three changes can occur. The aggregate skeleton may collapse due to local softening at the aggregate-aggregate contacts. Because the gross volume is fixed, this effect will be manifested as a rapid decrease in the measured swelling pressure. Also, as water becomes available, the aggregations may swell. If the soil skeleton can resist the increase in pressure due to this, there will be an increase in the boundary or confining pressure. Finally, as the moisture content of each aggregate increases due to swelling, its strength will decrease to allow plastic deformation of the soil skeleton into the previously empty skeletal voids. This effect occurring alone would result in a decrease in the measured swelling pressure.

Thus, the effects of water on this system are not additive. Because all three phenomena will occur simultaneously, the observed swelling pressure will be a reflection of the dominant mechanism occurring during some time increment. According to this explanation, the temporary decrease in the swelling pressure exhibited by most of the samples is caused by structural collapse, and the slow decrease from some peak value (as shown in Figure 4) is due to the dominance of plastic structural rearrangement over the swelling of individual aggregates.

SUMMARY AND CONCLUSIONS

In this study, a model or mechanism has been developed to explain the effects observed during the laboratory static compaction of kaolinite. The mechanism includes the influences of the precompaction soil preparation and conditioning as well as those of the soil interactions that occur during compaction.

Many of the swelling-pressure tests exhibited a temporary collapse or at least a decrease in the swelling pressure generated. This effect is also explained by the model. At the lower level of compaction, the maximum swelling pressure increased as the compaction moisture content increased. But at the higher compaction level, the maximum swelling pressure was largest at intermediate compaction moisture content. The final measured swelling pressures have the same type of relationship with the compactive load-moisture content combination.

ACKNOWLEDGMENT

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Evaluation of the Use of Indirect Tensile Test Results for Characterization of Asphalt-Emulsion-Treated Bases

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The results of a laboratory investigation of cold-mixed asphalt-emulsion-treated mixtures used for black bases are reported. The tensile properties for several mix variables and test temperatures were evaluated by the indirect tensile test. One type of asphalt emulsion and two types of aggregate were used. Two asphalt-emulsion contents and two initially added moisture contents were used. Specimens were cured at two curing conditions to represent early and long-term field curing. The relationships between load and horizontal deformation and between vertical and horizontal deformation were recorded during the test on X-Y recorders. The indirect tensile properties evaluated included indirect tensile strength, Poisson's ratio, indirect tensile stiffness, total strain at failure, and indirect tensile index. The indirect tensile index is represented by the secant modulus of the load versus horizontal deformation curve. Other parameters evaluated included compactability (unit weight after compaction), unit weight at time of testing, and percentages of retained moisture and voids at time of testing. The indirect tensile properties of the mixtures were very sensitive to the test temperature and were also affected by the other factors included in the study. In most cases, the interactions of the different factors had significant effects on the mixture properties. The indirect tensile index provided a high correlation with the asphalt-emulsion content, the type of aggregate, and the test temperature and proved to be a better mixture-characterization factor than the indirect tensile stiffness.

Emulsified-asphalt-treated mixtures are being widely accepted by engineers because of their many ecological-performance and economic advantages. Unlike asphalt cement, emulsified asphalt requires little or no heating when mixed with aggregates, which significantly reduces energy demands and air pollution.

In recent years, emulsified asphalt bases have been used under both concrete and asphalt pavements. Emulsified asphalt provides cohesion to aggregates and minimizes segregation and blowing dust during placement. Either road-mix or plant-mix procedures can be used for preparation of emulsified asphalt mixtures.

The most critical disadvantage of asphalt-emulsion-treated materials is their relatively low strength at early ages and slow development of strength [which is limited by the rate of water loss in the mixture (1-3)]. In addition, the possibility of erosion and decrease in mixture strength, due to the presence of water in the system, before curing is completed can be important. A thorough understanding of the integral behavior of emulsified asphalt mixtures—including the effects of different components and at different curing stages and environmental conditions—does not exist at present.

The indirect tensile test was developed in 1953. In this test, cylindrical specimens are failed by applying compressive loads along a diametrical plane through two opposite loading heads. This type of loading produces a relatively uniform tensile stress that acts perpendicular to the applied load plane. The theory and stress patterns of the test have been described in previous studies (4-6). Maupin (7) has reported the following advantages of the indirect tensile test: (a) it is simple, (b) Marshall specimens may be used, (c) surface irregularities do not seriously affect the results, and (d) the coefficient of variation of the test results is low.

Several studies of asphalt concrete materials have used the indirect tensile test. A long-term project was performed at the University of Texas at Austin to evaluate the tensile properties of highway pavement materials (8, 9), and indirect tensile tests, as well as fatigue tests, have been conducted on asphalt concrete specimens by Maupin and Freeman (10), who found that the indirect tensile test can be used to predict the fatigue characteristics of bituminous concrete. However, black bases using asphalt-emulsion-treated mixes have not been studied as much as other mixture types and there is still need for a comprehensive characterization of asphalt emulsion mixtures.

In this study, the performance of emulsified-asphalt-treated mixtures at different mix variables and environmental conditions was evaluated by using the indirect tensile test. As the properties of asphalt emulsion mixtures are highly affected by curing, both early and long-term curing stages were investigated.

MATERIALS

Aggregate

Two types of aggregates were used in this study. The first was totally a mixture of sand and gravel consisting of approximately 50 percent each calcareous and siliceous pieces; 56 percent of the gravel particles retained on a 4.75-mm (no. 4) sieve had crushed faces. The second was totally crushed limestone. The aggregate gradation used followed the midspecification of the Indiana State Highway Commission 73B gradation band, which has a maximum size of 19 mm (¾ in). The aggregate gradation and properties are given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
19	100
9.52	67
4.76	47.5
2.38	38.5
1.19	29.5
0.59	21
0.295	15
0.148	9
0.074	2.5

Property	Sand and Gravel	Limestone
Apparent specific gravity	2.71	2.74
Bulk specific gravity (SSD)	2.61	2.70
Absorption (%)	1.20	1.28

Asphalt Emulsion

Indiana State Highway Commission designation AE-150 mixing-grade emulsified asphalt was used in this study. Its physical properties are given below [t°C = (t°F - 32)/1.8]:

Property	Value
Residue by distillation (%)	70.0
Penetration of residue after distillation (25°C, 5 s, 100 gm)	>200
Specific gravity at 25°C of residue after distillation	1.010

This type of asphalt emulsion is similar to HFMS-2S (ASTM D977).

DESIGN OF THE EXPERIMENT

Response Variables

Response variables that were measured to evaluate the performance of the mixture include the following:

1. Indirect tensile strength, which is the maximum load the specimen can resist;
2. Poisson's ratio, as determined from the relationship between the vertical and the horizontal deformations of the specimen during the loading operation;
3. Indirect tensile stiffness, as determined from the relationship between the applied load and the horizontal deformation of the specimen;
4. Total tensile strain at failure, as determined from the total horizontal deformation at failure, where failure is defined to occur at maximum load;
5. Indirect tensile index, as represented by the slope of the line between the origin and the point corresponding to 50 percent of the maximum load on the load versus horizontal deformation curve—this new parameter is a measure of the relationship between load increments and the resulting horizontal deformation and may, in addition to other conventional design parameters, provide a good characterization and design concept for asphalt emulsion mixtures;
6. Compactibility, which is the unit weight of the specimen immediately following compaction and is determined from the specimen weight and height just after compaction;
7. Wet and dry unit weights at time of testing, where wet unit weight refers to the density of the specimen including the moisture portion and dry unit weight is determined by excluding the moisture portion in the specimen;
8. Percentage of moisture retained in the specimen at time of testing, as a percentage by weight of the dry aggregate; and
9. Percentage of voids at time of testing, which in-

cludes (a) percentage of air voids and (b) percentage of total voids, i.e., the sum of the air voids and the voids filled with moisture (where both are calculated on a basis of the apparent specific gravity of the aggregate and assuming no asphalt is absorbed into the aggregate).

Figure 1. View of indirect tensile test assembly.

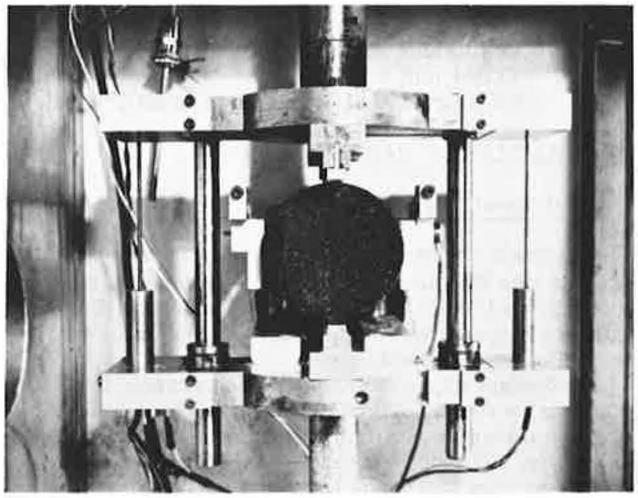


Figure 2. Relationship between load and horizontal deformation.

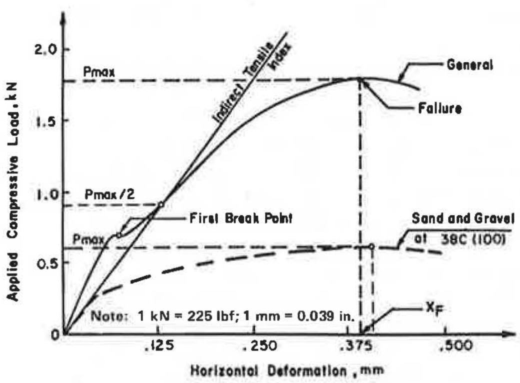
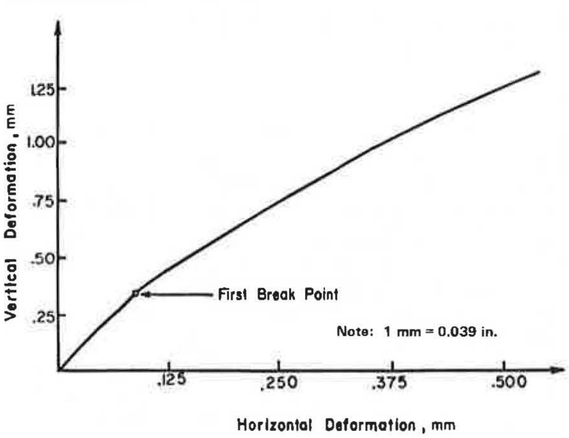


Figure 3. Relationship between vertical and horizontal deformations.



Independent Variables

The independent variables included the following:

1. Type of aggregate—sand and gravel versus crushed limestone;
2. Asphalt emulsion content—expressed as the percentage (3.25 versus 4) of asphalt emulsion residue (AER) in the mixture, based on dry weight of aggregate;
3. Initially added moisture (IAM)—expressed as percentage (3 and 4.5) of dry weight of aggregate;
4. Curing conditions—1-day air-dry versus 3-day oven-dry at 49°C (120°F) to represent early versus long term (3); and
5. Test temperature—10°C (50°F) versus 24°C (75°F) versus 38°C (100°F).

Three replicates of each combination were tested. One replicate for all combinations was performed first, then the second replicate was performed, and then the third. This method of design allows tests of all factors and interactions despite the restrictions on randomization (11).

EXPERIMENTAL PROCEDURE

Specimen Preparation

Specimens 102 mm (4 in) in diameter and 64 mm (2.5 in) in height were prepared according to the mix procedure suggested by Gadallah (3). They were compacted in a model 4C gyratory compaction machine manufactured by Engineering Developments Co., Inc., Vicksburg, Mississippi, by using a fixed roller. Twenty revolutions of the gyratory machine and 1380 kPa (200 lbf/in^2) vertical pressure were used. This compaction effort gave a specimen density almost identical to that given by applying 50 blows on each side of the specimen with the Marshall hammer. Immediately after compaction, specimen height was determined according to ASTM D3387. Specimen weight was determined while it was still in the mold to avoid damage.

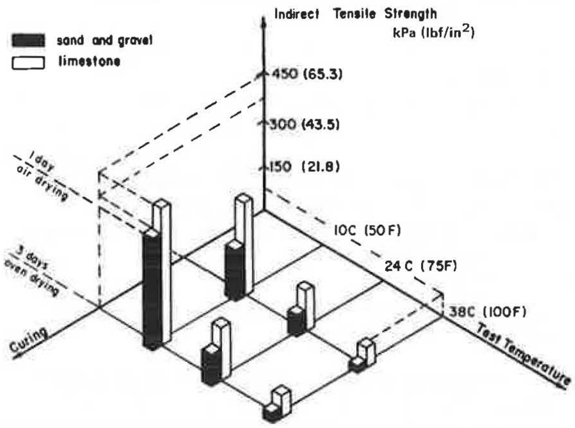
After curing, the specimen height was measured again. The wet unit weight was determined according to ASTM D1188 by dusting the surface with zinc stearate rather than by coating the specimen with wax (2). Zinc stearate is easy to use and, at the same time, does not affect the moisture content of the specimen, especially when the specimen surface is smooth.

Experimental Arrangement

An MTS electrohydraulic closed-loop testing machine was used for the indirect tensile test. The machine had a temperature control chamber in which the specimens were placed for 2-4 hours after curing to reach the required test temperature. During this period, the specimens were placed in sealed plastic bags to prevent moisture loss.

The specimens were loaded by using two 12.7-mm (0.5-in) wide, curved stainless steel loading strips (see Figure 1). Load was applied at a constant rate of 51 mm/min (2 in/min). Two guide rods were used to prevent any eccentricity in loading. Vertical deformation was measured by using two identical linear variable differential transformers (LVDTs) fixed at equal distances from the specimen on both sides. Horizontal deformation was measured by an LVDT attached to a special device consisting of two arms touching the specimen across the horizontal diameter. The load was measured by a load cell connected to the

Figure 4. Indirect tensile strength as a function of type of aggregate, curing conditions, and test temperature.



MTS machine. The outputs of the LVDTs and the load cell were calibrated and connected to two X-Y recorders. The X-Y recorders were adjusted to plot load versus horizontal deformation and vertical versus horizontal deformation (see Figures 2 and 3).

After the test was completed, the specimens were broken apart and dried in a forced-draft oven for 24 h at 110°C (230°F) and then weighed. The dry unit weight was calculated by dividing the dry weight of the crushed specimen by the difference between the specimen weights in air and in water.

ANALYSIS OF RESULTS

The general shape of the load versus horizontal deformation curve is as shown in Figure 2. At a certain load—the so-called first break point (9)—there is an increase in horizontal deformation without increase in load. For those specimens tested at 10°C, the first break load was much lower than the maximum load while, at 38°C, the first break load was closer to the maximum load. For the sand and gravel specimens at 38°C, the first break point was not clear.

The general shape of the vertical deformation versus horizontal deformation curve is as shown in Figure 3. The curve is fairly close to a straight line. At a point corresponding to the first break in the load versus horizontal deformation curve, the slope of the line is slightly changed. However, in some cases the vertical deformation versus horizontal deformation is a continuous curve.

The equations used to determine the indirect tensile parameters are given below:

$$\sigma_{IT} = 0.156\ (P_{max}/h) \quad (1)$$

$$\nu = (0.0673DR - 0.8954)/(-0.2494DR - 0.0156) \quad (2)$$

$$E_{IT} = (P/X)(1/h)(0.9976\nu + 0.2692) \quad (3)$$

$$\epsilon_T = X_T\ (0.1185\nu + 0.03896)/(0.2494\nu + 0.0673) \quad (4)$$

[these equations are valid for English units only and are restricted to 102-mm diameter specimens and a loading-strip width of 12.7 mm (9, 10)]

where

σ_{IT} = indirect tensile strength (lbf/in²);
P_{max} = maximum load at failure (lbf);
h = specimen height (in);
ν = Poisson's ratio;
DR = deformation ratio, i.e., the slope of the least-squares line of best fit between the vertical deformation and the corresponding horizontal deformation up to the first break point (for those cases where there is no first break point, the first portion of the curve is used);
E_{IT} = indirect tensile stiffness (lbf/in²);
P/X = the secant modulus at 50 percent of the first break point on the load versus horizontal deformation curve;
ϵ_T = total tensile strain at failure (in/in) [the length over which strain is estimated = 0.1 mm (0.004 in)]; and
X_T = total horizontal deformation at failure (in).

EVALUATION OF PARAMETERS

Indirect Tensile Strength

The indirect tensile strength varied between 25 and 596 kPa (3.6 and 86.4 lbf/in²). This wide range of the indirect tensile strength is due to the significant effects of type of aggregate, curing conditions, test temperature, and IAM.

In contrast to the smooth sand and gravel, the limestone had a rough surface and angular shape that increased the aggregate interparticle friction and, consequently, the tensile strength of the mixture.

Curing also increases the tensile strength of the mixture. As shown in Figure 4, the indirect tensile strength after three days of oven curing is always greater than the indirect tensile strength after one day of air-dry curing. This is due to the fact that curing breaks the asphalt emulsion, which allows water to evaporate and leaves the asphalt residue adhering to the aggregate particles.

Test temperature proved to be a major factor in determining the tensile strength of the mixture. Increasing the test temperature softens the asphalt emulsion residue and weakens the mixture.

To some extent, increasing the percentage of IAM makes the asphalt emulsion more effective in coating the aggregate particles. However, in most combinations the effect on the indirect tensile strength was greater with 3 percent IAM than with 4.5. Thus, the effect of IAM depends on its interaction with other factors.

The effects of interactions of aggregate type, curing conditions, and test temperature on the indirect tensile strength are summarized in Figure 4. The highest value of the indirect tensile strength found was that for the combination of limestone, a test temperature of 10°C, and 3-day oven curing. The lowest value was that for the combination of sand and gravel, a test temperature of 38°C, and 1-day air curing.

Poisson's Ratio

The majority of the values of Poisson's ratio found were between 0.2 and 0.45. Poisson's ratio was very sensitive to test temperature; at the higher temperatures, the Poisson's ratio values were higher. At the 10°C test temperature, a small number of the values of Poisson's ratio were negative, although most of the values found at 38°C exceeded 0.5. Thus, the asphalt emulsion mixture does not wholly meet the assumptions in the original derivation of the equations (8), and Poisson's ratio should not be determined by using the indirect tensile test, especially at high temperatures. In the remainder of this analysis, Poisson's ratio was

Figure 5. Indirect stiffness as a function of asphalt emulsion content, test temperature, and type of aggregate.

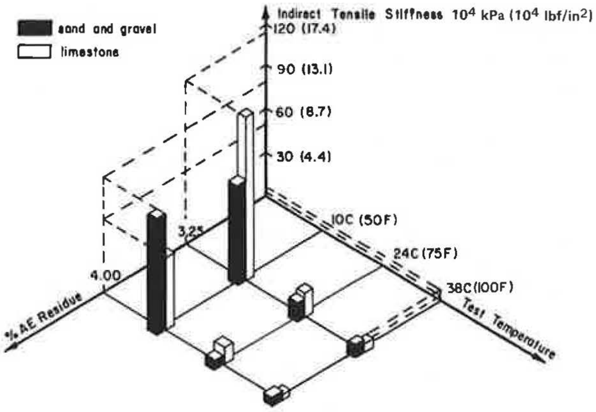


Figure 6. Total tensile strain at failure as a function of curing conditions, asphalt emulsion content, and test temperature.

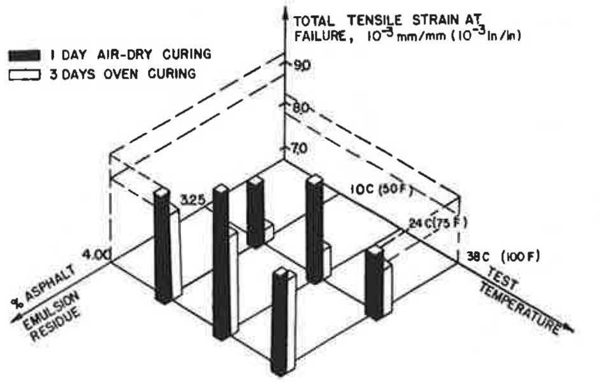


Figure 7. Indirect tensile index as a function of asphalt emulsion content, test temperature, and type of aggregate.

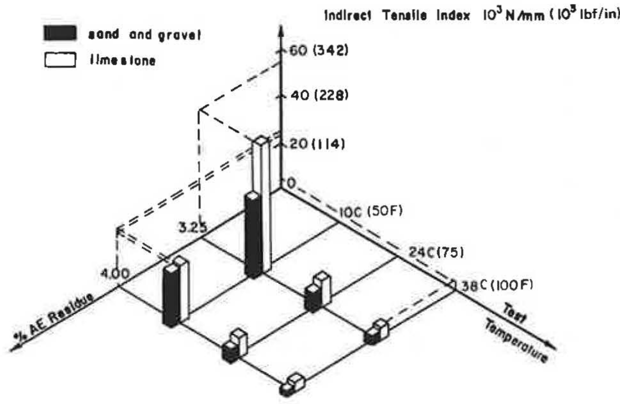


Figure 8. Effect of asphalt emulsion content, type of aggregate, and added moisture on unit weight at time of compaction.

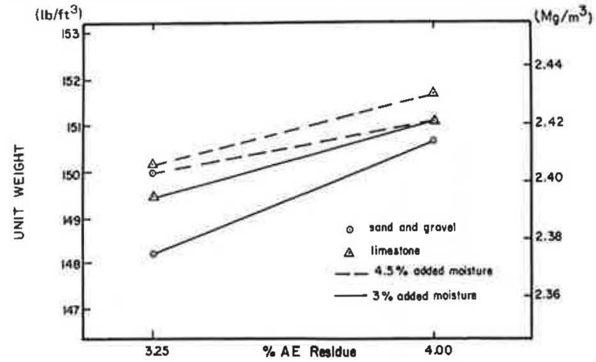
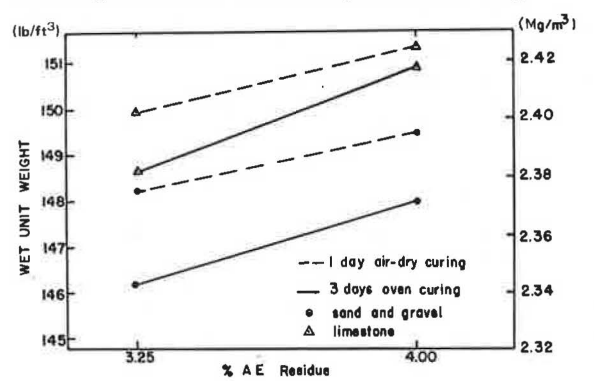


Figure 9. Effect of asphalt emulsion content, type of aggregate, and curing conditions on wet unit weight at time of testing.



assumed to be 0.3, 0.35, and 0.4 at test temperatures of 10°C, 24°C, and 38°C, respectively.

Curing conditions had a significant effect on the values of Poisson's ratio found. Specimens air dried for 1 day were tender and, consequently, had high values of Poisson's ratio while those oven dried for 3 days had low values. Other factors did not significantly affect the values of Poisson's ratio found.

Indirect Tensile Stiffness

The indirect tensile stiffness values determined by using the experimentally found values of Poisson's ratio varied between 2.4×10^4 and 206.8×10^4 kPa (0.35×10^4 and 30×10^4 lbf/in^2). However, the stiffness values determined by using the assumed values of Poisson's ratio (i.e., 0.3, 0.35, and 0.4 at test temperatures of 10°C, 24°C, and 38°C, respectively) varied between 1.7×10^4 and 248.2×10^4 kPa (0.24×10^4 and 36×10^4 lbf/in^2).

The stiffness values found by using the assumed values of Poisson's ratio were greatly affected by temperature. As the test temperature increased, the stiffness decreased to a very small value. Stiffness was also affected by the interactions of test temperature, asphalt emulsion content, and type of aggregate. As shown in Figure 5, no trend could be found for the effects of asphalt emulsion content of type of aggregate. At some combinations, the sand and gravel mixtures had higher stiffness values than did the limestone mixtures, while at other combinations, the opposite was true. The significant effect of type of aggregate was apparent at a test temperature of 10°C.

The highest stiffness value was that found for the combination of limestone, 3.25 percent AER, and a test temperature of 10°C.

Total Tensile Strain at Failure

The total tensile strain at failure varied between 7.4×10^{-3} and 9.6×10^{-3} mm/mm (in/in) (calculated by using the assumed values of Poisson's ratio).

Figure 6 shows the effect of the asphalt emulsion content on the total tensile strain at failure. Asphalt emulsion acts as a lubricant between the aggregate

Figure 10. Effect of asphalt emulsion content, type of aggregate, and curing conditions on moisture retained at time of testing.

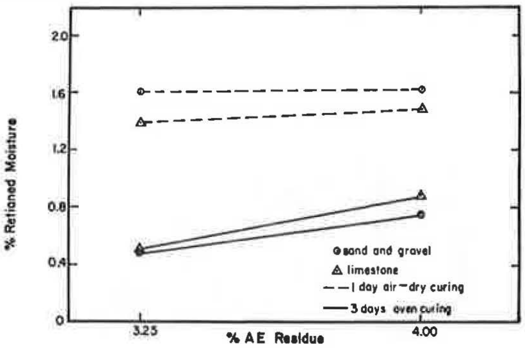
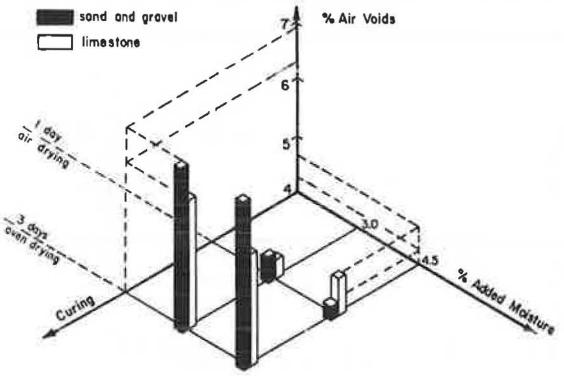


Figure 11. Percentage of air voids at time of testing as a function of curing conditions, added moisture, and type of aggregate.



particles and, thus, the tensile strain at failure was higher at higher asphalt emulsion contents. The tensile strain at failure was also affected by curing, which increases the rigidity of the mixture and so decreases the total tensile strain at failure. The largest value of tensile strain was that found at the intermediate test temperature (i.e., 24°C).

Indirect Tensile Index

The indirect tensile index (Figure 2) varied between 0.8 and 119 kN/mm (4.5×10^3 and 680×10^3 lbf/in). The value was very sensitive to test temperature; as the test temperature increased, the value decreased significantly. In addition to test temperature, type of aggregate and asphalt emulsion content also affected the indirect tensile index. Limestone mixtures always had higher indices than did sand and gravel mixtures, and 3.25 percent AER mixtures had higher indices than did 4 percent AER mixtures (see Figure 7).

The indirect tensile index values provided a good correlation with the test temperature, the aggregate type, and the asphalt emulsion content but were independent of Poisson's ratio. This leads to the conclusion that the use of the indirect tensile index in conjunction with other parameters (such as indirect tensile strength) can provide a good characterization of an asphalt-emulsion-treated mixture.

Unit Weight at Time of Compaction

The unit weight at the time of compaction (which can be used as a measure of compactibility) varied between 2.36 and 2.44 Mg/m^3 (147.3 and 152.3 lb/ft^3). Both asphalt emulsion content and IAM affected the compactibility of the mixture. Increasing either (or both) increases the lubrication between the aggregate particles. This allows the aggregate particles to move smoothly during compaction to fill the air voids (which increases the unit weight of the mixture) and, at the same time, both asphalt emulsion and moisture fill the air voids between the aggregate particles.

The interaction of asphalt emulsion content, IAM, and type of aggregate had a significant effect on compactibility (Figure 8). The highest value found was that for the combination of limestone (because of its angular particles), 4 percent AER, and 4.5 percent IAM.

Unit Weight at Time of Testing

The wet unit weight was affected by the asphalt emulsion content, curing conditions, and type of aggregate (Figure 9). Increasing the asphalt emulsion content helps to fill the air voids in the mixture and also lubricates the mixture, which allows more compaction and increases the wet unit weight. However, increased curing allows moisture to leave the mixture and decreases the wet unit weight. Limestone, because of its angular shape, allows fewer voids in the mixture, which increases the wet unit weight.

The dry unit weight was affected only by asphalt emulsion content and type of aggregate. It was not affected by curing conditions, as expected, because, regardless of the amount of moisture that leaves the specimen during curing, the oven-dried weight and the dry unit weight of the specimen will remain the same. The effects of asphalt emulsion content and type of aggregate followed the same pattern as the case of the wet unit weight.

Percentage of Moisture Retained at Time of Testing

The percentage of moisture retained at the time of testing varied between 0.26 and 2.15 of the dry weight of aggregate. It was affected mainly by curing conditions but also by asphalt emulsion content.

As shown in Figure 10, the oven-cured specimens retained much less moisture than the air-dried specimens, and the 4 percent AER specimens retained more moisture than the 3.25 percent AER specimens. Thus the highest percentages of retained moisture were those found for the combination of 4 percent AER and air-dry curing.

Percentage of Voids at Time of Testing

The percentage of air voids at time of testing was markedly affected by asphalt emulsion content and curing conditions. The value decreased as the asphalt emulsion content increased because the asphalt emulsion can replace the air voids and thus allow greater densification. The effect of curing is to increase the percentage of air voids because curing allows water to leave the mixture.

The interaction of curing, IAM, and aggregate type was found to be significant, as shown in Figure 11.

The percentage of total voids at time of testing (including voids filled with moisture) was not affected by curing because, while curing allows water to leave the mixture, the total voids remain the same. Thus, the total voids are affected only by asphalt emulsion content.

SUMMARY AND CONCLUSIONS

Asphalt-emulsion-treated mixtures were evaluated by using the indirect tensile test. Different design parameters were evaluated at several mix variables and temperatures. Two types of aggregate, two asphalt emulsion contents, two values of initially added moisture, and two curing conditions were investigated. One type of asphalt emulsion and grade was used. The test was performed at three different temperatures. The important findings of the study are as follows:

1. Test temperature was the most important factor that affected the indirect tensile properties of the mixtures. High test temperatures increased the values of Poisson's ratio and decreased the indirect tensile strength, stiffness, and index. Test temperature also affected the total tensile strain at failure.
2. Limestone mixtures had higher indirect tensile strengths and indices than did sand and gravel mixtures. Aggregate type had a significant effect on the indirect tensile stiffness, especially at low temperature. In addition, limestone mixtures had higher unit weights and lower percentages of air voids than did sand and gravel mixtures.
3. In most cases, increasing the asphalt emulsion content decreased the indirect tensile stiffness and index and both air voids and total voids at time of testing and increased the total tensile strain at failure, compactibility, unit weight, and moisture retained at time of testing.
4. The curing conditions affected the characteristics of the specimens markedly. Oven curing increased the indirect tensile strength and the air voids and decreased the Poisson's ratio values, the total strain at failure, the wet unit weight, and the moisture retained at time of testing.
5. Increasing the initially added moisture from 3 to 4.5 percent of the dry weight of aggregate decreased the indirect tensile strength and increased the compactibility of the specimens.

Based on the results of the overall study, the following recommendations should be noted:

1. The indirect tensile test is a simple and suitable method for characterizing asphalt-emulsion-treated mixtures.
2. The indirect tensile index proved to have a good correlation with asphalt emulsion content, type of aggregate, and test temperature. The use of this index, together with other indirect tensile parameters, should provide a good characterization of an asphalt emulsion mixture.
3. It should be remembered that these results are based on the use of one emulsion system (which has rates of cure, water loss, and strength and stiffness development and electrochemical properties that are inherent to that one emulsion type and grade and are not necessarily the same for other emulsion types).

ACKNOWLEDGMENT

The contents of this report reflect our views; we are responsible for the facts and the accuracy of the data presented herein.

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