DESIGN OF EMULSIFIED ASPHALT-AGGREGATE BASES FOR LOW VOLUME ROADS

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This paper briefly summarizes procedures that have been developed for both mixture and structural design of emulsified asphalt-aggregate bases for low volume roads. The procedures are based on laboratory, analytical, and field studies. The Marshall equipment, resilient modulus, and a capillary moisture soak test are used for determining structural and durability properties. The mix design procedure determines the following: (1) suitability of aggregate and emulsified asphalt, (2) compatibility of emulsified asphalt and aggregate (including acceptable range of premix aggregate water content), (3) optimum moisture content at compaction, (4) optimum residual asphalt content, and (5) adequacy of mixture structural and durability properties. These procedures are developed specifically for dense graded cold mix base courses of low traffic volume roadways. The use of local aggregates has been particularly emphasized in this study. A method to relate the cold mixture structural properties, as determined from laboratory tests, to the "structural coefficient" of the base course was developed. Data obtained from specially cured specimens during the mixture design are used to determine the material's structural coefficient. The structural coefficient of the base is then used to select the required structural thickness using the AASHTO Interim Guide or similar design procedure. The procedures were evaluated over a range of actual in-service pavements and materials, and found to give satisfactory results.

Stabilization of granular base materials, particularly substandard aggregates, with emulsified asphalt has increased in recent years in Illinois and other states because of economical and environmental advantages. Field performance has been generally good, but because of lack of knowledge of mixture and structural design, and construction criteria, many problems have occurred.

Mixture design for cold EAMs has largely been based on field experience and simple laboratory mixing tests to estimate proportions of materials. Some emulsion producers have over the years developed simplified mix design methods such as McConnaughay (23) and Armak (18). A few more detailed methods have evolved in the past few years including Chevron (7, 17), U. S. Forest Service (24), California (13), Asphalt Institute (8), Chevron (9), the Asphalt Institute Pacific Coast Division (20), and Purdue University (22). Most of these procedures are very similar to each other and based mainly on hot mix design procedures. These procedures do not necessarily optimize the material proportions, but only attempt to meet certain minimum criteria such as percent coating, or stability. Since many additional emulsified asphalt-aggregate mixture (EAM) projects will be constructed on low volume roads in the future, there is a great need for standardized and verified design procedures.

A major effort has been underway at the University of Illinois, sponsored by the Illinois Department of Transportation and the Federal Highway Administration, to develop practical mixture and structural design procedures that could be used by various governmental agencies and others for low volume roads. These procedures have been completed and field tested. It is the objective of this paper to briefly describe the design procedures and practical results obtained from laboratory and field studies. Detailed descriptions of the research results and design procedures and background on their development are contained in References 1, 2, 3, 4, 5, and 6.

EAM Mixture Design

The mixture design procedure involves the following major parts:

1. Aggregate quality tests.
2. Emulsified asphalt quality tests.
3. Estimate of amount of asphalt emulsion content.
4. Compatibility of emulsion and aggregate.
5. Optimum water content at compaction.
6. Selection of optimum asphalt content.

Aggregate Quality Tests

Tests are conducted to determine aggregate properties and general suitability. Field experience has shown that a wide variety of aggregates can be successfully used in EAM bases. These aggregates include crushed stone or gravel, pit or bank run gravel, slag, sand, and silty sand. Use of substandard aggregates (that do not pass current specifications) have made satisfactory EAM bases on low volume roads in Illinois. Only aggregates containing excessive amounts of clay and certain hard to coat aggregates have caused problems in cold EAMs. Excessive clay results in difficulty in mixing due to severe ball-up of the emulsified asphalt, a longer time period required to gain strength, and a relatively large amount of residual asphalt content required for strength and durability requirements. A washed sieve gradation is required to determine the actual amount of fines in the aggregate.

Perhaps the most useful and simple test is the Sand Equivalent, which is a good indicator of the amount of excessive clay present. A Sand Equivalent value above 35 percent is predominantly granular and no excessive clay contents exist. Most pit run gravels in Illinois are well above this level, provided the soil overburden has not been mixed into the pit. Aggregates having a Sand Equivalent from 20 to 30 percent are much more difficult to stabilize and the amount of free mixing water and mixing procedures are more critical. Aggregates having a Sand Equivalent of less than 20-25 percent are usually not considered suitable for EAMs (7, 8, 9, 10, 11, 12). However, some aggregates have been used in Illinois with Sand Equivalent values of 17-22 with apparent success. Laboratory tests on the compacted mixtures show potential problems, and a large amount of residual asphalt is required (13).

Emulsified Asphalt Quality Tests

Standard ASTM or AASHTO tests and specifications are required:

Anionic	ASTM D 977	AASHTO M 140
Cationic	ASTM D 2394 or	AASHTO M 208

In some cases, additional specifications are required for other emulsion types such as High Float Emulsions (HFE)(13) which have been used in Illinois.

Estimate of Asphalt Emulsion Content

The determination of pre-mixing water content, compatibility of asphalt and aggregate, and optimum water content at compaction requires mixtures containing approximately the optimum residual asphalt content. Based upon several emulsified asphalt mixture design data, a regression equation was derived that gives an approximate optimum residual asphalt content. The information required to use this method is obtained from the washed sieve aggregate gradation.

$$R = 0.00138AB + 6.358 \log_{10}C - 4.655 \qquad (1)$$

where

R = trial residual asphalt content by weight of dry aggregate, %
A = percentage of aggregate retained on #4 sieve
B = percentage of aggregate passing #4 sieve and retained on the #200 sieve
C = percentage of aggregate passing on the #200 sieve
(Note: Gradation based only on washed sieve gradations.)

The R is rounded off to the nearest half percent to yield the trial residual asphalt content.

Example:
Retained on #4 sieve = 35%
Passing #4 and retained on #200 sieve = 57%
Passing #200 sieve = 9%

$$R = 0.00138 \times 35.0 \times 57.0 + 6.358 \log_{10}(8.0) - 4.655)$$
$$= 3.84\%$$

Thus, the trial residual asphalt content, R = 4.0% by weight of dry aggregate. To obtain an emulsified asphalt content, it is necessary to divide the trial residual asphalt content, R, by the fraction of residual asphalt contained in the emulsion. The following is an example for a CSS-1 emulsion:

Trial residual asphalt content = 4.0
Residual asphalt in CSS-1 emulsion = 65%

$$\text{Trial emulsion content (by wt. dry aggregate)} = \frac{4.0}{.65} = 6.15\%$$

Compatibility of Emulsion and Aggregate

The compatibility between asphalt and aggregate is a major mix design consideration. Two criteria that can be used to judge the compatibility are (1) coating achieved after mixing, and (2) the compacted EAM resistance to moisture (i.e., stripping). Several factors affect coating: aggregate/asphalt electro surface charge, free moisture existing in the aggregate before mixing with emulsion, temperature of materials, and aggregate surface texture. It is believed that coating is an important variable in providing mixture water resistance and strength. Both anionic (including HFEs) and cationic emulsions have been used successfully in Illinois with pit-run gravel and crushed limestone. The HFEs, however, contain up to 7 percent oil distillate that aids in the coating. Emulsion producers of both cationic and anionic (including HFEs) emulsions claim that they can adjust the emulsifying agent to provide satisfactory coating for most aggregates. For particular problem aggregates, however, one type of emulsion may clearly provide superior coating.

The amount of coating achieved depends upon the amount of premix free water existing in the aggregate. The optimum range of premix moisture in the aggregate can be determined by preparing laboratory bowl mixes at various premix moisture contents. A quantity of air dried aggregate is placed in the mixing bowl, and a desired amount of water added and mixed thoroughly with the aggregate. The asphalt emulsion is then added and mixed for a specified time period. To simulate cold mixing, none of the materials should be heated. After the EAM is mixed adequately it is placed on a flat pan until it breaks (as noted by a gradual change in color from brown to black). The coating can be judged visually by several persons and their estimates averaged, and a range of acceptable premix water content determined. In areas where the addition or removal of water is impossible or uneconomical, mixtures should be prepared at the in-situ aggregate water content.

Cationic and anionic emulsions behave differently with regard to coating and the amount of free premix water in the aggregate. Cationics generally require additional free water over anionic emulsion for good mixing, thus cationics can be used with aggregates containing relatively high water content.

Curves in Figure 1 illustrate results for a typical Illinois limestone aggregate using anionic (HFE) and cationic (CMS) emulsions. The anionics frequently do not require much free mixing water for good coating, whereas the cationic type requires some free moisture in the aggregate and it tends to ball up resulting in poor coating. If the anionic mixtures contain too much water, they begin to strip asphalt. Each aggregate/emulsion mix has its own characteristic curve, that must be determined through actual testing. Based on the coating tests, a range of acceptable premix aggregate water content is recommended for construction, considering that 50 to 100% coating is acceptable. If this coating cannot be achieved, the emulsion is rejected.

The determination of asphalt/aggregate compatibility with regard to its resistance to moisture effects is determined by subjecting compacted EAM Marshall sized specimens to free moisture in a test that simulates an in-service pavement base.

Water Content at Compaction

The total moisture content that exists in the CAM at time of compaction has significant effects on the resulting density, voids and stability. Several design procedures recommend that optimum compaction water content should be selected to maximize density, similar to granular materials (8, 9, 20).

There are, however, other factors that must be considered, including the breaking of the emulsion, mixture stability and the residual asphalt content. The water content obtained for maximum density when only water is used may not give the best liquid content to be used for mix design and construction. Results show that both residual asphalt content and water content at compaction affect the resulting stability as shown in Figure 2 for gravel EAMs. There is a specific residual asphalt content and moisture content at compaction that gives optimum stability. If residual asphalt content is held constant, typical results such as Figure 3 are obtained in the field and laboratory. Both show a characteristic peaking curve with an optimum moisture content of 4-6 percent. The loss of stability as moisture content decreases below about 3 percent is very rapid. Observations of mix color indicate that the mix is beginning to break at approximately 3 percent moisture as indicated by a change in color from brown to black. The field mix was initially compacted at about 3.3 percent moisture. Other field and laboratory observations indicate that moisture content for maximum stability and the beginning of breaking of the mix occurs at about the same time. EAMs that are allowed to break significantly before compaction become difficult or impossible to compact in the field. Addition of water will not bring the mixture back to a workable condition.

If the EAM is being placed as a road mix, the mixing process can continue until breaking begins (at optimum water content), and then immediately compacted. If a laydown machine is used, the total lift will begin to break at the top before the bottom because of surface dyring. The best solution is probably to limit lift thickness to 51-76 mm (2-3 in.) so that the entire lift will break at about the same time.

The typical effect of total liquid content on density and stability are shown in Figure 4 for specimens prepared with Marshall equipment. A maximum stability and density can occur at differing total liquid contents. The maximum dry bulk density typically occurs at a higher total liquid content than occurs for stability. These results are similar to hot mix where usually maximum bulk density corresponds to a higher asphalt content than does Marshall stability. The liquid content resulting in maximum density using Proctor compaction is higher than that obtained using the Marshall compaction equipment.

In summary, field and laboratory experience indicates that there is an optimum moisture content at compaction for a given residual asphalt content at which both stability and density will be near maximum. At moisture contents just below this optimum, the emulsion begins to break, and compaction must begin before much additional moisture is lost. If additional moisture is lost the EAM will be difficult to compact, and density and stability will be reduced greatly. Also if compaction is begun wet of optimum, the mix will not compact since all voids will be filled.

Selection of Optimum Residual Asphalt Content

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. Moisture susceptibility of the mixture is evaluated by subjecting a series of specimens to a special capillary water soak test for four days (referred to as soaked tests). The typical effects of residual asphalt content on mix properties are shown in Figure 5. The test property curves shown have been found to vary considerably between aggregate types and gradations. General trends are described as follows:

1. The one day dry stability will generally show a peak at a particular moisture content at compaction for a given residual asphalt content. Sometimes this curve is very flat and no peak is apparent, indicating a wide range of possible compaction moisture contents.
2. Soaked stability will generally show a peak at a particular residual asphalt content while dry stability will generally show a continually decreasing curve with increasing residual asphalt content. Some mixes may show a continual increase in soaked stability over the range of asphalt content evaluated, which indicates the increased beneficial effect of additional asphalt content on soaked stability.
3. Percent stability change is computed by (dry stability - soaked stability)100/dry stability. The amount of loss of soaked as compared to dry stability decreases as residual asphalt content increases.
4. Dry bulk density generally peaks at a particular residual asphalt content.
5. Percent moisture absorbed during the soak test decreases with increased residual asphalt content.
6. Percent total voids (air plus moisture) decreases as residual asphalt content increases.

The capillary absorption (or soak) test is believed to be the most realistic test available that represents field moisture conditions of an EAM base course. Extensive use and evaluation of the test has shown it to be very simple, convenient, and realistic test (13, 3). The only disadvantage is the relatively long soaking time required. Based upon experimental testing, a 4-5 day soak is believed adequate to provide a realistic indication of the moisture durability of the EAM. This test is shown in Figure 6.

Based upon results from field and laboratory studies (1, 2, 3) in Illinois and other studies (14, 15, 16, 17, 18, 9, 19, 4, 21, 11) the following design criteria are considered important in selecting the optimum residual asphalt content:

1. EAM must provide an adequate stability when tested in a "soaked" condition to provide adequate resistance to traffic load during wet seasons. There is considerable free moisture available in Illinois. Most subgrade soils are poor draining and most low volume roads are constructed with poor drainage characteristics (i.e., no side ditches, high watertable).
2. The percent loss of stability of the EAM when tested "soaked" as opposed to "dry" should not be excessive. A high loss is indicative of the EAM having high moisture susceptibility and may cause softening and disintegration during wet seasons.
3. The total voids within the EAM should be within a specified range to prevent either excessive permanent deformation and moisture absorption (for too high 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 to minimize the potential of stripping or weakening the bond between residual asphalt and aggregate.
5. Residual asphalt should provide adequate coating of the aggregate and should be resistant to stripping.

The basic design philosophy is that a residual asphalt content should be selected that meets all of the criteria, and maximizes the soaked stability. Specific design criteria are summarized in Table 1.

Structural Design

Procedures were developed for use in design that related cold mix base structural properties to pavement performance (4). Thus, the structural properties can be measured in the laboratory and the results used in structural design of the pavement using the AASHTO Interim Design Guides, or similar design procedure. The resilient modulus (M_R) of the cold mix base was correlated with the structural coefficient of the base. A stress dependent finite element pavement structural analysis program along with performance data and results from the AASHO Road Test were used to develop the approximate correlation as described in Reference 4.

The structural coefficient for cold mix bases (a_2) is believed to fall between that of non-stabilized granular materials ($\simeq$ 0.11) and hot mix asphalt stabilized ($\simeq$ 0.35). The M_R for these materials ranges between approximately 68,940-206,820 KPa (10,000-30,000 psi) for non-stabilized granular materials to 689,400-6,894,000 KPa (100,000-1,000,000 psi) for hot mix asphalt stabilized granular materials. It is within these bounds (and only for asphalt stabilized materials) that an approximate correlation exists. A correlation curve between the base structural coefficient (a_2) and the base resilient modulus is shown in Figure 7.

The measurement of the resilient modulus of the cold mix requires expensive equipment which many laboratories may not have available. Hence, it is highly desirable that a simpler test such as Marshall Stability be correlated with the M_R test. During the experimental laboratory phase of this study the M_R and modified Marshall Stability tests (at 22.2°C) were conducted on many of the same specimens. A reasonable correlation was found to exist between the two tests (4). Using this correlation a relationship can be established between the modified Marshall Stability (at 22.2°C) and the a_2 coefficient. Such a relationship is shown in Figure 9. It should be emphasized that this is only approximate and that the best procedure is to measure the M_R directly on the specimens.

The structural coefficient of asphaltic cold mixtures used in design is determined as follows:

1. Conduct laboratory testing on compacted asphaltic cold mixture specimens containing the recommended residual asphalt content and compacted at the recommended moisture content. The following alternative tests may be conducted:

Alternative A. (preferred)	Diametral resilient modulus as described in Reference 4.
Alternative B.	Modified Marshall stability at 22.2°C (same standard test procedures except conducted at 22.2°C).

The following sequence of testing should be followed for either alternative:

3 compacted specimens retained in mold and dry cured for 3 days in laboratory at 22.2°C, then tested by alternative A or B;

3 compacted specimens retained in mold and dry cured for 3 days in laboratory and then placed in the capillary soak test for 4 days (specimens are rotated after 2 days) at 22.2°C, then tested by alternative A or B.

This data can be obtained routinely from the mixture design tests previously described.

2. Using the data obtained routinely from the mixture design tests, the resilient modulus or modified Marshall stability values are converted to "design" values using one of the following expressions.

Alternative A. Resilient Modulus

$$M_{R_{design}} = M_f \left(\frac{M_m}{M_d}\right)$$

where

M_f = final average resilient modulus of mixture after long term curing, psi
= M_d x CF
M_d = resilient modulus determined after 3 days of dry cure at 22.2°C
CF = a curing factor (2.0 for construction May-Sept. in Illinois and not sealed for >7 days)
M_m = resilient modulus determined after 3 days of dry cure and 4 days of capillary moisture cure at 22.2°C

Alternative B. Modified Marshall Stability

$$MS_{design} = MS_f \left(\frac{MS_m}{MS_d}\right)$$

where

MS_f = final maximum modified Marshall Stability of mixture after long term curing at 22.2°C lbs
= MS_d x CF

MS_d = modified Marshall Stability determined after 3 days of dry cure at 22.2°C

CF = a curing factor (2.0 for construction May-Sept. in Illinois and not sealed for >7 days)

The CF may range from 1 to over 4 depending on time of construction and when the base is sealed. For general design purposes in Illinois a CF = 2.0 is recommended if the base is constructed during the May-September period and is allowed a few days (>7 days) to cure before an overlay or seal is placed.

MS_m = modified Marshall Stability determined after 3 days of dry cure and 4 days of capillary moisture cure at 22.2°C

3. The $M_{R_{design}}$ or MS_{design} is then used in either Figure 7 or 8.

Base Design Application

A county road in Illinois which has an existing granular surface is being up-graded by stage construction. The first stage includes placing an emulsified asphalt stabilized base course over the existing granular surface, which will be compacted and used as a 101.6 mm (4 in.) subbase.

The aggregate is from a pit located near the project and, if acceptable, would provide considerable economic advantage over hauling in other aggregate. The aggregate properties are given in Table 2 and the emulsion properties in Table 3. The washed gradation reveals a relatively high fines content, which was apparently due to the failure to strip overburden at the pit. A relatively high amount of clay is indicated by the low Sand Equivalent value of 22. The 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.

The optimum residual asphalt content is estimated to be 5.4 percent as computed by Eq. 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 optimum asphalt content. The best aggregate coating was obtained at pre-mix 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 optimum asphalt content), and compacted over a range of moisture contents. The specimens were air cured 1 day on a laboratory shelf, extruded from their molds, and tested in the Marshall stabilometer at 22.2°C (72°F). A curve shown in Figure 9 was obtained, with maximum stability occurring at 3.5 percent total moisture content (by weight of dry aggregate). This optimum moisture content at compaction was used for compaction of all other specimens.

Compacted EAM specimens were then prepared over a range of residual asphalt contents. Specimens were tested after 3 days of laboratory air curing, called dry curing, for Marshall stability at 22.2°C (72°F). Other specimens, after the 3 day dry cure, were subjected to 5 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 moisture contained in the specimens were also determined as described in Reference 5. Total voids were computed utilizing these data (13). Results are plotted in Figure 9. Maximum soaked stability occurs at approximately 5.3 percent residual asphalt. There is a large loss of stability between the dry cured specimens and soaked specimens, but the amount of difference decreases with increasing asphalt content. A large loss such as this has only occurred with aggregates having a low Sand Equivalent (<25) and a large amount of fines (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 content:

Mix Parameter	Value at 5.3% Asphalt	Limiting Criteria
% Stability Loss	57	50 max
% Total Voids	6.7	2-8
% Moisture Absorption	3.6	4 max
Modified Marshall Stability, lbs	550	500 min
% Aggregate Coating (3-5% premix moisture)	60-70	50 min

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

The following mixture design and construction recommendations are obtained:

1. Residual asphalt content = 5.6% by weight of dry aggregate.
2. Asphalt emulsion content (for an asphalt residue of 70%) = 5.6/0.70 = 8.0% by wt. of dry aggregate, or approximately 19.4 gal emulsion/ton dry aggregate.
3. Pre-mixing water content = 3-5% by weight of dry aggregate.
4. Optimum water content at compaction = 3.5% by weight of dry aggregate (that is, total water content in EAM).

Structrual design of the base makes use of data from the mix design tests at optimum asphalt content. The Marshall stabilities at 22.2°C and 5.6% residual asphalt are as follows:

3 day dry cure = 590 Kg (1300 lbs)
3 day dry cure and 4 day capillary soak = 250 Kg (550 lbs)

The loss of stability after soaking is very significant for this aggregate. The structural coefficient of the base material is determined as follows:

$$\text{Design Marshall Stability} = (1300 \times (2.0)(\frac{550}{1300}) = 499 \text{ Kg } (1100 \text{ lbs})$$

Using Figure 8 the a_2 = 0.17.

Traffic over the 15 years design life is estimated for the average year as follows:

Passenger Cars = 413/day
Single Unit Trucks = 94/day
Multiple Unit Trucks = 20/day

Total Vehicles = 527/day

The total 18-kip ESAL over the 15 year period is computed to be 69195 80 KN (18-kip) ESAL. Subgrade soils along the project are A-6 classification and have measured CBR values of approximately 3. The required structural number for the 15 year period is determined using the AASHTO Interim Guide with a Regional Factor of 1.5 to be 2.7. Thus, the required thickness of base is computed as follows (the surface will be 3 in.):

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

$$2.7 = 0.22(3\text{ in.}) + 0.17\ D_2 + 0.11 \times 4\text{ in.}$$

$$\text{Base thick } (D_2) = 239\text{ mm } (9.4\text{ in.})$$

This large thickness is required because of the low quality of mixture.

The project was constructed in 1976 using road mix procedures. The actual construction did not exactly follow the recommended design. Three lifts were used: 64, 64, and 51 mm (2.5, 2.5, 2.0 in.) thickness, for a total of 178 mm (7 in.) which is less than that recommended. The water content of the gravel prior to mixing was 5.9 percent (which is greater than the optimum 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 results obtained are given in Table 4. These data indicate that the field obtained mix has less stability and greater moisture content than the lab mixtures. 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.

Conclusions

The construction of cold mix bases has been based on field experience and/or simple mixing tests. This has led to field performance problems in several pavements. Standardized procedures have been developed to improve the design and construction procedure so that acceptable performance can be assured. The procedures have been field tested and found to give reasonable results. Economically, this research can result in a reduction in the cost of the construction of roads carrying low-volume traffic. This will occur when substandard aggregates can be stabilized successfully with emulsified asphalts for the construction of quality bases for economical use of low-traffic roads. A second benefit, that may become quite important in the future, is the conservation of rapidly disappearing, quality aggregate sources. When substandard aggregates are used instead of quality aggregates, the demand for quality aggregates is reduced and thus more quality aggregates are available to be used in construction of higher-type roads.

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Table 1. Emulsified asphalt-aggregate mixture design criteria.

Test Property	Minimum	Maximum
<u>Stability</u>, N (lb) at 22.2°C (72°F)		
Paving Mixtures	2224 (500)	
<u>Percent Total Voids</u>		
Compacted Mix (granular mixes, no requirement for sand)	2	8
<u>Percent Stability Loss</u>		
After 4 days soak at 22.2°C (72°F)	--	50
<u>Percent Absorbed Moisture</u>		
After 4 day soak at 22.2°C (72°F)	--	4
<u>Aggregate Coating (%)</u>	50	--

Table 2. Properties of gravel pit aggregates.

	Sieve Analysis		
	Sieve	Dry	Washed
	1 1/2	100	100
	1	98	98
Specific Gravity - Surface dry 2.36	3/4	96	96
Absorption % - 5.0	1/2	90	92
Abration, Los Angeles % Loss 24.4	3/8	86	87
	#4	67	70
	#16	27	39
	#200	4	17
Sand Equivalent (-#40 sieve)	22		
Standard Proctor Dry Density 123.7 pcf Water Content 9.8%			
Natural Water Content of Pit ≈4%			

Table 3. Emulsified asphalt properties for HFE-300 grade used.

Specific gravity at 15.5°C (60°F)	0.990
Viscosity, Saybolt Furol, at 50°C (122°F)	110.4 secs.
Sieve test, retained on No. 20 sieve	.016%
Settlement	1.4%
Coating test 3 minutes	Passed
Float test at 60°C (140°F)	1200+ secs.
Distillation test to 260°C (500°F)	
Residue from Distilation	70%
Oil distillate, by volume	1.5%
Characteristics of residue from distillation test to 260°C (500°F)	
Specific Gravity at 25°C (77°F)	0.980
Penetration at 25°C (77°F), 100 g., 5 sec.	380+

Table 4. Comparison of field and laboratory data for gravel aggregate project.

Curing	Laboratory Mix Design Stability at 4% Asphalt (N)	Field Mix Stability at 4% Asphalt (N)	Moisture Content at Testing %	
			Lab	Field
3 Day Dry	9786	6174	2.2	2.6
3 Day Dry + 5 Day Soaked	2002	1299	7.0	7.7
		% Water Absorption =	4.8	5.1

(1 lb = 4.448 N)

Figure 1. Illustration of coatings obtained for a typical Illinois crushed limestone for two emulsions.

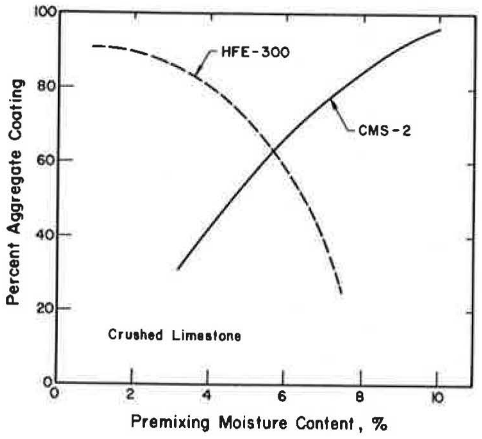

Figure 2. Contours of equal soaked stability for various residual asphalt and compaction moisture contents for gravel aggregate (3-day cure and 75 blows).

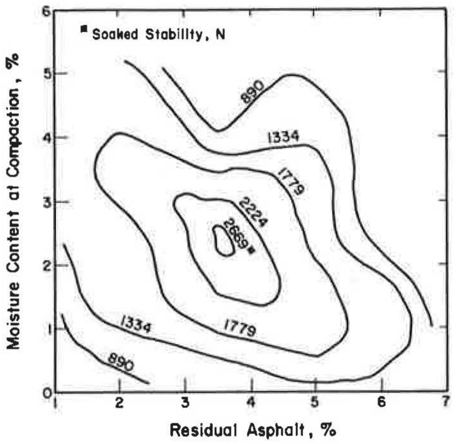

Figure 3. Effect of water content at compaction on Marshall Stability at 25°C (HFE-300, crushed limestone).

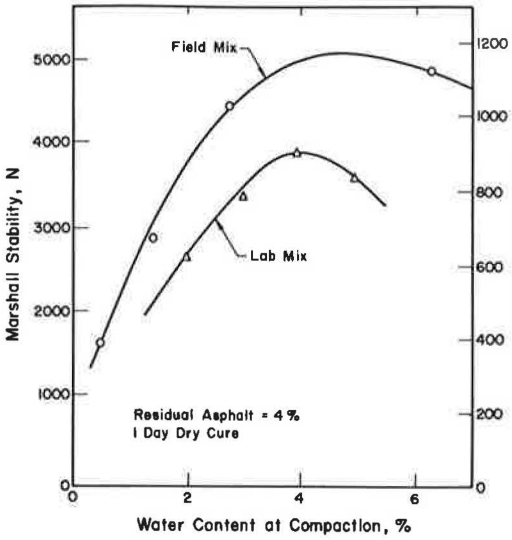

Figure 4. Effect of total liquid (asphalt + water) at compaction of EAM on stability and dry density using Marshall equipment (75 blows)(residual asphalt = 3-6%, water content = 4%).

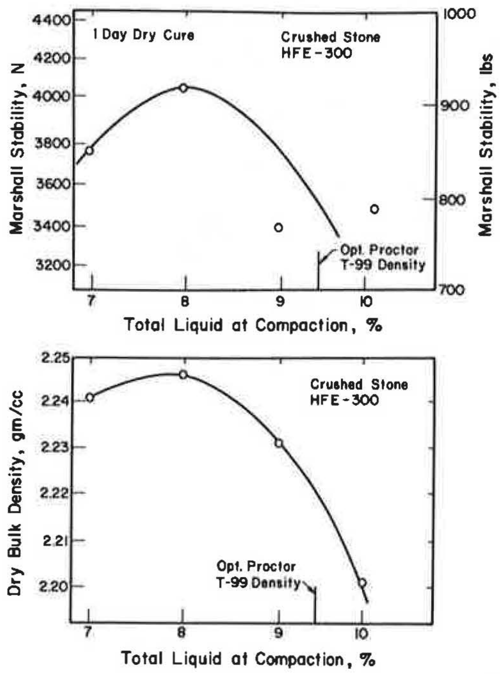

Figure 5. Typical emulsified asphalt-aggregate mixture design plots.

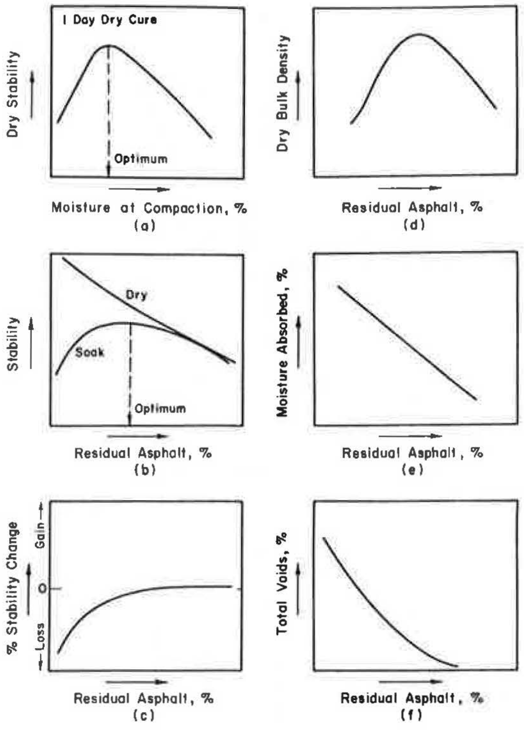

Figure 6. Emulsified asphalt-aggregate mixture soak test equipment (Note: a top cover is required to prevent moisture loss).

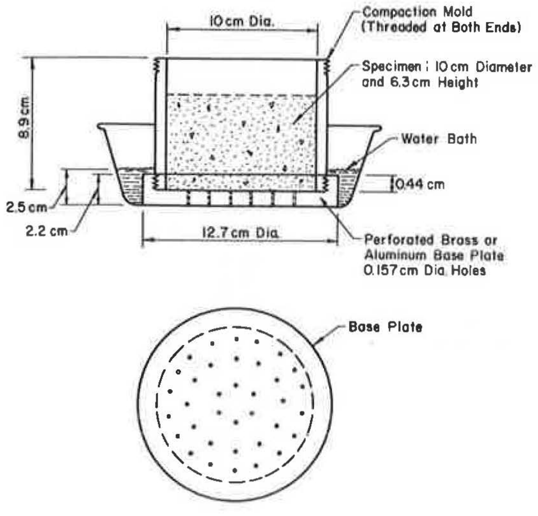

Figure 7. Correlation between base structural coefficient, a_2, and resilient modulus, M_R, at 22.2°C.

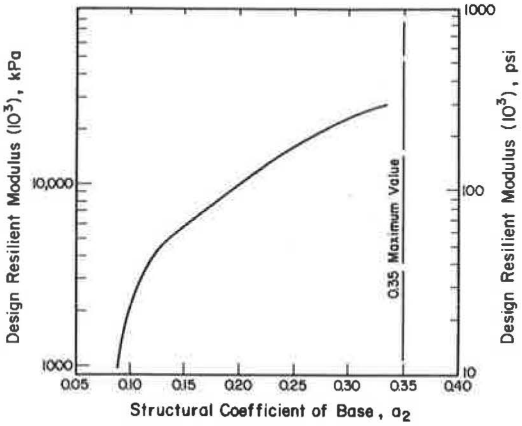

Figure 8. Correlation between base structural coefficient, a_2, and design Marshall Stability at 22.2°C.

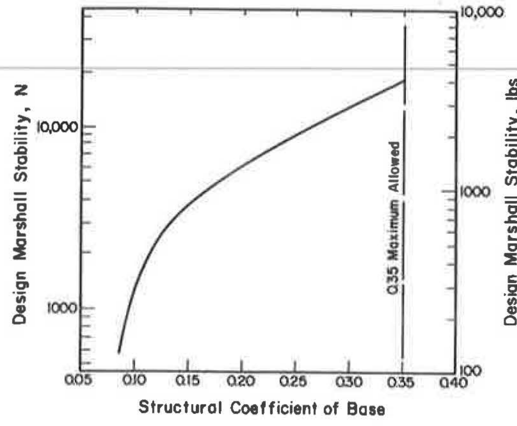

Figure 9. Mix design for pit run gravel and HFE-300 emulsion.