
6. M.I. Darter, P.L. Wilkey, and S.R. Ahlfield. Factors Affecting the Structural Response of Emulsified Asphalt-Aggregate Cold Mixtures. Univ. of Illinois, Urbana-Champaign, Res. Rept. 505-3, 1978.
7. M.I. Darter and A.J. Devos. Structural Analysis of Asphaltic Cold Mixtures Used in Pavement Bases. Department of Civil Engineering, Univ. of Illinois, Urbana-Champaign, Res. Rept. 505-4, 1977.
8. R. Williamson. State of the Art of Emulsion Pavements in Region 6 of the U.S. Forest Service. In Low-Volume Roads, TRB, Special Rept. 160, 1975, pp. 245-254.
9. R.J. Schmidt and P.E. Graf. The Effect of Water on the Resilient Modulus of Asphalt-Treated Mixes. Proc., AAPT, Vol. 41, 1972, pp. 118-162.
10. F.N. Finn, R.G. Hicks, W.J. Kari, and L.D. Coyne. Design of Emulsified Asphalt Treated Bases. HRB, Highway Research Record 239, 1968, pp. 54-75.
11. R.L. Terrel and C.L. Monismith. Evaluation of Asphalt-Treated Base Course Materials. Proc., AAPT, Vol. 37, 1968, pp. 159-199.
12. Bituminous Emulsions for Highway Pavements. NCHRP, Synthesis of Highway Practice 39, 1975.
13. Redicote Reference Manual. Armak Co., Chicago, 1974.
14. L.D. Coyne and R.M. Ripple. Emulsified Asphalt Mix Design and Construction. Proc., AAPT, Vol. 44, 1975.
15. K.P. George. Stabilization of Sands by Asphalt Emulsion. TRB, Transportation Research Record 593, 1976, pp. 51-56.
16. R.L. Dunning and F.E. Turner. Asphalt-Emulsion Stabilized Soils as a Base Material in Roads. Proc., AAPT, Vol. 34, 1965.
17. T. Scrimsher, G.W. Mann, G.B. Sherman, and M. Johnson. Selection of Optimum Binder Content for Bituminous-Treated Bases. California Division of Highways, Sacramento, Rept. CA-HY-MR-3378-1-73-03, 1973.
18. Mix Design Methods for Asphalt Concrete. Asphalt Institute, College Park, MD, Manual Series 2, March 1974.

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Laboratory Evaluation of Asphalt Emulsion Mixtures by Use of the Marshall and Indirect Tensile Tests

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A laboratory procedure for specimen preparation, developed to characterize the asphalt emulsion mixtures used in base courses, is described. The main factors considered in the technique are aggregate coating, workability of the mix, and rate of moisture loss from the mix before and after compaction. The Marshall test was performed at room temperature to evaluate the performance of the mixture. The mixture was further characterized by conducting the indirect tensile test at various temperatures. Both types of tests were conducted for different mix compositions and curing conditions. The specimens were vacuum saturated after different curing times to evaluate the resistance of the mixture to adverse moisture conditions. An evaluation system for asphalt emulsion mixtures is recommended based on the results of the investigation.