A comparison of Properties of laboratory prepared Cold Mixed Emulsified and Hot Mixed Asphalt Mixtures

Phase I

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SUMMARY

Basic objectives of the study was to address the often used equivalency ratio of l.4;l when emulsified asphalt mixtures are used in place of hot-mixed asphalt concrete. If valid, this equivalency ratio requires emulsified asphalt mixtures to be 1.4 times as thick as hot-mixed asphalt concrete.

This study compared four mixtures that included two aggregate gradations (surface and base courses) and two binders (emulsified asphalt and conventional paving grade asphalt cement).

Mixture physical properties considered include:

Marshall Stability and Flow

Density-Voids

Resilient Modulus

Tensile Strength

Properties of emulsified asphalt mixtures were measured after compacted specimens were dried to constant weight by vacuum desiccation -
General conclusions based on mixtures used for this study are:

1. Hot mixed specimens produced higher Marshall stabilities than cured emulsified asphalt mixtures.

2. Dense graded surface mixtures with emulsified asphalt meet stability requirements (1,000 lbs.) for most street and highway surfaces and full-depth applications.

3. Coarse graded base mixtures with emulsified asphalt meet stability requirements for many street and highway applications and for most base course applications.

4, In general, emulsified asphalt mixtures showed less variability, as measured by standard deviation, than did conventional hot mixtures.

5. All mixtures meet flow criteria of 8-16 units. There was no significant difference between mixtures.

6. Dense graded mixtures with emulsified binders exhibited higher voids than other mixtures. All mixtures had void contents slightly in excess of most criteria.

7, Hot mixed asphalt concrete showed higher tensile strengths than mixtures using emulsified asphalt binders.

8. When emulsified asphalt mixtures were cured to constant weight, average resilient modulus is higher than hot-mixed asphalt concrete.

9. Emulsified asphalt mixtures show an increase in resilient modulus with water loss during vacuum desiccation. At about 70-80 percent water loss, emulsified asphalt mixtures had the same modulus as hot-mixed asphalt concrete. This equilibrium occurred after approximately one week of vacuum desiccation.

10. Finally, from a Marshall properties point of view, emulsified asphalt mixtures of the type used for this study should be able to be substituted for hot-mixed asphalt concrete on a 1:1 basis for most highway and street applications except, perhaps, for the most heavy traffic applications.

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Three areas of interest for additional research are discussed. These areas include:

1. Development of molds and compaction procedures to promote removal of water during specimen preparation. This is necessary to produce laboratory specimens with void content and densities that more nearly simulate field placement and compaction. This study suggests that unrealistically low laboratory stabilities may result if pore pressures, developed during laboratory compaction, cause low density (or high voids). See Figure 18.

2. A field study is suggested to monitor rate of moisture loss of actual emulsified asphalt mixtures. This study would serve as the basis of recommendations for length of curing time by laboratory vacuum desiccation necessary before testing of specimens. Information could also be used to estimate length of field cure necessary to develop mixture strength before opening a facility to traffic. The experiment should be statistically designed for replications and should be conducted with a companion laboratory vacuum desiccation study of field mixtures. Probable sampling points include:

   A. Immediately after mixing.
   B. After haul.
   C. Immediately after lay-down.
   D. At several intervals during compaction.
   E. After compaction.
   F. At several intervals during field cure after compaction.
   G.

3. A third study that should be conducted is to consider water sensitivity (strip potential) of emulsified asphalt mixtures. This study could be conducted using standard immersion compression ore retained stability after water immersion It is recommended that this study include specimens that have been fully cured but subjected to several cycles of wetting and drying. It is also recommended that resilient moduli be measured during the wet-dry cycling.

1.0 INTRODUCTION

1.1 The purpose of this study was to compare properties of bituminous mixtures using paving - grade asphalt cement and emulsified asphalt binders to evaluate thickness requirements of paving materials using emulsified asphalt binders.

Comparison tests used in this study included Marshall stability, diametral resilient modulus, indirect tensile strength, and density-voids analyses. Mixtures using emulsified asphalt were subjected to vacuum desiccation to simulate loss of mixture moisture after field placement of these mixtures.

1.2 Present thickness design practice, typically, involves a first design for a full-depth hot mix asphalt concrete layer that is based on limiting strain and fatigue characteristics of the asphalt concrete plus other considerations such as limiting subgrade stress (by layer thickness) to prevent consolidation of the subgrade and consequent pavement rutting.

Subsequent or alternate thickness designs based on full depth designs are often made to reduce pavement costs. These alternate designs are based on empirical layer equivalency of the alternate paving material. For instance, high quality crushed stone can replace a portion of the required asphalt concrete at a 2 to 1 ratio (2 inches of stone can replace 1 inch of hot mixed asphalt concrete). Typically, substitution ratios are approximately as follows (1):

Material	Substitution Ratio
High Quality Granular Base	2.0
Low Quality Granular Base	2.7
Hot-Mix Sand	1.3
Liquid and Emulsified Asphalt	1.4

1.3 This study addresses the substitution ratio for bituminous mixtures using emulsified asphalt binders that are often rated at 1.4:1. That is, 1.4 inches of emulsified asphalt mixture is required to replace 1 inch of asphalt concrete. It has been contended that if relevent properties of emulsified asphalt mixtures are the same as hot-mixed asphalt concrete or if design criteria can be obtained in mixtures using emulsified asphalt that a 1:1 equivalency should be considered.

1.4 This study compares certain properties of hot-mixed and emulsified asphalt mixtures that include:

- Marshall Stability and Flow.
- Density-Voids.
- Resilient Modulus.
- Tensile Strength.

Mixtures studied included dense and coarse graded crushed aggregate from Salt River deposits from Phoenix, Arizona. Emulsified asphalt binders were cationic mixing grade prepared by Armak Highway Chemicals Department. Hot mixed asphalt concrete used AR-4000 grade asphalt cement.

Emulsified asphalt mixtures were vacuum desiccated (to simulate field evaporation of mixture water) before testing.

2.0 CONCLUSIONS

2.1 .Marshall Stability.

- Hot Mix specimens produce higher stabilities than cured emulsified asphalt mixtures

- Dense graded emulsified asphalt mixtures meet stability requirements (1,000 lbs.) for most street and highway surfaces and full-depth applications.

- Coarse graded emulsified asphalt mixtures meet stability requirements for many street and highway applications and for most base course applications.

- Emulsified asphalt mixtures showed less variability, as measured by standard deviation, than did conventional hot mixes.

2.2 Marshall Flow.

- All mixtures meet flow criteria of 8-16. There is no significant difference between mixtures.

2.3 Air Voids.

- Dense graded mixtures with emulsified asphalt binders exhibited higher voids than other mixtures. All mixtures had void contents slightly in excess of most criteria.

2.4 Tensile Strength at 77F.

- Hot-mixed asphalt concrete showed higher tensile strengths (152 psi) than emulsified asphalt mixtures (117 psi). Aspects of tensile stress and strength will be more fully discussed in a subsequent section.

2.5 Resilient Modulus at 77F.

- When emulsified asphalt mixtures are vacuum desiccated to constant weight, average modulus of emulsified asphalt mixtures is higher than hot mixed asphalt concrete (10.4×10^5 vs. 6.46×10^5 psi)

- Emulsified asphalt mixtures show an increase in modulus with loss of water during desiccation. At about 70-80 per cent water loss, emulsified mixtures had approximately the same modulus as hot mixed asphalt concrete. This equilibrium occurs after approximately one week of vacuum desiccation.

2.6.1 General Conclusions.

- From a Marshall properties point of view, emulsified asphalt mixtures should be able to be substituted for hot mixed asphalt concrete on a 1:1 basis for most highway and street applications. This is based, of course, on equal levels of production and construction quality.

- Approximately one week of laboratory vacuum desiccation will remove about 60-70 per cent of the water (mixing water and water from the emulsion) from the mixture. It is not unreasonable to assume that this simulates early moisture loss during construction plus a short in-service cure.

  Vacuum desiccation should be included as part of the routine laboratory evaluation of bituminous mixtures using mixing grade emulsified asphalt binders.

  It should be noted that the scope of this study was limited to a single mixing grade emulsified asphalt and, hence, these conclusions should not be extrapolated to materials that vary widely from those used for this study.

3.0 EXPERIMENTAL LAYOUT

3.1 This experiment was designed as a completely randomized two by two factorial with six replications per cell.

The factorial is:

BINDER TYPE (Bj) x	GRADATION (Gi)	
	DENSE	COARSE
Emulsified Asphalt		
Asphalt Cement		

3.2 Model for analysis of variance is:

$$Yijk = \mu + Gi + Bj + (GB)ij + \varepsilon\,(ij)k$$

Where;

Yijk = Response (Stability, Flow, Resilient modulus, Tensile Strength, Voids, etc.)

μ = Effect of overall mean.

Gi = Effect of Aggregate Gradation

Bj = Effect of binder type.

(GB) ij = Interaction between aggregate gradation and binder type.

ε = Experimental Error

3.3 Analysis

Source	df
Gi	1
Bj	1
(GB)ij	1
Error	20
Total	23

3.4 Specimen preparation and testing.

- Each of the 24 specimens was assigned an identification code (DE-1 through DE-6, DA-i through DA-6, CE-i through CE-6, and CA-i through CA-6 where D designates dense gradation, C designates coarse gradation, E designates emulsified asphalt binder, and A designates asphalt cement binder).

  Each specimen was selected at random for fabrication and subsequent testing. 24 specimens were prepared for resilient modulus and tensile strength and 24 were prepared for Marshall testing.

4.0 <u>MATERIALS</u>

4.1 Aggregates used for the study were crushed Salt River gravel from Phoenix$_1$ Arizona. These aggregates meet all quality requirements for Arizona Department of Transportation for highway construction.

Specific gravity and absorption of coarse (+ No. 4) and fine (minus No. 4) fractions were determined in accordance with ASTM C127 and C128. Results of these tests are shown in Table 1.

Aggregates were separated into four fractions. Gradations of these fractions are shown in Table 2.

Dense and coarse gradations for the study are as described by The Asphalt Institute. Both gradations are 3/4 inch maximum with the dense gradation as recommended for surface courses (Type IV-b) and the coarse gradation as recommended for base courses (Type Ill-b). Gradations are shown in Table 3 and on Figures 1 and 2.

Blends of aggregate fractions to produce dense and coarse gradations are shown in Table 4.

4.2 Paving grade asphalt cement.

Paving grade asphalt cement was an AR-4000 supplied by Arizona Refining Company of Phoenix, Arizona. Physical properties of the AR-4000 before and after aging (RTFCO) are shown in Table 5.

4.3 Emulsified asphalt cement

Emulsified asphalt for the study was formulated to produce, as close as possible, a material with a residual asphalt with the same properties as the AR-4000 asphalt cement would have after laboratory mixing to produce hot mix asphalt concrete. Base stock for the emulsified asphalt was AR-8000 from Douglas Oil Company. Physical properties are shown in Table 6. Comparison of Tables 5 and 6 shows that properties of the emulsified asphalt base stock are practically the same as the aged residue of the asphalt cement used for the hot mixtures

Emulsified asphalt was formulated to provide 61.2 per cent residue (38.8 per cent water and emulsifier)

5.0 <u>MIXTURE DESIGNS</u>

5.1 Hot mixed asphalt concrete.

Mixtures were designed according to the Marshall method as described by The Asphalt Institute (2) with the following. exceptions:

a) 3600 g. batches were mixed at 30OF. Three 1200 g. specimens were split from the mixed master batch, stored in containers, and brought to the compaction temperature of 275 +/- 5F.

b) 75 blow compaction was applied to each specimen side with a mechanical hammer.

Mixture design data for coarse graded base course mixtures (Type Ill-b) are shown in Table 7 and on Figure 3.

Optimum asphalt content for the base course mixture is 4.7 per cent by weight of mixture. Mixture characteristics are as follows:

a.	Air Voids	-	5.0%
b.	VMA	-	15.0
c.	Stability	-	1750 lbs.
d.	Flow	-	10.5
e.	VFWA	-	71%
f.	Unit Weight	-	145.0 pcf

Optimum asphalt content for surface course mixture is 4.9 per cent by weight of mixture. Mixture characteristics are as follows:

a.	Air Voids	5%
b.	VMA	15.7
c.	Stability	2120 lbs
d.	Flow	10.5
e.	VFWA	68%
f.	Unit Weight	144.7 pcf

5.2 Emulsified asphalt mixtures.

For purposes of this study, design residual asphalt content was selected to provide calculated asphalt film thicknesses the same as equivalent hot-mixtures discussed in Section 5.1. Mixtures were designed using The Asphalt Institute Pacific Coast Division Method (3) as a guide. More specifically, the method used for this study is outlined as follows:

a) Mixing water requirements were established by trial and error with a laboratory mixer and 1200 g. batches of aggregate. Mixing water was added and mixed. After incorporation of mixing water, emulsified asphalt was added in an amount to give six percent residual asphalt and mixed for one minute. Mixtures were subjectively evaluated for ease of mixing, complete coating, and excess water in the mixture.

   Two percent mixing water (based on dry weight of aggregate) was selected for study mixtures.

b) Two percent mixing water was added to 3600 g. of oven dried aggregate and mixed in a laboratory mixer for one minute.

c) The appropriate amount of emulsified asphalt was added to the moistened aggregate and mixed until complete coating was obtained.

d) Three specimens of approximately 1250 g. were split from the master batch and compacted with 75 blows to each specimen side with a mechanical hammer.

e) Compacted specimens were stored in the molds for 18 hours.

f) Specimens were extracted from the molds and vacuum desiccated to constant weight (12 in. Hg. vacuum). Unit weight and resilient modulus were measured periodically during drying.

g) After constant weight (full cure) was obtained, stability and flow tests were conducted.

Mixture design data for coarse graded base course mixtures are shown in Table 9 and Figure 5. Mixture design data for dense graded surface course mixtures are shown in Table 10 and on Figure 6.

Emulsified asphalt mixture characteristics for base course mixtures (Type Ill-b) containing 4.7 per cent residual asphalt are as follows:

a.	Air Voids	8.5%
b.	VMA	16.5%
c.	Stability	1150lbs
d.	Flow	17.5
e.	VFWA	52%
g.	Unit Weight	142 pcf

Emulsified asphalt mixture characteristics for surface course mixtures (Type IV-b) containing 4.9 per cent residual asphalt are as follows:

a.	Air Voids	10.8%
b.	VMA	19.5%
c.	Stability	1100lbs
d.	Flow	19.0
e.	VFWA	44%
f.	Unit Weight	138pcf

6.0 FABRICATION OF EMULSIFIED ASPHALT SPECIMENS.

Mixing and fabrication followed the method discussed in Section 5.2.

7.0 RESULTS AND DISCUSSION

7.1 Bulk specific gravity (full cure for emulsified asphalt binder mixtures).
Raw data are shown in Table 11. Analysis of variance shows both gradation and binder type to be highly significant. Newman- Keuls analysis. shows the following ordering:

MIXTURE	MEAN
CA	2.330 (145.4 pcf)
DA	2.296 (143.3 pcf)
CE	2.246 (140.2 pcf)
DE	2.215 (138.2 pcf)

Where C= coarse gradation, D= dense gradation, A= asphalt cement, E= emulsified asphalt

A plot of means and two standard deviations for the ordered mixture is shown on Figure 15.

7.2 Air voids (full cure for emulsified asphalt binder mixtures).
Raw data are shown in Table 12. Analysis of variance shows gradation, binder type, and the interaction to be highly significant. Newman- Keuls analysis shows the following ordering:

MIXTURE (S)	MEAN
DE	8.5 %
DA	7.1 %
CE & CA	6.6 %

A plot of means and two standard deviations for the ordered mixtures is shown on Figure 16. All mixtures exhibit voids in excess of most criteria (5 or6 per cent maximum) but the levels do not appear to be excessive.

It is interesting to note that dense graded mixtures have slightly higher voids than the coarse graded mixtures which is the reverse of that expected for conventional hot mixtures. It is beyond the scope of this study but it is postulated that the phenomena may be unique to laboratory compaction with the Marshall hammer and may not occur in the field.
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One possibility to consider is that pore water pressures develop during laboratory compaction of mixtures with emulsified asphalt binders that prevent densification to the degree achieved in hot mixtures. Furthermore, these pressures cannot be fully dissipated because of confinement by the steel mold. It should be noted that some of the water is removed as moisture accumulations at specimen surfaces can be observed during compaction. It would be interesting to compare results with those obtained with a kneading compactor to determine if this kneading action would promote removal of pore water. It may be desirable, if pore water does exist, to consider development of a molding and compaction system that will allow escape of excess water.

There is also some question as to the similarity between laboratory and field compaction. Field mixtures may allow release of more water than laboratory compacted mixtures (this will be discussed further in the section dealing with moisture release); if this can be demonstrated by field experiments, it is conceivable that all that would be necessary is to specify the field density to produce the desired void volume.

Lastly, it should be noted that minor adjustments of gradation could also be used to produce lower void contents.

7.3 Marshall stability: (Full cure for emulsified asphalt binder mixtures).

Raw data are shown in Table 13.
Analysis of variance shows binder type is highly significant and that the interaction between binder type and gradation is significant. Gradation (coarse versus dense) is not significant. Newman-Keuls analysis shows the following ordering:

MIXTURE (S)	MEAN
CA	2032
DA	1751
CE & DE	1022

A plot of means and two standard deviations for the ordered mixtures is shown on Figure 17.

Mixtures used for this study meet most criteria for highways and streets (1,000 lb. minimum) but it should be recognized that some agencies are requiring higher stabilities (up to 1800 lbs.) for heavy duty highway pavements.

It is noted that there is a strong relationship between stability and specific gravity or unit weight as can be seen on Figure 18. It is clear that mixtures using asphalt cement binders (CA and DA) have higher unit weight and corresponding higher Marshall stability. It is well known that hot mix stability is strongly influenced by unit weight and it should be expected in the case of mixtures using emulsified asphalt binders.

Stability and voids do not have a clear relationship (Figure 19), perhaps because of the narrow range of voids in mixtures used in this study.

Scope of this study limited the number of variables under study. This study selected equal bitumen contents and gradations. This constraint confounded the effect of density but experience with hot mixes and Figure 18 strongly suggests that stabilities of laboratory emulsified asphalt mixtures can be increased, and probably more nearly simulate field conditions, by increasing laboratory density. It is believed that the measures discussed to allow moisture release would, ipso facto, increase density for a given set of laboratory conditions.

Nonetheless, it can be concluded from these data that emulsified asphalt mixtures can be produced in the laboratory that will meet stability criteria for most highway, street, and some airport paving purposes.

7.4 Marshall flow (full cure for emulsified asphalt binder mixtures)

Raw data are shown in Table 14. Analysis of variance shows no significant differences due to binder type, gradation, or the interaction. Overall mean is 8.6 units which is within the usual criterion of 8-16 that applies to most paving mixtures.

7.5 Resilient modulus as measured by the Schmidt device at 77F.

Resilient modulus by this method is a dynamic measurement of the ratio of tensile stress to tensile strain, or stated another way, tensile stiffness. The higher the modulus, the stiffer the material. Modulus values serve as input for elastic layered analysis to predict stress or strain for various conditions and situations. Another use of the property is to predict fatigue behavior; in general, all things being equal, stiffer (higher modulus) materials have lower fatigue life (endurance limit) than less stiff materials.

Comparisons with emulsified asphalt binder mixtures fully cured by vacuum desiccation: Analysis of variance shows binder type to be highly significant. Gradation and the interaction between binder type and gradation are not significant. Newman-Keuls analysis shows the following ordering:

MIXTURE(S)	MEAN(10^5 psi)
DE & CE	10.398
DA & CA	6.459

A plot of means and two standard deviations for the ordered mixtures is shown on Figure 20.

It is Clear that mixtures of this study using emulsified asphalt binders, when fully cured, produce significantly stiffer mixtures than hot-mixed asphalt concrete. It should be pointed out that the value of modulus is strongly influenced by the extent of cure. This will be discussed further in a subsequent section.

It can be generalized that for equal conditions of load and pavement service environment, that higher modulus pavements will exhibit higher stress levels under the same load. From this same reasoning, fatigue life may be lower for the higher modulus materials.

Several trends of the relationship between resilient modulus and other mixture properties from this study, will be outlined below and some will be discussed later.

A. Resilient modulus appears to vary inversely with specific gravity (Figure 21), Marshall stability (Figure 22), and tensile strength (Figure 23).

B. There also appears to be an inverse relation ship between resilient modulus and the ratio between Marshall stability and flow (S/F), (Figure 24).

C. As was the case for Marshall stability, there appears to be no strong relationship between resilient modulus and voids (Figure 25).

7.6 Tensile Strength

Raw data are shown in Table 16. Analysis of variance shows binder type to be highly significant. Gradation and the interaction between binder type and gradation are not significant. Newman-Keuls analysis shows the following ordering:

MIXTURE(S)	MEAN (psi)
DA & CA	152.2
DE & CE	116.8

A plot of means and two standard deviations for the ordered mixtures is shown on Figure 26.

This analysis shows that tensile strength of asphalt cement binder mixes is significantly higher (about 23 per cent) than that of mixtures using emulsified asphalt binders. Implications of tensile strength for comparing mixtures are not completely clear from the limited data generated by this study partly because there is presently no design and performance criteria for bituminous mixtures based on this property.
Two areas of use of the property were considered and explored somewhat suhjectively as part of the. study. First, an attempt was made to analyze tensile stresses in typical paving systems and

compare stress levels with tensile strength of the materials. Secondly, to use stress levels to consider fatigue life based on the ratio of actual stress to ultimate strength of the material. This is the usual approach for conventional elastic materials. Traffic loads (10 and 100 average daily 18 kip axle loads) and soil support (CBR 3' 5' 7 and 10) were used and pavement designs based on The Asphalt Institute method (1) were made. The analysis was made by the Chevron N-Layered Elastic Program.

Results of this analysis are inconclusive because the elastic analysis would indicate that calculated tensile stresses exceed measured tensile strength in most cases for hot mixed asphalt concrete as well as for emulsified asphalt mixtures.

Recent discussions with other workers in the field have shown this to be the case in other studies that have involved tensile stress considerations. It is agreed that loading rate of the diametral tensile test (2 inches per minute) may not be realistic and this can severely affect indicated tensile strength of viscoelastic materials.

At this point and with the limited data generated in this study, the safest conclusion is that the mixtures using emulsified asphalt binders appear to have somewhat lower tensile strengths than hot mixed asphalt concrete. The effect of this difference in strength on layer equivalency is unknown at this time.

7.7 Effect of moisture loss (cure) on properties of mixtures using emulsified asphalt binders.

Data shown and discussed for mixtures using emulsified asphalt binders were obtained after specimens were fully cured. That is, after specimens reached essentially constant weight after vacuum desiccation to remove emulsion and mixing water.

As part of this study, weights and resilient modulus were measured periodically' during the desiccation. Weight loss is shown on Figures 7-10. Resilient modulus is shown on Figures 11-14. It can be seen that resilient modulus increases with curing and that the value of approximately 600,000 psi (equivalent to hot mixed asphalt concrete) occur after 10 to 12 days and that complete curing produces resilient moduli that exceed those of hot mixed asphalt concrete. While not measured as part of this study, it is reasonable to assume that Marshall stability will increase with cure (see Figures 22 and 24) and that other strength related properties may be likewise affected.

A question arises in the use of generalized cure rates and with the correlation of field cure rates and moisture loss in the laboratory by means of vacuum desiccation. There is not, to the knowledge of these researchers, a generalized relationship and it is suggested that modest field studies could be helpful in determining the amount of moisture lost during mixing, placement, and curing. This would be helpful in determining a design modulus or in selecting desiccation period termination before strength testing.

7.8 Moisture sensitivity (strip potential) of mixtures using emulsified asphalt binders.

It was not within the scope of this study to measure moisture sensitivity by retained strength after immersion or by other means. Discussions with other workers has, however, pointed up some questions that should receive consideration as part of a discussion on equivalency of emulsified and conventional hot-mix binder systems.

There is some concern that due to the higher voids content of mixtures using emulsions that moisture can more easily intrude these mixtures than is the case for conventional hot mix binder systems. Secondly, there is some data available that may indicate lower retained strengths for emulsified Systems after immersion.

This study suggests that the concern about voids is not justified inasmuch as there was not a great difference in voids between emulsified and conventional hot-mix binder systems (especially in the case of coarse graded type Ill-b mixtures)

With regards to retained strength testing, it should be noted that testing should not be conducted until specimens have received some degree of cure. Furthermore, it should be noted that, just as for conventional asphalt cement, there are a variety of anti-strip agents and admixtures available and that not all function alike for different asphalt-aggregate combinations. If anti-strip agents are required, consideration should be given to not only the type of anti-strip agent, but to how and where the agent~is introdu~ to the base asphalt, emulsified asphalt, or to the mixture.

7.9 A comment on thickness requirements to satisfy tensile strain requirements.

An accepted design procedure (3) makes an initial thickness design based on subgrade stiffness (modulus), average annual air temperature, equivalent 18 kip axle loads, and mixture resilient modulus. This initial thickness is then adjusted to reflect relative volumes of residual asphalt and voids.

A convenient comparison between conventional hot-mixed and emulsified asphalt binder thickness can be made using this method although the method is not recognized for hot-mix thickness design.

Using constant subgrade modulus (6000 and 12,000 psi), teperature (40-55F), axle loads (l x $l0^6$ EAL), and volume relationships from the study mixtures (hot-mix = 0.61, emulsified = 0.56) and varying the mixture resilient modulus (hot-mix = 600,000 psi, emulsified = 900,000 psi), the following thicknesses are required:

	MIX MODULUS	
	HOT MIX 600,000	EMULSIFIED 900,000
*Initial Thickness (T_i)	6.0	5.1
Corrected Thickness (T_c)	7.0	6.7

*Subgrade modulus = 6000 psi (CBR 4)

It can be seen that the effect of mixture modulus is to require less initial thickness, T. (0.9 inch) for the emulsified system because of higher modulus. The effect of increased voids of the emulsified asphalt binder system, while requiring a greater thickness adjustment (1.6 vs 1.0 inch), produces an adjusted thickness requirement, Tc that is slightly less, or for practical purposes, the same as would be required for the hot-mixed asphalt system.

REFERENCES

(1) "Thickness Design-Full-Depth Asphalt Pavements for Highways and Streets," Manual Series No. 1 (MS-l), Revised eighth edition, Aug., 1970, The Asphalt Institute.

(2) "Mix Design Methods for Asphalt Concrete and Other HotMix Types," Manual Series No. 2 (MS-2), March, 1979, The Asphalt Institute.

(3) "Interim Guide to Full Depth Asphalt Paving Using Various Asphalt Mixes," The Asphalt Institute, Pacific Coast Division Publication PCD-l, January, 1976.

Table 3

Grading Specifications and Gradations Selected

Sieve Size	Base Course		Surface Course	
	III-B Specification	Selected Gradation	IV-B Specification	Selected Gradation
3/4"	100	100	100	100
1/2"	75-100	89	80-100	89
3/8"	60-85	78	70-90	79
#4	35-55	47	50-70	59
#8	20-35	25	35-50	44
#30	10-22	-	18-29	-
#40	8-18	13	16-26	24
#100	4-12	7	8-16	12
#200	2-8	4	4-10	8

Table 4

Percentages of Salt River Aggregate Fractions
Used in Mixture Proportioning

	Mixture Type	
Fraction	Base (Ill-b)	Surface (Iv-D)
3/4"	15.5%	13.0%
1/2"	15.5%	13.0%
3/8"	39.5%	28.0%
Rob Sand	29.5%	46.0%

TABLE 5

AR-4000 ASPHALT CEMENT

PROPERTY	UNAGED	AGED
Penetration: 39.2F, 200 gm., 60 sec. (0.lmm)	8	8
Penetration: 77F, 100 gm., 5 sec.(0.lmm)	60	36
Absolute Viscosity, 140F (Poises)	1580	3935
Kinematic Viscosity, 27SF (cSt)	269	340
R&B Softening Point (^{0}C)	48.0	51.0
Loss on Heating (%)	0.27	

Table 6

Physical Properties of AR-8000 Asphalt Cement (Unaged)

Propertv	Value
Penetration; 39.2^{0}F-, 200 gm, 60s; (0.1 mm)	9
Penetration; 77^{0}F, 100 gm, 5s; (0.lmm)	35
Absolute viscosity; 140^{0}F; Poises	3695
Kinematic viscosity; 275 ^{0}F; cSt	413
Softening Point; ^{0}C	53

Table 7

AR-4000 Hot-Mix Design Properties - Type III-B Mixtures

Asphalt Content, (%)	Unit wt. (pcf)	Bulk S.G.	Theoretical S.G.	% Air Voids	VMA(%)	Effective A.C. (%)	VFMA(%)	Stability (lbs)	Flow (1/100")
4.0	143.8	2.304	2.472	6.8	15.4	3.78	56.0	1953	12
4.0	146.1	2.341	2.472	5.3	14.1	3.78	62.1	1770	10
4.0	144.6	2.317	2.472	6.2	15.0	3.78	57.8	1840	11
Average	144.8	2.321	2.472	6.1	14.8	3.78	58.7	1854	11
4.5	143.6	2.301	2.454	6.2	16.0	4.28	60.9	1900	10
4.5	146.4	2.346	2.454	4.4	14.3	4.28	69.5	1990	10
4.5	144.2	2.311	2.454	5.8	15.6	4.28	62.8	1380	10
Average	144.7	2.319	2.454	5.5	15.3	4.28	64.2	1787	10
5.0	145.7	2.335	2.436	4.1	15.2	4.79	72.9	2160	11
5.0	144.7	2.319	2.436	4.8	15.8	4.79	69.6	1442	10
5.0	146.0	2.340	2.436	3.9	15.0	4.79	74.0	1789	11
Average	145.5	2.331	2.436	4.3	15.3	4.79	72.2	1797	10.7
5.5	147.4	2.362	2.418	2.3	14.7	5.28	84.0	1966	15
5.5	146.5	2.348	2.418	2.9	15.2	5.28	80.0	1901	13
5.5	146.8	2.353	2.418	2.7	15.0	5.28	82.0	1744	12
Average	146.9	2.354	2.418	2.6	15.0	5.28	82.0	1870	13.3

Table 8

AR-4000 Hot-Mix Design Properties - Type IV-B Mixtures

Asphalt Content, (%)	Unit wt. (pcf)	Bulk S.G.	Theoretical S.G.	% Air Voids	VMA(%)	Effective A.C.(%)	VFWA(%)	Stability (lbs)	Flow (1/100")
4.0	142.6	2.285	2.474	7.6	16.1	3.71	52.3	2474	8
4.0	144.8	2.321	2.474	6.2	14.7	3.71	57.9	2458	12
4.0	145.3	2.329	2.474	5.9	14.4	3.71	58.3	2650	11
Average	144.2	2.311	2.474	6.6	15.1	3.71	56.2	2527	10.3
4.5	143.5	2.299	2.456	6.4	16.3	4.21	58.8	2130	12
4.5	143.8	2.305	2.456	6.2	15.8	4.21	61.0	1987	9
4.5	144.4	2.314	2.456	5.8	15.4	4.21	62.5	2540	13
Average	143.9	2.306	2.456	6.1	15.7	4.21	61.2	2219	11.3
5.0	144.2	2.311	2.438	5.3	16.0	4.72	67.5	2010	10
5.0	144.6	2.318	2.438	4.9	15.7	4.72	68.7	2190	11
5.0	145.6	2.333	2.438	4.3	15.2	4.72	71.7	2120	10
Average	144.8	2.320	2.438	4.8	15.7	4.72	69.1	2107	10.3
5.5	145.6	2.334	2.423	3.7	15.6	4.72	77.3	2122	10
5.5	146.8	2.352	2.423	2.9	14.9	5.22	81.3	2392	11
5.5	147.1	2.357	2.423	2.7	14.8	5.22	82.4	2278	11
Average	146.5	2.348	2.423	3.1	15.1	5.22	80.3	2264	10.7

Table 9

Emulsified Asphalt Mix Design Properties - (Tvpe Ill-b Mixture)

Residue content (%)	Unit wt.(pcf)	Bulk S.G.	Theory S.G.	% Air Voids	Effective VMA(%)	(%) A.C.	(%) VEMA	Stability (lbs)	Flow (l/100")
4.0	142.6	2.285	2.505	8.8	6.1	3.25	45.7	2442	18
4.0	141.6	2.269	2.505	9.4	16.7	3.25	43.7	1498	14
4.0	141.9	2.275	2.505	9.1	16.5	3.25	44.4	1786	12
Average	142.0	2.276	2.505	9.1	16.4	3.25	44.7	1909	14.7
4.5	143.3	2.297	2.486	7.6	16.1	3.75	53.0	1220	15
4.5	142.8	2.287	2.486	7.9	16.5	3.75	51.5	1330	20
4.5	143.3	2.297	2.486	7.6	16.1	3.75	53.0	1139	15
Average	143.1	2.294	2.486	7.7	16.2	3.75	52.0	1230	16.7
5.0	140.7	2.254	2.467	8.6	18.1	4.26	52.5	1050	18
5.0	141.5	2.268	2.467	8.1	17.6	4.26	54.4	1086	22
5.0	139.1	2.229	2.467	9.6	18.0	4.26	52.2	900	16
Average	140.4	2.251	2.467	8.8	18.2	4.26	52.2	1012	18.7
6.0	137.6	2.206	2.430	9.2	20.7	5.26	55.5	614	24
6.0	139.5	2.236	2.430	8.0	19.7	5.26	59.1	552	22
6.0	138.3	2.217	2.430	8.8	20.3	5.26	56.9	712	25
Average	138.5	2.219	2.430	8.7	20.1	5.26	57.5	620	23.7

Table 10

Emulsified Asphalt Mix Design Properties- (Tvoe IV-b Mixture)

Residue content (%)	Unit wt.(pcf)	Bulk S.G.	Theory S.G.	% Air Voids	Effective VMA(%)	(%) A.C.	(%) VEMA	Stability (lbs)	Flow (l/100")
4.5	139.0	2.228	2.499	10.8	18.6	3 .50	41.5	1193	19
4.5	139.9	2.241	2.499	10.3	18.1	3.50	42.9	1175	20
4.5	139.9	2.243	2.499	10.2	18.0	3.50	43.2	1581	20
Average	139.6	2.237	2.499	10.5	18.3	3.50	43.9	1316	19.7
5.0	138.7	2.222	2.480	10.4	19.2	4.00	45.8	1062	20
5.0	137.5	2.203	2.480	11.1	19.9	4.00	43.8	1041	18
5.0	137.2	2.199	2.480	11.3	20.1	4.00	43.3	1068	19
Average	137.8	2.208	2.480	11.0	19.7	4.00	44.2	1057	19
5.5	135.3	2.169	2.462	11.9	21.6	4.51	44.8	772	21
5.5	134.6	2.157	2.462	12.3	22.0	4.51	43.8	843	21
5.5	135.7	2.174	2.462	11.7	20.6	4.51	47.1	747	20
Average	135.2	2.167	2.462	12.0	21.6	4.51	44.8	787	20.7
6.0	135.6	2.176	2.443	10.9	21.7	5.01	49.7	791	22
6.0	134.9	2.162	2.443	11.5	22.2	5.01	48.3	623	22
6.0	133.6	2.142	2.443	12.3	23.0	5.01	46.2	689	28
Average	134.8	2.160	2.443	11.6	22.3	5.01	48.0	701	24

	EMULSIFIED		ASPHALT CONCRETE	
	DENSE	COARSE	DENSE	COARSE
	2.234	2.251	2.296	2.321
	2.250	2.239	2.316	2.335
	2.226	2.242	2.272	2.349
	2.245	2.255	2.311	2.327
	2.194	2.249	2.290	2.317
	2.197	2.249	2.292	2.343
	2.218	2.254	2.277	2.332
	2.202	2.232	2.277	2.341
	2.218	2.246	2.295	2.353
	2.193	2.236	2.311	2.309
	2.189	2.250	2.311	2.329
	2.213	2.254	2.303	2.306
Σ	26.5790	26.957	27.551	27.962
x̄	2.2149	2.2464	2.2959	2.3302
s	0.0207	0.0075	0.0150	0.0150

TABLE 11

BULK SPECIFIC GRAVITY

RAW DATA

	EMULSIFIED		ASPHALT CONCRETE	
	DENSE	COARSE	DENSE	COARSE
	7.7	6.5	7.0	6.8
	7.1	7.0	6.3	6.2
	8.1	6.9	8.0	5.6
	7.3	6.3	6.5	6.5
	9.4	6.6	7.3	6.9
	9.3	6.6	7.3	5.9
	8.4	6.4	7.8	6.3
	9.1	7.3	7.8	6.0
	8.4	6.7	7.1	5.5
	9.4	7.1	6.5	7.2
	9.6	6.6	6.5	6.5
	8.6	6.4	6.8	7.4
Σ	102.4	80.4	84.9	76.8
$\bar{x}$	8.53	6.70	7.08	6.40
s	0.855	0.310	0.579	0.602

TABLE 12

AIR VOIDS

RAW DATA

BINDER, B_j

GRADATION, G_i

	EMULSIFIED		ASPHALT CONCRETE	
	DENSE	COARSE	DENSE	COARSE
	1219	989	1634	1908
	1149	938	1791	1947
	1160	1006	1723	2004
	1089	991	2147	2370
	1103	933	1660	1946
	860	828	1549	2020
Σ	6580	5685	10,504	12,195
$\bar{x}$	1096.7	947.5	1750.7	2032.5
s	124.76	65.8	210.7	170.39

TABLE 13

MARSHALL STABILITY

RAW DATA

EMULSIFIED

	DENSE			COARSE		
	AXIS	AXIS 2	AVERAGE	AXIS 1	AXIS 2	AVERAGE
	10.31	11.42	10.685	11.38	11.04	11.210
	10.52	12.70	11.610	10.12	9.59	9.855
	10.49	11.76	11.125	11.17	10.22	10.695
	10.88	10.27	10.575	11.87	12.28	12.075
	10.37	10.67	10.520	9.36	9.00	9.180
	10.29	11.00	10.645	8.91	9.35	9.130
	10.45	11.43	10.940	9.41	9.41	9.410
	10.12	10.41	10.265	10.19	9.92	10.055
	9.37	10.45	9.910	8.77	6.95	7.860
	11.17	10.22	10.695	9.51	9.27	9.390
	9.27	11.30	10.285	11.34	11.00	11.170
	10.33	9.51	9.920	14.51	9.81	12.160
Σ			127.355	Σ		122.190
$\bar{x}$			10.613	$\bar{x}$		10.183
s			0.4906	s		1.3018

ASPHALT CONCRETE

	5.03	5.24	5.135	5.89	6.87	6.380
	7.82	7.36	7.590	7.82	6.59	7.205
	5.21	4.81	5.010	8.13	6.41	7.270
	8.71	8.71	8.710	5.76	5.28	5.520
	6.82	6.14	6.480	8.19	7.22	7.705
	5.01	5.57	5.290	5.20	6.23	5.715
	5.80	5.08	5.440	6.51	7.28	6.895
	5.18	5.65	5.415	6.21	7.31	6.760
	6.28	7.39	6.835	5.47	4.19	4.830
	4.34	6.39	5.365	7.20	8.16	7.680
	6.33	6.03	6.180	7.76	6.54	7.150
	6.74	5.82	6.280	7.09	9.27	8.180
Σ			73.730			81.290
$\bar{x}$			6.144			6.774
s			1.1262			0.9946

TABLE 15

RESILIENT MODULUS (10^5 psi)

RAW DATA

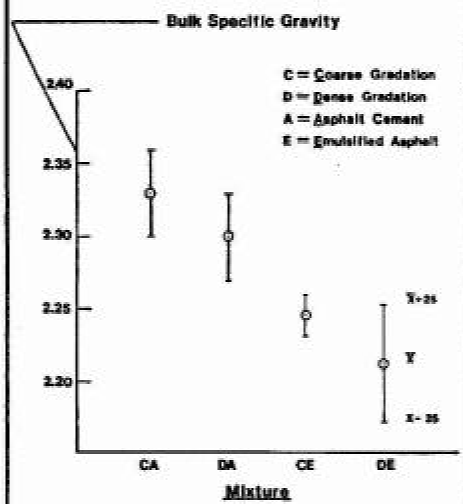

Figure 15
Bulk Specific Gravity

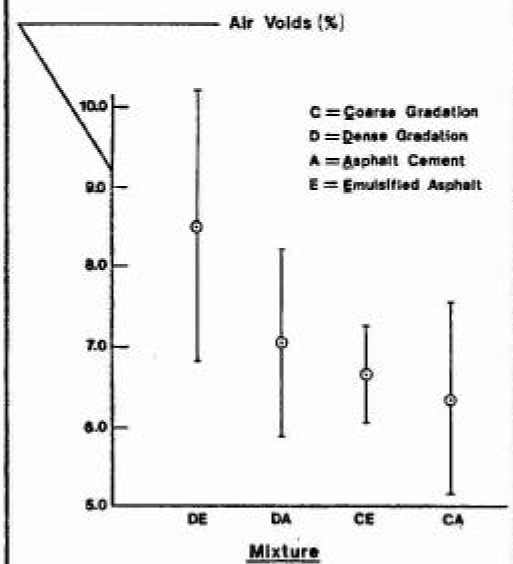

Figure 16
Air Voids

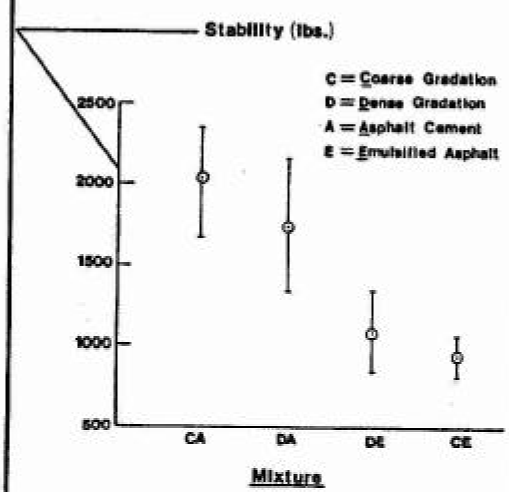

Figure 17
Marshall Stability

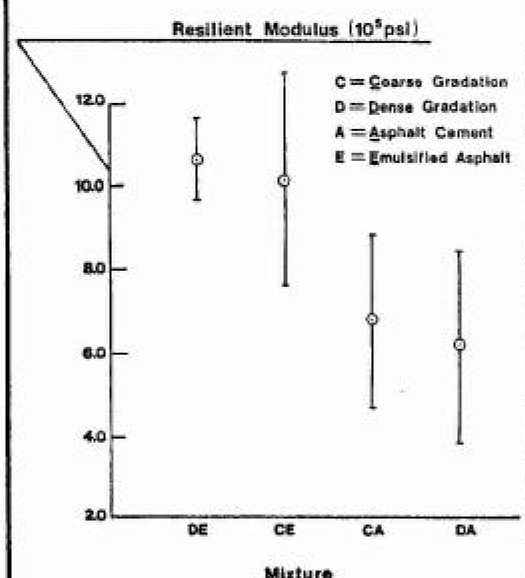

Figure 20
Resilient Modulus

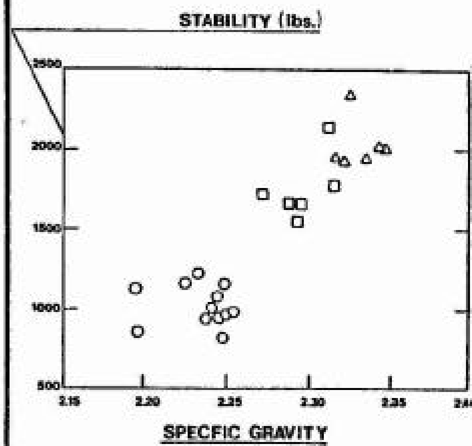

Figure 18

Stability vs Specific Gravity

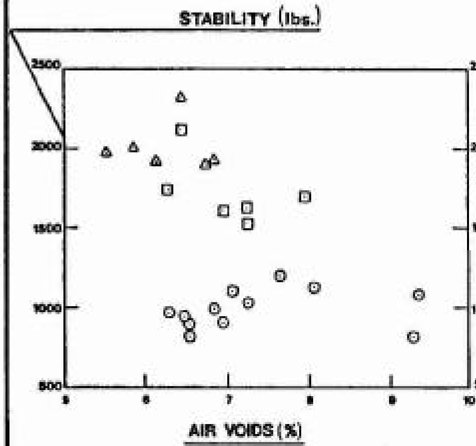

Figure 19

Stability vs Voids

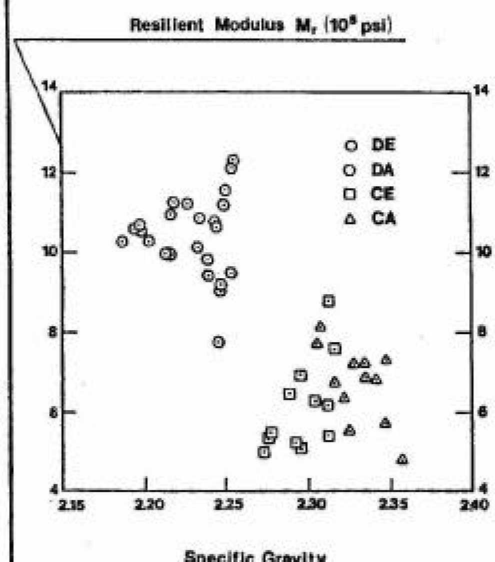

Figure 21

Resilient Modulus vs Specific Gravity

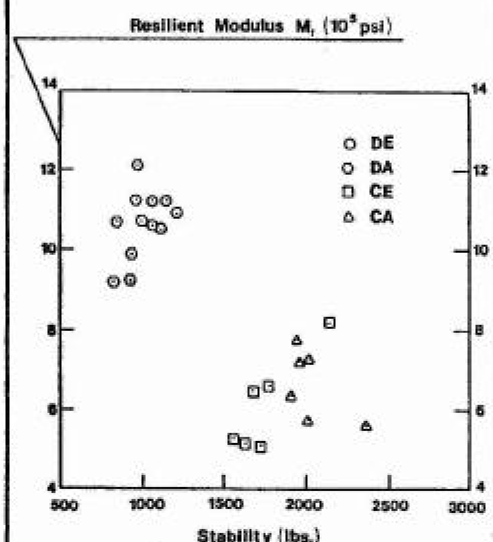

Figure 22

Resilient Modulus vs Marshall Stability

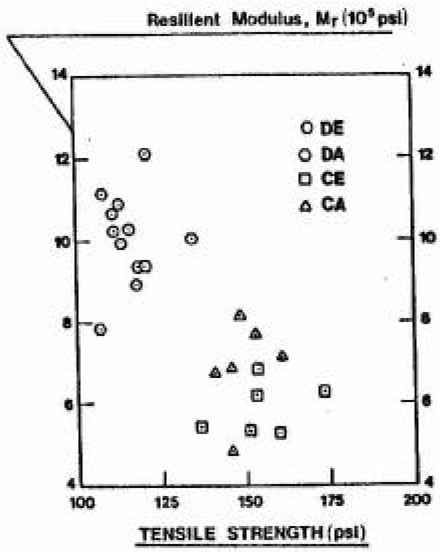

Figure 23

Resilient Modulus vs Tensile Strength

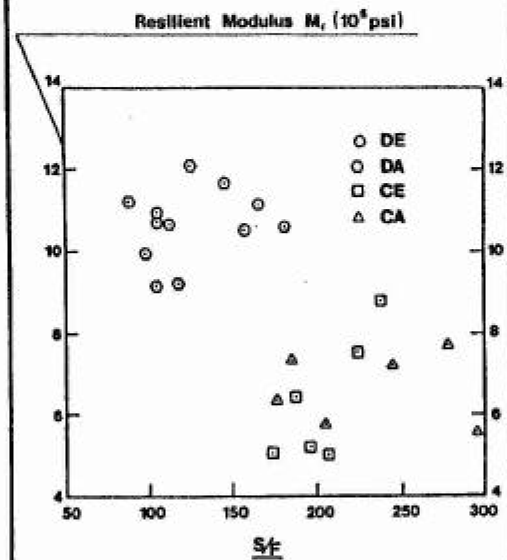

Figure 24

Resilient Modulus vs Stability-Flow Ratio

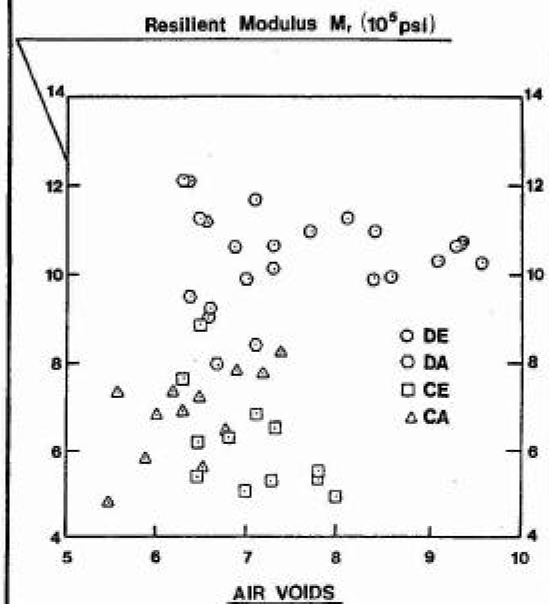

Figure 25

Resilient Modulus vs Air Voids