MIX DESIGN CRITERIA FOR CEMENT MODIFIED EMULSION TREATED MATERIAL

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This paper is the second part of a comprehensive investigation of the stabilization of sands and sand-clay aggregates with asphalt emulsion. The objective here is to develop mix design criteria for emulsion treated soil aggregates. Previous investigations by author and others suggest that cement in trace quantities is indispensible in order to enhance the durability of sand-emulsion mixtures; accordingly Cement-modified Emulsion Treated Material (CETM) only is studied herein. With due consideration to the prevailing distress mechanisms in cold mix bases, several tests are proposed to evaluate CETM. Marshall stability and shear strength tend to exhibit an optimum, respectively, with emulsion content and fines content. It appears feasible to predict the Marshall stability of CETM from a simple soil property such as particle size distribution. Using the test results on five naturally occurring soils and one synthetic aggregate mix design criteria for sands and sandy soils is proposed. Minimum Marshall stability of 4.23 kN (950 lbs) insures that CETM will not undergo shear failure under heavy truck tire pressure. Another criterion to detect and avoid moisture susceptible mixtures is that Marshall cylinders during vacuum soaking should not absorb more than 8.5% moisture. A third criterion to safeguard against stiff mixtures is that the seven day "dry bearing strength" shall not exceed 2760 kPa (400 psi). The recommended design values and test method are presented and discussed in the paper.

Bituminous emulsions are used widely in the construction and maintenance of low-volume rural roads and city streets. Two classes of asphalt emulsion are commonly used. Cationic emulsions (positively charged particles) adhere better to such electronegative aggregates as silica and quartz; anionic emulsions (negatively charged particles) have better adhesion on carbonate aggregates. Because such a wide variety of aggregates is used in pavements, ionic characterization may, however, be of secondary importance.

Because emulsified asphalt in base stabilization has been used on a limited scale only insufficient data are available concerning the response of emulsion to various aggregates; for this reason, select aggregates have, for the most part, been used in roads during the last two decades. For instance, of the thirty projects which Finn et al. (5) surveyed in seven states, only seven of the bases included sandy or fine-grain soils. Kerston and Pederson (11) and Korfhage (12) reported poor performance with SS-1 in Minnesota loess and a poor quality aggregate. Scrimsher et al. (18) reported that two cold aspalt emulsion mixtures - one a dense graded and the other an open graded - placed as a 25 mm (1 in.) overlay on an existing pavement showed noticeable raveling and the surface caused rough riding. Meier (14) recently reported three projects in the Northwest in which fine sand was stabilized with slow setting grade emulsified asphalt. Again, the performance of two of the three projects was less than satisfactory. One problem involved the difficulty of aerating the mixture, a circumstance which was attributed to the finer gradation. Nevertheless, successful use of emulsified asphalt in sand and cohesive graded sand has been reported by Fruedenberg (6). As Bratt (2) remarked, however, numerous problems exist; for example, finding a specification that will guarantee consistent behaviour of emulsions. The numerous failures reported in the literature suggest the lack of a system for evaluating the amenability of a soil to stabilization with asphalt emulsion. Various factors affecting emulsion stabilization of sands and silty sands have been reported in a previous paper (7). That study, as well as others (17,19), shows that portland cement in trace quantities (1-1 1/2%), acting as a stabilizing agent, greatly enhances the soak-stability of sand-emulsion mixtures. In this study, therefore, we are concerned only with Cement-modified Emulsion Treated Material (CETM).

Because of the increased interest in emulsion, due in no small part to the influence of the Federal Energy Administration and the E.P.A. plus the recommendation of the Federal Highway Administration, investigators at the University of Mississippi have embarked on a research program to determine whether local sands and silty sands can be economically used for base stabilization. This report, therefore, focuses on developing mix design criteria for emulsified asphalt bases. This objective will be accomplished in three steps: (1) Choose feasible test methods and procedures for evaluating the desired properties of cold mixes. (2) Use these methods to evaluate the strength, deformation, and moisture absorption properties of CETM. (3) Use these results to propose appropriate mix design criteria.

Materials

Soils

Six sandy soils were selected for study; their physical properties are given in Table 1. For convenience a one letter two digit system is used to identity each soil; for example K38 designates soil #38 with Kaolin as the predominant clay mineral. The percentage fines (percentage fines refers to the amount of material passing through a #200 sieve) of these soils varies widely - namely two of 10%, 12%, 14%, 16% and 17% - as does the uniformity coefficient. All, except K46, are naturally occurring soil aggregates from various locations in Mississippi. Soil K46, however, is a 3:2 blend of a coarse sand and silty clay.

Asphalt Emulsion

Because siliceous aggregates (for that matter, most other highway aggregates) are electronegative cationic emulsion (CSS1) is preferred and is being used in this investigation. The properties of the asphalt emulsion, as furnished by the manufacturer, are listed in Table 2.

Mix Preparation

Air-dried aggregate was first blended with cement and subsequently moistened with water before mixing with the emulsion. The ingredients (aggregate and emulsion) were hand-mixed for one minute, followed by machine mixing until the aggregate was evenly coated. To facilitate even coating, excess moisture (2% to 3%) was added during mixing and subsequently evaporated by a blower.

Organization of the Report

In accordance with the stated objectives, the results of this study are presented in four distinct phases. A brief description of the proposed tests constitutes the first part of this report. Relevant material properties such as Marshall stability, triaxial shear strength, and permanent deformation are presented in the second part of the report. In the third phase of the study, the results are analyzed to propose mix design criteria for CETM. The last section presents a systematic step-by-step procedure (or a methods manual) for design of CETM mixtures in the laboratory.

Selection of Test Methods

The methodology used in making mix-design recommendations was to first determine the significant failure modes in cold mix bases. Then, considering these failure modes, basic required material properties of cold mix bases were identified. Available tests were then evaluated in respect to their effectiveness in measuring these required properties.

A recent study (10) reported that distortion caused by instability is the distress most prevalent in the existing cold mix bases; followed by disintegration and cracking. The survey study currently reported by the writer tends to substantiate this observation (8). Two types of permanent deformations are identitied: the first, consolidation deformation; and the second, plastic deformation, which is due to appreciable vertical and lateral shear failure movement of large masses under wheel loads. Shear strength, therefore, is considered a basic property in a cold mix.

Stability Test. The stability of CETM is the relevant property utilized in proposing mix design criteria. Marshall stability results have generally been considered satisfactory for assessing the overall strength and stability under repeated application of wheel loads. Other factors in favor of the Marshall test are (a) ability of the test method to simulate in-service conditions, (b) reproducibility of test results and (c) simplicity of execution.

Marshall test specimens 102 mm (4 in.) in diameter by 64 mm (2.5 in.) high were prepared according to ASTM D 1559, except for the modification that 75 blows, instead of 50, were applied on both sides. These specimens, wrapped except for the top face, were air dried for seven days at 50% relative humidity (RH) and 25° C (72°F) before testing at a loading rate of 51 mm (2 in.) per minute. This curing procedure is referred as "partial air-cure" in this report.

Shear Strength Test. In considering the principal failure mechanisms observed in ETM bases, one realizes that shear strength is an important property of the mixture. Undrained shear strength parameters (by triaxial test) are obtained from vacuum soaked specimens, 70 mm (2.8 in.) in diameter and 152 mm (6 in.) high. In order to minimize the effect of viscous resistance on shear strength parameters (thereby rendering a very conservative estimate of shear strength parameters), the rate of strain is set at 0.13 mm (0.005 in.)/min.

Repeated Triaxial Tests. Permanent or plastic deformation of pavement materials is especially significant in estimating the rutting of pavements. Each specimen tested, 70 mm (2.8 in.) in diameter by 152 mm (6 in.) high, was subjected to thirty load pulses per minute. The pulse used had a triangular shape and a duration of 0.20 seconds. Specimens were tested to an average of 10,000 load repetitions using constant confining pressures of 35 and 70 kPa (5 and 10 psi). Deviator stresses varying from approximately one to six times the confining pressure were used in the repeated load tests. Permanent axial and elastic deformations occurring at the mid-height of the specimens were measured by means of a pair of linear variable differential transducers (LVDT). It should be noted that elastic or rebound strain is used in modulus of resilience calculation, whereas the plastic or permanent strain is important in estimating the distortional characteristics.

Moisture Susceptibility Test. Of the various moisture susceptibility tests reviewed, the vacuum saturation method appeared to be most appropriate. The advantage of this method over others is that the distribution of moisture in the soaked specimen is nearly uniform within the whole mass of the specimen. When the moisture distribution within the specimen was not uniform, as occurred in the MVS test, strength results were not reproducible. Althrough several variations of vacuum soaking are

TABLE 1. Soil identification and compositional data

Soil No.	Location	Passing #200 Sieve, %	Liquid Limit, %	PI	Unified System Classification	Fines Ratio*	CKE Oil Ratio
K-38	Highway 6, Oxford	10	14	NP	SW-SM	0.133	5.5
K-40	Highway 6, Oxford	17	15	NP	SM	0.200	6.0
K-44	Calhoun Co., MS	14.5	18	NP	SM	0.184	6.5
K-45	Oxford, MS	10.0	--	NP	SP-SM	0.120	---
K-46	Oxford, MS	16.0	16	NP	SM	0.276	---
K-48	Rankin Co., MS	12.0	--	NP	SP	0.122	6.5

*Fines Ratio = material passing #200 sieve/material passing #40 sieve

TABLE 2. Properties of asphalt emulsion

Property	Cationic CSS-1
Emulsion:	
Furol viscosity @ 28°C	35-65
Settlement, 5 days, %	---
Cement mixing, % broken	0.1
Residue (by distillation), %	64.0-68.0
Base Asphalt:	
Penetration at 28°C, 100 g, 5 sec.	±140
Solubility in CS^2, %	---
Ductility @ 28°C 5 cm/min, cms	100+
Ionic charge	positive

presently in use, the water susceptibility test method suggested by the Asphalt Institute was adopted in this study. Marshall test specimens were subjected to one-hour vacuum saturation at 100 mm (4 in.) mercury followed by one hour of soaking at normal atmospheric pressure. A complete description of the vacuum soaking procedure can be seen in reference 16.

Strength Properties of CETM

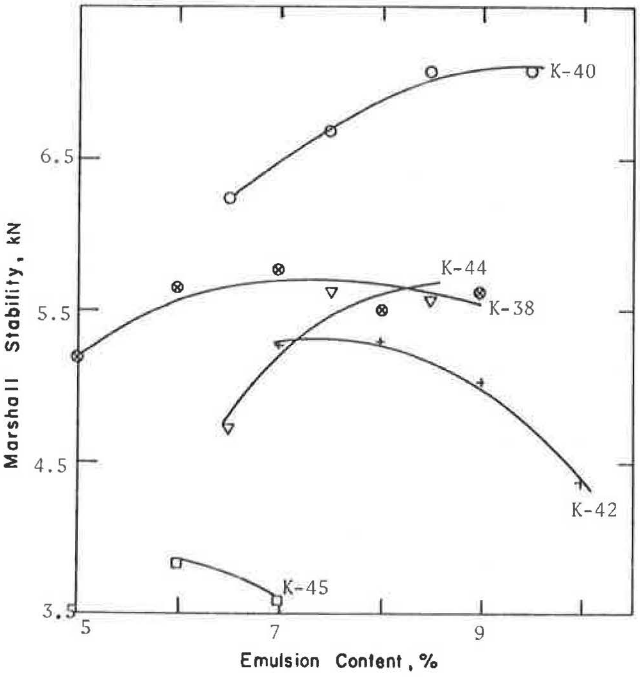
The investigations, as described in references 8, 17 and 19, show that for ETM mixtures with trace cement (1% to 1-1/2%) would be a satisfactory material for base construction. In order to propose mix design criteria, however, the strength and deformation properties of CETM were determined, and the results are presented herein.

Marshall Stability

The effect of different variables, such as emulsion content and fines content on the stability of CETM mixtures at 25±1°C (72±2°F) was investigated by the modified Marshall test. The seven-day air-dry (air-dried from top face only) stability values generally decrease with an increase in emulsion content from 6% to 10%. Dunn and Salem (4) reported optimum bitumen content of 5% for Leighton Buzzard sand after seven days curing. The soaked stability results (Fig. 1) are more consistent in that they increase with emulsion content; attain an optimum value somewhere between 6% to 9%, depending on the fines content; and then either remains constant or slightly decreases. In other words, in many aggregates it is possible to find an optimum emulsion content giving the most stability.

The effect of fines content is such that both the dry and the soaked stabilities increase with fines, peak at about 15% to 18%, and then gradually decreases (7,8). As the fines content increases, the density also increases; this increase in density is primarily responsible for the increase in strength. On the other hand, a large fines content in excess of the optimum has an adverse effect on the mixture. The fines absorb a large quantity of water which causes swelling in the mixture and negates some or all of the stability gained from increased density.

Figure 1-Variation of Marshall Strength (7-day air cured and vacuum soaked) with emulsion content. Temperature 25±1°C.



Note: 1 kN = 225 lbs.

This brief discussion reveals that numerous factors pertaining to soil, emulsion, and mixture-properties govern the stability of the end product. Therefore, it would be significant if Marshall stability (soaked) could be correlated to the various properties. Those properties thought to have some bearing on Marshall stability are:

1. Percentage fines (PF)
2. Fines ratio (FR = $\frac{\text{percent fines passing sieve \#200}}{\text{percent fines passing sieve \#40}}$
3. Particle index (PIn, Particle index is a measure of geometric characterisitcs which include shape, angularity and surface texture.)
4. Emulsion content (EC), percent
5. Penetration of emulsified asphalt (Pen) (The penetration of the bitumen in emulsion samples varied around 140.)
6. Dry density of compacted mix (γ_d), pcf
7. Cement content (Cm), percent

TABLE 3: Experimental Marshall stability values of CETM after soaking compared with those prodicted by Eq. 1.

Soil No.	Cement, %	Emulsion, Water, %	Dry Density, kg/m^3	Marshall Stability, kN	
				Experimental	Predicted by Eq. 1
K-38	1.5	6 + 4 + 3[a]	1874	6.00	5.49
	0.5	7 + 3 + 3	1895	1.78	1.82
	1.0	7 + 3 + 3	1911	4.76	3.29
	1.5	7 + 3 + 3	1910	6.31	5.93
	1.5	8 + 2 + 3	1895	5.98	5.84
K-40	1.5	6.5 + 5 + 3	1953	9.78	11.15
	0.5	7.5 + 4 + 3	2002	3.44	2.82
	1.0	7.5 + 4 + 3	2019	4.89	5.69
	1.5	7.5 + 4 + 3	2019	10.44	11.51
	1.5	8.5 + 3 + 3	1950	11.02	10.84
K-44	0.5	6 + 6.5 + 3	1921	4.00	3.84
	1.0	6 + 6.5 + 3	--	6.67	5.53
	1.5	6 + 6.5 + 3	--	8.00	7.98
	1.5	7.5 + 5.8 + 3	1948	9.38	8.69
K-45	1.5	5 + 7 + 3	1828	3.53	4.62
	1.5	6 + 6.5 + 3	1844	5.29	5.47
	0.5	7 + 5.3 + 3	1850	1.78	1.82
	1.0	7 + 5.3 + 3	1841	3.47	3.29
	1.5	7 + 5.3 + 3	1847	4.98	5.93
K-46	1.5	5 + 5.5 + 3	--	9.69	8.13
	0.5	6 + 5 + 3	2046	3.42	4.64
	1.0	6 + 5 + 3	2065	8.44	6.69
	1.5	6 + 5 + 3	2031	9.87	9.64
	1.5	7 + 4.5 + 3	--	10.49	10.44
K-48	0.5	7.5 + 5.6 + 2	1871	1.33	1.75
	1.0	7.5 + 5.6 + 2	--	4.00	3.55
	1.5	7.5 + 5.6 + 2	--	6.00	7.15
	1.5	8.0 + 5.4 + 2	--	7.29	7.07

Note: 1 kg/m^3 = 0.0624 lb/ft^3, 1 kN = 225 lbs

[a] Legend 6 + 4 + 3, respectively, Emulsion, %+Compaction Moisture, %+Excess Moisture during mixing, %

Data from six soils were used to develop a functional relationship between these variables and the Marshall stability of seven-day cured, vacuum-soaked CETM mixtures. A sub-program named SSP-stepwise regression was used for this purpose. After a series of trials, properties two, three, five and six from the list were deleted because they showed little influence on stability. The functional relationship thus derived is given below:

$$\ell n(MS) = 6.7420 + 0.0943\ (FC) - 1.9866\ (Cm) - 0.0462\ (EC)^2 + 0.4529\ (EC \times Cm) \qquad (1)$$

in which Marshall stability (MS) is in pounds. (1 lb = 4.448N). Using Eq. 1, the Marshall stability values of six soils were predicted, and they were reasonably close to the experimental values, as can be seen in column 6 of Table 3. An important advantage of Eq. 1 is that in order to determine the stability values of a given soil, one needs to know only the particle size distribution of the soil.

Triaxial Shear Strength

Effect of emulsion content on shear strength parameters of mixture. The results show that the ϕ_u (friction angle) values of all soils tend to decrease with emulsion content. Cohesion values, however, increase slightly at low emulsion contents attain an optimum, followed by a gradual drop with further increase in emulsion.

Effect of fines content of soils on shear strength parameters of mixture. The cohesion of CETM increases with an increase in the fines content of the soil (Fig. 2a). This phenomenon may be attributed to the fact that on addition of emulsion to a soil, silt and clay size particles preferentially absorb emulsion, which in turn spreads and tends to coat the bigger sized particles. The surface area of contact is thus increased owing to the presence of such asphalt covered fine particles in the bituminous matrix thereby augmenting the cohesive characteristics of the mix. This hypothesis has been corroborated by microscopic examination of CETM mixtures, where the asphalt coated fine particles were seen sticking on to the surface of the larger ones (see Fig. 1 of reference 7). The increase in c_u value can also be attributed to the increase in density brought about by the fines.

The angle of internal friction, however, decreases with increasing amount of fines (Fig. 2b). As pointed out earlier, the fines, after absorbing the emulsion, spread and stick to the larger grains. Fines sticking to the bigger grains tend to diminish the grain-to-grain contact among the larger grains and thereby the angle of internal friction.

Using the c_u and ϕ_u values, it is possible to calculate the bearing strength of CETM mixture in accordance with the following equation, which is due to McLeod (13):

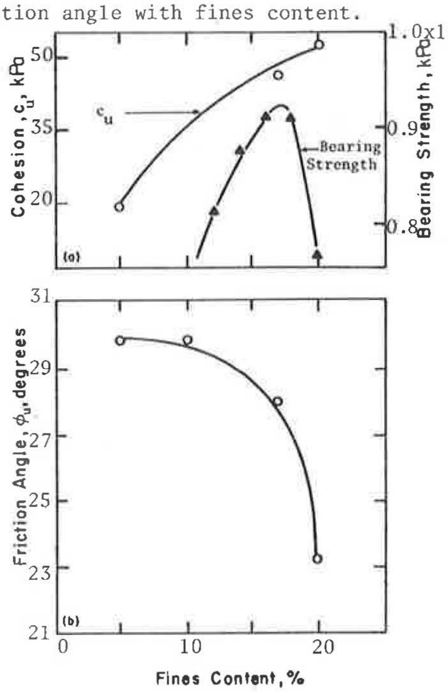
$$V=2c_u\left(\frac{1+\sin\phi_u}{1-\sin\phi_u}\right)^{\frac{1}{2}}\left(\frac{2}{1-\sin\phi_u-0.2\ \cos\phi_u}\right) \qquad (2)$$

The variation of bearing strength with fines content is plotted in Fig. 2a along with the c_u and ϕ_u values. The observation that a mixture with 17% fines exhibits optimum bearing strength is in excellent agreement with the Marshall stability values where the optimum is also approximately 17% (7). Considering the fact that uniformity of mixing is greatly hampered by a large amount of fines, the researcher recommends that the optimum fines content be one or two percentage points below 17%.

Permanent Deformation in CETM

The deformation data from repeated triaxial test show that both resilient strain (recoverable or rebound strain) and permanent strain increase with the deviator stress. The fact that the curvilinear relationship is concave upward suggests that the permanent strain increases at a faster rate beyond a resilient strain of approximately 0.02%.

Figure 2. Variation of cohesion, bearing strength and friction angle with fines content.



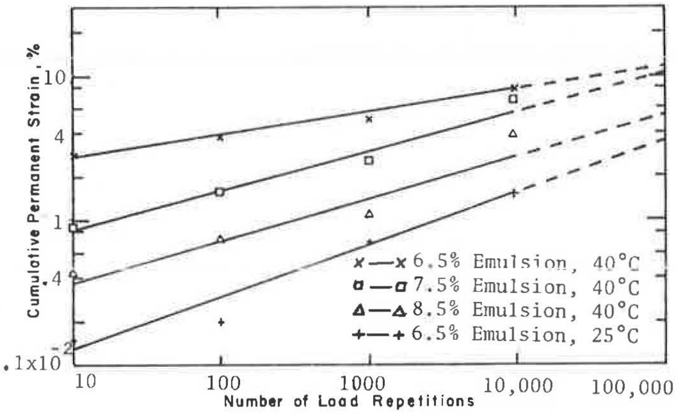
Note: 1 kPa = 0.145 lbf/in.^{2}

The relationship between cumulative plastic strain and the number of stress applications for varying emulsion contents is shown in Fig. 3. The permanent strain is seen to accumulate logarithmically with the number of load applications. Assuming a linear relationship between permanent strain and load repetitions, the anticipated strain at 40°C (105°F) after 100,000 cycles is extrapolated to be somewhat below 0.15%. In view of the tentative criterion that a rut depth of 6.3 mm (0.25 in.) is tolerable (20), we conclude that evidence is lacking to indicate that CETM will undergo such permanent deformation as to result in objectionable rut depth.

Development of Design Criteria

The overall design problem from the standpoint of stability consists of preventing detrimental shear within any one of the three elements of the composite structure - the subgrade, the base course and the wearing surface. In this discussion, the author assumes that an adequate thickness of base and surface has been provided to prevent subgrade failure. The fundamental problem, therefore, is to design CETM mixtures having sufficient stability to support the wheel loads to which they will be subjected. The discussion that follows attempts to provide a rational answer to this problem on the basis of test results provided by the triaxial test, Marshall stability test and vacuum soak test.

Figure 3. Influence of number of load repetitions on permanent strain. Deviator stress 275 kPa (40 psi) and confining pressure 69 kPa (10 psi). Soil K40.



Mix design criteria will be developed on the basis of strength and durability considerations as expressed by (1) stability of the mixture and (2) resistance to moisture intrusion, respectively.

Minimum Required Stability

Because shear failure is most crucial in CETM mixtures, the first step is to estimate the maximum shear stress or the equivalent vertical pressure that the pavement base is called upon to withstand. Considering that truck tire pressure varies from 551 to 689 kPa (80 to 100 psi), the pressure at the base level, in a typical pavement with 51 to 76 mm (2 to 3 in.) surfacing, shall be taken 517 kPa (75 psi). Assuming a load factor of 1.20 we may arrive at a design pressure of 620 kPa (90 psi).

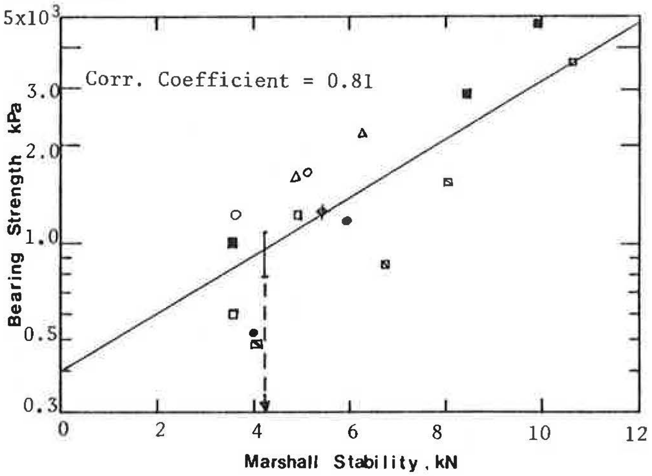
Field Methods are different from the laboratory methodology of mixing, compacting and curing. The writer's field experience with CETM suggests that 80% of laboratory strength is achievable in the field. Accordingly, the required equivalent soaked laboratory bearing strength will be 620/0.8 = 780 kPa (113 psi).

The analysis at this point shall focus on selecting a minimum bearing strength value using either the triaxial or Marshall test. If the triaxial test is chosen, Eq. 2 may be used to arrive at a combination of c_u and ϕ_u values required of a mixture to withstand a pressure of 780 kPa. A criticism often levelled against the triaxial test is that it is difficult to perform on a routine basis. Encouraged by the simplicity of the Marshall test procedure we may inquire how this test result could be used for mixture design. Using the Marshall stability and corresponding flow values, one can calculate the ultimate bearing strength in accordance with the following equation (6).

$$\text{Bearing Strength (psi)} = \frac{\text{stability}}{\text{flow}} \times \frac{120\text{-flow}}{100} \quad (3)$$

where stability is expressed in pounds and flow in units of 1/100 in. The accuracy of bearing strength calculation depends primarily upon the accuracy with which strength, and especially flow, is determined. The flow value determination during Marshall test has been subjected to criticism in that consistent reproducible flow values are difficult to obtain (7,10). Accordingly, the writer asserts that Marshall stability alone be used as a criterion. The question now is what value of Marshall stability in general corresponds to a bearing strength of 780 kPa. By plotting Marshall stabilities of several soils against the bearing strengths, as calculated by Eq. 3., a relation between these two quantities is established (Fig. 4). A safe stability value— defined as Marshall stability to withstand a vertical pressure of 780 kPa is obtained from the correlation in Fig. 4. For a Marshall stability of 4.23 kN (950 lbs) the 95% confidence interval for the mean estimated value of bearing strength is 780 kPa — 1082 kPa (113 psi— 157 psi). Stated differently a CETM mixture which exhibits a laboratory soak stability of 4.23 kN (950 lbs) would insure a bearing strength in the field of 620 kPa (90 psi) at 5% level of significance.

Figure 4. Bearing strength related to Marshall stability.



Note: 1 kPa = 0.145 lbf/in.^{2}, 1 kN = 225 lbs

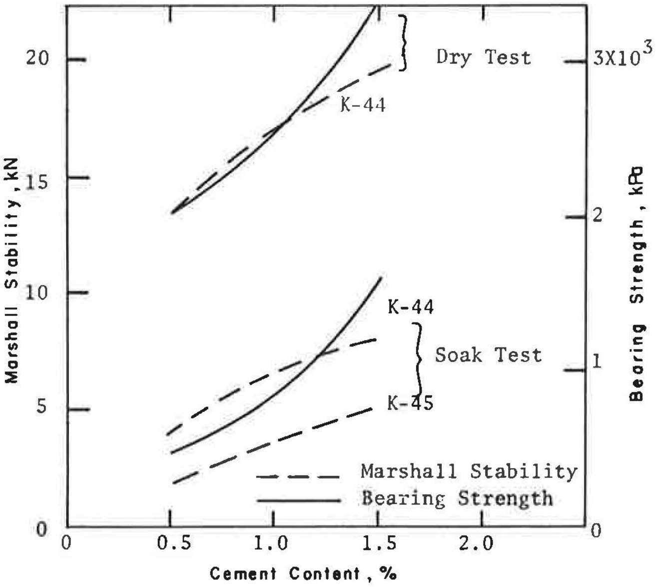
The question now arises as to whether a safety factor of 1.20 is acceptable for design purposes. Considering the test procedure and other design parameters, one can show that the present criterion will tend to give an actual safety factor greater than 1.20. For example, the pavement base will never be subjected to as severe water intrusion as is simulated in the vacuum soak test. The fact that the CETM mixture gains strength for a period of 120 days or more would tend to make the criterion based on seven-day strength conservative. If, in any particular case, a number of the above factors were operative and their effects additive, it can be shown that the safety factor of 1.20 in accordance with 4.23 kN soak strength may, in actuality, be as high as 1.5 to 2.

The minimum acceptable Marshall value of 4.23 kN suggested here appears to be in order, considering that the Asphalt Institute recommended a minimum value of 3.34 kN (750 lbs) for cutback asphalt paving mixtures (16).

Cement Requirment

Cement treatment of ETM is shown to be very effective with sands (7,17,20). Terrel and Wang (19) recommended up to 1% cement in selected aggregates primarily as a measure to overcome the detrimental effect of adverse curing conditions. Schmidt et al. (17) reported that the effectiveness of cement diminished as the cement approached 3%; accordingly, they favored 1.3% cement in ETM.

Figure 5. Variation of Marshall stability and bearing strength with cement content.



Note: 1 kN = 225 lbs, 1 kPa = 0.145 lbf/in.^{2}

The question not yet addressed in these studies is whether one can prescribe an optimum cement content for a given sand emulsion mixture. Marshall stability, flow and, thereby, bearing strength of all six soils with cement 0.5%, 1% and 1.5% were determined. A typical plot is shown in Fig. 5. A general trend in these results is that although the Marshall stability increment decreases with cement content, corresponding bearing strength increase is somewhat exponential at the high end of cement content, due primarily to the decrease in deformation. The fact that environmental stresses and consequent pavement cracking will be more prevalent in less flexible materials, therefore, led the writer to propose that, in order to be of optimum benefit to CETM, the cement content should be limited to 1.5%.

This result was corroborated in a recent field test program where a CETM base was constructed with K-44 soil at 6% emulsion and 2% cement. Although the drying shrinkage of the CETM was well below what is considered to be critical for pavement cracking, the base developed cracks to the tune of 0.39 m/m^2 (.12 ft./ft.^{2}). That the core strength has typically increased from 10,340 kPa (1500 psi) in 28 days to 17,230 kPa (2500 psi) in 18 months suggests that cement not only acts as a catalyst to increase the rate of curing of ETM but plays a major role in stabilizing the sand.

When the cement content was decreased from 1.0% to 0.5%, a good many of the soils became so susceptible to moisture intrusion that not only did their soak stabilities drop below the minimum of 4.23 kN, but also their retained strength plunged to somewhere in the neighborhood of 20% to 30%. Cement content of 0.5% is insufficient; therefore, the writer proposes that the optimum cement content should be between 1% and 1.5%. Exceptions to this general rule may be cited; for example, K-46 is sufficiently modified with 0.5% cement. Only a larger cement content of 1.5% has brought the soak stability and moisture absorption of K-45 to acceptable levels.

The writer asserts that the selection of cement content should be governed by the dry strength of CETM. In other words, a dry strength criterion is in order here. This can be accomplished by estimating a dry bearing strength corresponding to the acceptable soak bearing strength of 1082 kPa (157 psi). Anticpating a soaking condition in the field as severe as that in vacuum soak a loss of 60% could be a conservative value. Accordingly, the desirable dry bearing strength would be (1082 x 2.5) nearly 2706 kPa (392 psi) rounded to 2760 kPa (400 psi). In fact, no requirement in the field justifies a bearing strength higher than 2760 kPa.

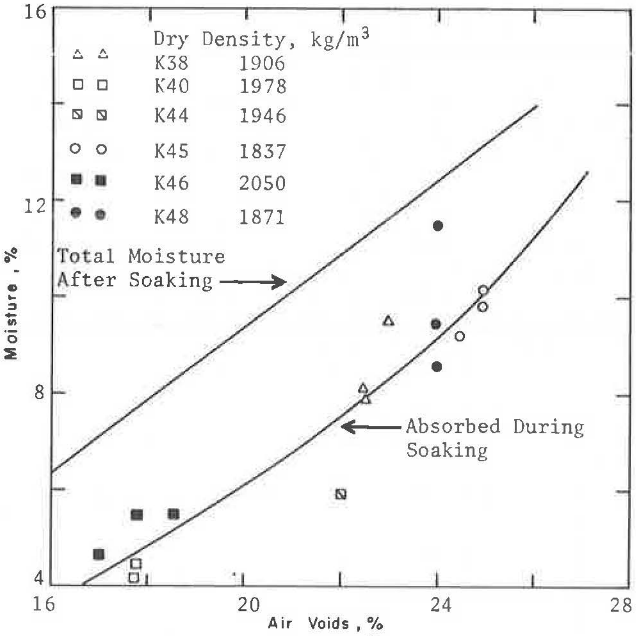
Permissible Moisture Absorption

Since moisture absorbed by the stabilized mixture is highly detrimental to its stability, and since this deterioration is dependent upon the extent of absorption, assigning a limiting value to the moisture absorption is considered important. The results show that the moisture absorption (percentage of moisture absorbed during vacuum soaking after seven-days air curing)increases with percentage of air voids (Fig. 6), which in turn is inversely proportional to the dry density of the mix (see inset of Fig. 6). Furthermore, the total moisture content (retained moisture after seven days plus moisture absorbed during soaking) increases linearly with the air voids. The spread between those two curves gives the moisture retention by CETM which slightly decreases with a decrease in density. When comparing the moisture contents during compaction, after seven-days curing, and after vacuum soak two important results emerge. First, the moisture retention after seven-days partial curing varies from 2.5% to 3.5%, depending on the fines content. Second, soils whose total moisture after soaking is much greater than the molding moisture (optimum moisture) would likely be susceptible to moisture in the field. As a rule of thumb the ratio of the former to the latter should not exceed 1.5; ideally, the ratio should be unity.

The importance of moisture absorption becomes even more subtle as we note that the Marshall stability decreases logarithmically with increasing absorption (Fig. 7). It is apparent from the curve that CETM mixture exhibiting a soaked Marshall strength of 4.23 kN (950 lbs) will normally have absorbed 9.4% moisture during vacuum soaking. Taking into account the 95% confidence interval for this estimate the writer suggests that maximum permissible moisture absorption by Marshall specimens should not exceed 8.5%.

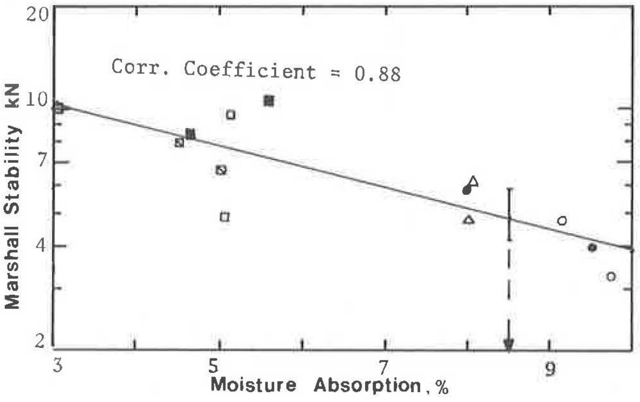
It is significant to note here that the moisture absorption value proposed in this study is compatible with the value sggested by the Asphalt Institute: 5% for selected aggregates. The moisture absorption, according to the Asphalt Institute, should be determined by MVS test. Our tests show that the moisture absorption during MVS test is about 40% to 50% of what would normally be absorbed in a vacuum soaking test. Thus, the permissible moisture absorption of 5% suggested by the Asphalt Institute is comparable to the 8.5% moisture pickup in this study where moisture absorption is determined by the vacuum saturation method.

Figure 6. Moisture absorption related to air voids.



Note: 1 kg/m^3 = 0.0624 lb/ft^3

Figure 7. Marshall stability related to moisture absorption.



Note: 1 kN = 225 lbs.

Conclusions

1. Portland cement in trace quantities, acting as a stabilizing agent, greatly enhances the soak-stability of sand-emulsion mixtures.
2. Soaked Marshall stability of CETM increases with emulsion content; attains an optimum value somewhere between 6% and 9%; and, for all practical purposes, remains constant, The effect of fines content on Marshall stability is such that the stability increases with fines, peaks at about 15% to 18%, and

then gradually decreases.

3. It is feasible to estimate the (seven-day cured vacuum soaked) Marshall stability of CETM from the particle size distribution of the soil (equation 1).

4. The trend of triaxial shear strength result is in agreement with that of Marshall strength in that the shear strength exhibited an optimum value, respectively, with the emulsion content (approximately 7%) and the fines content (approximately 17%).

5. Using the test results on several sandy soils mix design criteria for CETM is proposed. The two-part criteria read as follows:

(i) Seven-day partial air-cured vacuum soaked Marshall cylinders at 25±1°C (72±2°F) (with 1% cement) should exhibit a minimum stability of 4.23 kN (950 lbs.).

(ii) Moisture absorption during vacuum soaking should not exceed 8.5% by weight.

Proposed Mississippi Method for CETM Mixture Design

1. Determine the particle size distribution of soil aggregates (ASTM D1140 and D422).
2. Determine the plasticity index of fine fraction (ASTM D423 and D424).
3. Consider soil aggregates suitable for emulsion stabilization:
    (a) if the fines content lies between 5% and 25% and
    (b) if the product of the fines content and PI is less than 72.
4. Determine the CKE oil ratio (Reference 16).
5. Determine type and grade of emulsion by coating test (Reference 16).
6. Determine moisture and corresponding density of CETM from moisture density curve; the details of obtaining such a curve can be seen in reference 8. Mixing moisture may be 2%-3% more than that for compaction, depending upon the fines content.
7. Use the equation,

$$\ln(MS) = 6.7420 + 0.0943\ (FC) - 1.9866\ (Cm) - 0.0462\ (EC)^2 + 0.4529\ (EC \times Cm) \qquad (1)$$

to determine the stability value (lbs) at the emulsion content of 1.1 x CKE oil ratio and cement 1%. If the stability predicted by Eq. 1 is greater than 4.23 kN (950 lbs), it would appear that the soil can be stabilized with emulsion and trace cement.

8. (a) Mold Marshall specimens at emulsion contents of 1.1 x, 1.3 x, and 1.5 x CKE oil ratio (three for each emulsion content) and with 1% cement admixture. (b) Air-cure these specimens for seven days at a temperature of 25±1°C (72±2°F) and 55% RH. (while curing they should be kept in the mold or wrapped in such a way that they undergo drying from the top face only– partial air-cure.) (c) Vacuum soak the specimens for two hours and then test for Marshall stability. (d) Weigh the specimens before and after vacuum soak to determine the moisture absorption during vacuum soak.
9. The suitability of a CETM mixture is governed by the following design criteria.
    (a) Seven day partial air-cured vacuum-soaked Marshall cylinders (with 1% cement) should exhibit a minimum stability of 4.23 kN (950 lbs).
    (b) Moisture absorption during vacuum-soaking should not exceed 8.5% by weight.
10. (a) In the event that the mixture with 1% cement additive do not satisfy the criteria proposed in step 9, increase the cement to 1.5%, repeat step 8, and mold six specimens from each emulsion mixture. (b) Subject the six specimens to partial air-cure for seven days. (c) Test three of these specimens for Marshall stability when dry, and the remaining three after vacuum soak.
11. The selection of a CETM mixture is governed by the following criteria:
    (a) Criterion (a) of step 9
    (b) Criterion (b) of step 9
    (c) Seven-day dry bearing strength (calculated from Eq. 3) should not exceed 2760 kPa (400 psi).

NOTE: The purpose of criterion 11-c is to safeguard against selection of a mixture that beomces highly stiff upon drying. The bearing strength 2760 kPa (400 psi), therefore, should not be construed as an absolute maximum limit but should be viewed as a general guide only.

12. Although criteria of step 9, or alternatively those of step 11, govern the selection of emulsion content, the minimum emulsion in any event shall not be less than 1.1 x CKE oil ratio.
13. As the bitumen content in emulsion varies, the residual bitumen on weight basis should be specified for control purposes.

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