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16. Abstract

This report summarizes the effects of various mixing temperatures and stockpile moisture contents on asphalt mixtures, one of which contained an absorptive, lightweight aggregate.

The asphalt mixtures were produced from stockpile aggregates with moisture contents ranging from approximately zero to highly saturated, and placed on the road at temperatures ranging from 200°F to 360°F. Laboratory and compacted specimens and plant mixed, laboratory compacted specimens were tested to evaluate the effect of mixing temperatures and stockpile moisture on various engineering properties.

No consistent relationship between the construction variables of mixing temperature, stockpile moisture, strength, resilient modulus, and Hveem stability of the mixtures was observed. The resistance to moisture damage, however, increased with increasing mixing temperatures and increased stockpile moisture. Similar relationships were observed on the three projects which had been previously evaluated (Ref 2).

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by

Maghsoud Tahmoressi
Thomas W. Kennedy

Research Report Number 358-2F

Research Project 3-9-83-358

The Effect of Mix Temperature on Asphalt Mixtures as Related to Drum Mixers

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1989

PREFACE

This is the second and final of two reports for Project 3-9-83-358, "The Effect of Mixing Temperature and Stockpile Moisture on Asphalt Mixtures." This report summarizes the findings of the last two field projects, one of which contained an absorptive aggregate, and briefly discusses the findings from the previous field projects (Ref 2).

The assistance of the Texas State Department of Highways and Public Transportation, especially personnel from Districts 11 and 19, is acknowledged. In addition, appreciation is extended to the contractors involved with the last two field projects, East Texas Asphalt and Madden Contracting Company. Without their cooperation it would have been impossible to conduct the experimental field projects.

Thanks are also expressed to members of the Center for Transportation Research staff. In particular, the help of Messrs. James N. Anagnos and Eugene Betts is acknowledged for their efforts related to the field experiments and laboratory studies.

The support of the Federal Highway Administration and Department of Transportation is gratefully acknowledged.

Maghsoud Tahmoressi
Thomas W. Kennedy

LIST OF REPORTS

Report No. 358-1, "The Effects of Mixing Temperature and Stockpile on Asphalt Mixtures," by Thomas W. Kennedy and Gerald A. Huber, summarizes the result of a field study of asphalt mixtures with various mixing temperatures and aggregate moisture contents produced at three test sites.

Report No. 358-2F, "The Effect of Mixing Temperature and Stockpile Moisture on Asphalt Mixtures Containing Absorptive Aggregates," by Maghsoud Tahmoressi and Thomas W. Kennedy, summarizes the result of a study of asphalt mixtures with various mixing temperatures and aggregate moisture contents at two test sites.

ABSTRACT

This report summarizes the effects of various mixing temperatures and stockpile moisture contents on asphalt mixtures, one of which contained an absorptive, lightweight aggregate.

The asphalt mixtures were produced from stockpile aggregates with moisture contents ranging from approximately zero to highly saturated, and placed on the road at temperatures ranging from 200°F to 360°F. Laboratory mixed, compacted specimens and plant mixed, laboratory compacted specimens were tested to evaluate the effect of mixing temperatures and stockpile moisture on various engineering properties.

No consistent relationship between the construction variables of mixing temperature, stockpile moisture, strength, resilient modulus, and Hveem stability of the mixtures was observed. The resistance to moisture damage, however, increased with increased mixing temperatures and increased stockpile moisture. Similar relationships were observed on the three projects which had been previously evaluated (Ref 2).

KEY WORDS: asphalt mixtures, indirect tensile test, elastic properties, resilient modulus, tensile strength, aggregate moisture, stockpile moisture, mix temperature, drum mix plant, batch plant

SUMMARY

Previous studies have indicated that mixtures produced in drum mix plants have workability and short-term performances equal to mixtures produced in conventional batch plants and that anticipated long-term performance will be equivalent (Ref 1). There is a need, however, for information related to the effects of stockpile moisture contents and mixing temperatures on the engineering properties of the resulting mixtures. This information could possibly be used to develop cost-effective specifications and/or guidelines.

To determine these effects, the Center for Transportation Research at The University of Texas at Austin and the Texas State Department of Highways and Public Transportation initiated a series of field experiments involving an evaluation of the engineering properties of asphalt mixtures produced with a range of stockpile moisture content and mixing temperatures using both drum mix and batch plants.

This report covers the second phase of the study which involved two additional Texas aggregates. Mixing temperature ranged from 200°F to 360°F and stockpile moisture contents varied from dry to saturated. The engineering properties evaluated were Hveem stability, tensile strength, static and resilient modulus of elasticity, and moisture susceptibility.

The results of the first phase of the study, which involved three different aggregate-asphalt mixtures produced in a drum mix plant and one aggregate-asphalt mixture produced in a batch plant, were reported in Research Report 358-1 (Ref 2).

IMPLEMENTATION STATEMENT

Several studies have indicated that mixtures produced in drum mix plants have workability and short-term performances equal to those of mixtures produced in batch plants. It is also assumed that long-term performance of both will be equivalent; however, these studies evaluated material produced under existing specifications, with no effort made to establish the performance qualities of mixtures produced from aggregates that have a wide range of stockpile moisture conditions.

In this study and in the previous study, no consistent relationships were found between tensile strength, resilient modulus or Hveem stability, and either the mixing temperature or stockpile moisture content. There was, however, an apparent improvement in moisture damage resistance as mixing temperature increased and stockpile moisture changed from dry to saturated. The latter observation was unexpected and has not been explained. It should be noted that uncontrolled variation may well have masked possible effects and confounded others.

Based on these results, it appears that aggregate moisture content and mixing temperature are not major factors of concern provided that the plant can remove the water and that adequate compaction and coating can be achieved. The major impact on the contractor relates to production rates and drying costs.

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CHAPTER 1. INTRODUCTION

Currently, there are two types of mixing plants normally used to produce hot mix asphalt concrete mixtures. These are batch and drum mix plants.

A batch plant heats and dries the aggregate in a rotating drum (drier), separates the aggregate by size into hot storage bins, weighs appropriate quantities of each aggregate size, and mixes the aggregate with asphalt in a pugmill. In a drum mix plant, aggregates are heated and coated with asphalt in a drum mixer, with the aggregate gradation controlled at the cold feed by adjustable gates and variable speed belts. As a result the hot screens, hot aggregate storage bins, weighing scales, and pugmill of a batch mix plant are eliminated.

Previous research (Ref 1) has indicated that drum mix plants are capable of producing quality mixtures which are comparable to mixtures produced by batch plants. However, in drum plants some moisture is necessary in order to achieve foaming of the asphalt cement, which allows coating of the aggregate at lower temperatures. This requirement for available moisture and lower temperature indicated a need for information related to the effect of mixing temperature and stockpile moisture content on the engineering properties of asphalt mixtures for both types of plants. To determine these effects the Center for Transportation Research (CTR) at The University of Texas at Austin and the Texas State Department of Highways and Public Transportation (SDHPT), through their cooperative research program, initiated field experiments to evaluate the engineering properties of asphalt mixtures from selected batch and drum mix plants operating within the state.

The primary objective of the overall project was to determine the effects of mix discharge temperature and stockpile moisture content on the field performance and engineering properties of hot mixed asphalt mixtures. To accomplish this objective field experiments were developed involving the construction and monitoring of test sections containing asphalt mixtures produced with aggregates containing a range of moisture contents over a range of mix discharge temperatures. The engineering properties which were evaluated included indirect tensile strengths, static and resilient moduli of elasticity, Hveem stabilities, and the moisture susceptibilities of the mixtures.

The major portion of the study was previously reported in Research Report 358-1 (Ref 2). The findings of this initial work indicated that mixing temperate and moisture content of the stockpiled aggregate had minimal effect on the engineering properties of the asphalt mixtures. Thus, it was decided to conduct additional studies using other aggregates. This report describes these experiments which included the additional types of aggregates, the sampling plan, the testing program, the test methods, and the findings of this final phase of the overall study.

CHAPTER 2. EXPERIMENTAL PROGRAM

The properties which were evaluated included indirect tensile strength, static and resilient moduli of elasticity, Hveem stabilities, and moisture susceptibility. This chapter describes the experiments including the types of aggregates, the sampling program, the testing program, and the test methods utilized in this final phase of this study. The major portion of the study was previously reported in Research Report 358-1 (Ref 2).

STUDY DESIGN

This phase of study involved two field experiments (Table 1) in which asphalt mixtures containing two different aggregates were produced with a range of mixing temperatures and stockpile moisture contents (Table 2) using two different drum mix plants. These experiments were conducted near Marshall and Lufkin, Texas.

Mixing Temperatures and Stockpile Moisture Contents

The mixing temperature varied from 200°F to 360°F (Table 2). It should be noted that all mixing temperatures could not be achieved.

The stockpile moisture contents were varied from virtually dry to nearly saturated. The three levels of moisture content were qualitatively described as dry, wet, and saturated. Dry stockpiles were obtained by pre-drying the aggregate before mixing. Wet stockpiles were defined as the natural stockpile moisture, and saturated stockpile aggregates were obtained by applying water to the aggregates. Mixing (discharge) temperatures were varied by changing the burner flame control. The temperature of the asphalt cement prior to mixing was relatively constant, ranging from 275°F to 300°F.

Certain combinations of mixing temperature and stockpile moisture condition were not achieved. For the Marshall Project (Limestone Aggregate D) and the Lufkin Project (Lightweight Aggregate E), the lowest mixing temperatures (lowest burner setting) which could be achieved for mixtures containing dry aggregates were 250° and 300°F, respectively. In addition, mixtures involving saturated stockpile aggregates were difficult to produce at very low or very high temperatures. At low mixing temperatures uniform aggregate coatings were difficult to obtain, while high mixture temperatures were difficult to achieve for mixtures containing saturated aggregates. The highest mixing (discharge) temperature which could be attained for the Lufkin Project (Aggregate E) with saturated aggregates was 300°F.

Experimental Projects

The selection of the two construction projects was made in cooperation with the Texas State Department of Highways and Public Transportation, the Texas Hot Mix Pavement Association, and individual hot mix contractors. After identifying suitable highway projects, the proposed experiments were discussed with the contractor and the Federal Highway Administration.

The selected project and plant locations are shown in Fig 1. The Marshall Project involved a section of Interstate Highway 20, and the Lufkin Project was located on Loop 287.

Materials

Two different asphalt mixtures were used. At Marshall, the primary aggregate was limestone, while the Lufkin Project involved a lightweight manufactured aggregate. The individual aggregates in each of the mix designs and the gradation of the mixtures are shown in Table 4 and Figs 2(a) and 2(b), respectively. The asphalt cement used in both projects was an AC-20.

Sampling Program

Samples of both the aggregates and the asphalt-aggregate mixtures were collected for each experimental project. Stockpile aggregate samples were collected to determine moisture contents. In addition, samples of the individual aggregates were taken from the feed belts on the cold feed bins and a sample of the combined aggregate was taken from the charging conveyor, as shown in Fig 3. Mixture samples were also obtained from the truck after discharge from the surge-storage bin.

TABLE 1. LOCATION AND DESCRIPTION OF AGGREGATE MIXTURES

Aggregate	Asphalt Plant				Aggregate		
(District*)	Owner	Location	Type	Design	Aggregate Type	Producer	Source
Aggregate D (19, Marshall)	Madden Contracting Co.	Marshall	Drum	Type D**	Crushed Limestone	Texas Crushed Stone	Georgetown
					Limestone Screenings	Texas Crushed Stone	Georgetown
					Field Sand	Vaughn Field Sand	Marshall
Aggregate E (11, Lufkin)	East Texas Asphalt	Lufkin	Drum	Type D**	Lightweight,	Texas Industries	Streetman
					Fine Sand,	East Texas Asphalt	Lufkin
					Coarse Sand	East Texas Asphalt	Lufkin

* Texas State Department of Highways and Public Transportation (SDHPT) Districts
** Designation of Texas SDHPT, 1/2" maximum size aggregate

TABLE 2. BASIC EXPERIMENT DESIGN

		Stockpile Moisture Content		
Project	Mixing Temp, °F	Dry	Wet	Saturated
Marshall	200	**	x	x
	250	x	x	x
	300	x	x	x
Lufkin*	250	***	x	x
	300	x	x	x
	360	x	x	***

* The Lufkin Aggregate was a lightweight material. The lowest mixing temperature which could be attained with all moisture conditions was 250°F because of the high moisture contents of the aggregate.

** With dry aggregate a mixing temperature of 200°F could not be achieved.

*** With dry aggregate the lowest temperature which could be achieved was 300°F and the highest achievable temperature for saturated stockpile was also 300°F due to the burner limitation.

Specimen Preparation and Conditioning

Specimens, 2 inches high by 4 inches in diameter, were molded using the Texas Gyratory Shear compactor. Three compaction procedures were used: standard, modified-standard, and modified.

The standard compaction specimens were prepared using the standard procedures of the Texas State Department of Highways and Public Transportation in which the mixtures were compacted at 250°F (Ref 3). The modified-standard compaction specimens were prepared using the same method except that the compaction temperature was the same as the mixing temperature. The modified compaction procedure involved compacting specimens to a target density of 7 percent air voids at the plant discharge temperature.

Two conditioning methods were applied to each of the specimens. Dry-conditioned specimens were stored at room temperature for several days and wet-conditioned specimens were vacuum saturated under a 26-inch mercury vacuum for 30 minutes, placed through a freeze-thaw cycle, and then tested at room temperature.

Testing Programs

The testing programs for each field experiment are shown in Tables 3A and 3B.

TEST METHODS

The three basic tests conducted on the compacted asphalt mixtures were the Hveem stability test, the static and repeated-load indirect tensile tests, and the Texas boiling test.

Hveem Stability Test

Hveem stabilities were determined using the Hveem stabilometer as described in Texas Method Tex-208-F (Ref 3). Compacted asphalt mixture specimens, 2 inches high by 4 inches in diameter, were loaded at 140°F at a constant strain rate of 0.05 inches per minute to a maximum vertical load of 5,000 pounds, and the corresponding horizontal pressure was measured. These values were utilized to calculate the stability value using Equation 2.1.

Static Indirect Tensile Test

The indirect tensile test, which estimates the tensile strength of the asphalt mixtures, used the following equipment and procedures.

A cylindrical specimen was loaded with a compressive load acting parallel to and along the vertical diametrical plane (Fig 4[a]). The load was applied through 0.5-inch-wide steel loading strips curved to fit the specimen. A fairly uniform tensile stress, perpendicular to the plane of the applied load, caused the specimen to fail by splitting along the vertical diameter (Fig 4[b]). Estimates of the tensile strengths were calculated from the applied load at failure and the specimen dimensions using Equation 2.2. The test equipment included a loading frame, loading apparatus, and an MTS closed-loop electrohydraulic system to apply load and control the deformation rate. The loading apparatus contained platens, with each platen constrained so that both platens remained parallel. Curved (2-inch-radius) stainless steel loading strips were attached to both the upper and lower platens (Ref 4). All tests were conducted at 77°F.

Repeated-Load Indirect Tensile Test

The resilient modulus of elasticity was determined using the repeated-load indirect tensile test in which approximately 20 percent of the static failure load (stress) was applied repeatedly to the specimen (Ref 5). A small pre-load was applied to the specimens prior to applying the repeated loads to prevent impact loading and to minimize the effects of seating of the loading strip. The load was applied at a frequency of one cycle per second (1 Hz) with a 0.2-second load duration and a 0.8-second rest period. A typical load pulse and the resulting deformation relationships are shown in Fig 5. Tests were conducted at 77°F. The load-vertical deformation and load-horizontal deformation relationships were recorded using X-Y plotters and utilized to calculate resilient modulus, Equation 2.4.

Texas Boiling Test

The Texas boiling test is a rapid method to evaluate the moisture susceptibility, or stripping potential, of aggregate-asphalt mixtures (Ref 6). A visual estimate is made of the amount of asphalt stripping from the aggregate surfaces, which has occurred after the mixture has been subjected to the action of boiling water for a specified time.

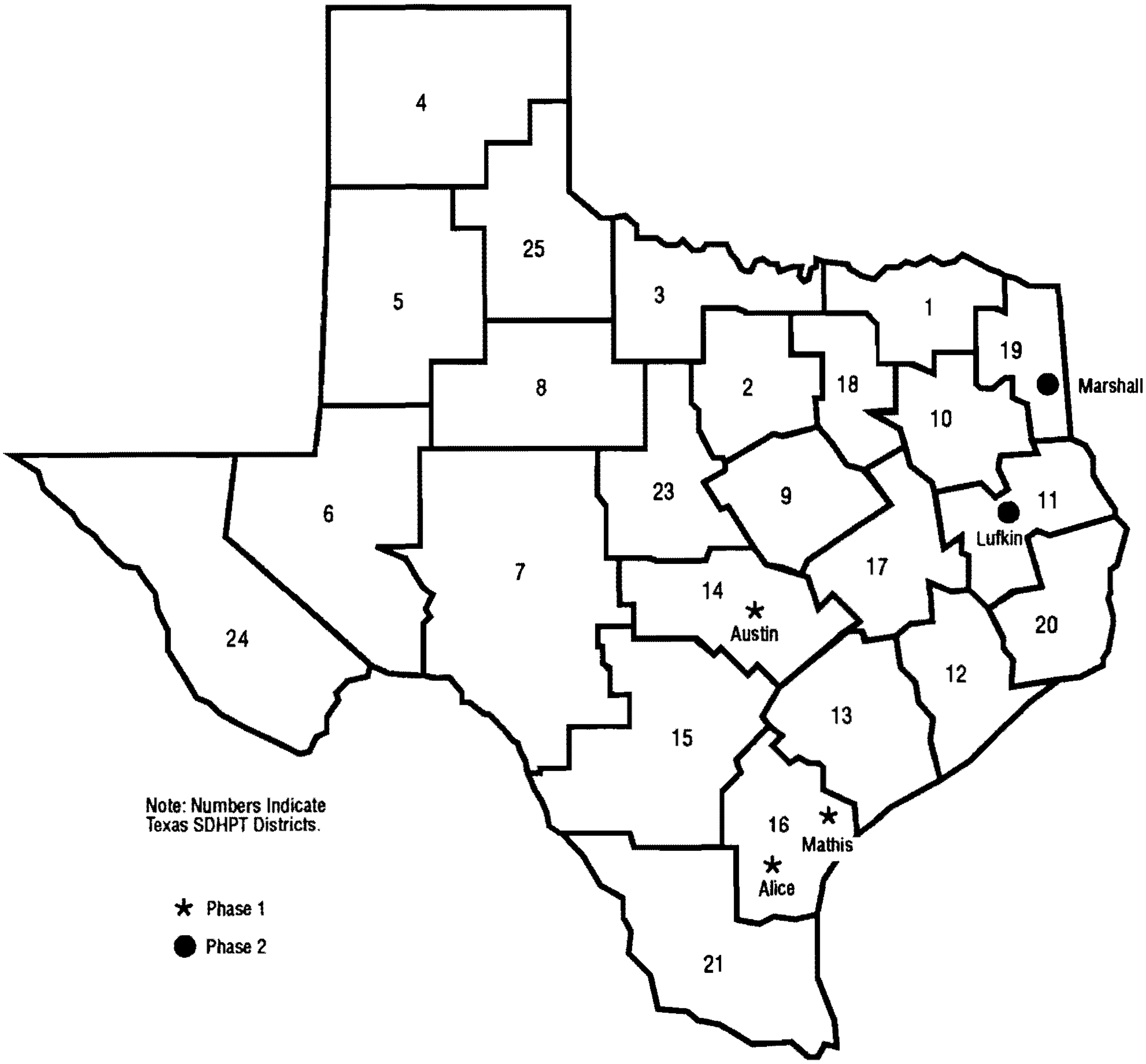

Fig 1. Plant locations of experimental sections.

TABLE 3A. TESTING PROGRAM FOR MOISTURE-TEMPERATURE EXPERIMENTS—AGGREGATE D

Standard Compaction Specimens*	
Dry Conditioned	Freeze-Thaw Conditioned
Static and Repeated Load	Static Indirect Tension
Indirect Tensile Test	
Hveem Stability	
Modified-Standard Compaction Specimens**	
Dry Conditioned	Freeze-Thaw Conditioned
Static and Repeated Load	Static Indirect Tensile Test
Indirect Tensile Test	
Hveem Stability	
Modified Compaction Specimens***	
Dry Conditioned	Freeze-Thaw Conditioned
Static and Repeated Load	Static Indirect Tensile Test
Indirect Tensile Test	
Bulk Specimens (Including Asphalt Mixture and Aggregates)	
Moisture Content Determination	
Texas Boiling Test	
Asphalt Extraction	
Aggregate Gradation	
Penetration of Extracted Asphalt	
Viscosity of Extracted Asphalt	
Theoretical Specific Gravity of Mixture	

* Standard – Standard SDHPT test method at 250°F
** Modified-Standard – Standard SDHPT test method at plant temperature
*** Modified (7% air) – Modified SDHPT test method at plant temperature

TABLE 3B. TESTING PROGRAM FOR MOISTURE-TEMPERATURE EXPERIMENTS—AGGREGATE E

Standard Compaction Specimens*	
Dry Conditioned	
Static and Repeated Load	
Indirect Tensile Test	
Hveem Stability	
Modified-Standard Compaction Specimens**	
Dry Conditioned	
Static and Repeated Load	
Indirect Tensile Test	
Hveem Stability	
Modified Compaction Specimens***	
Dry Conditioned	Freeze-Thaw Conditioned
Static and Repeated Load	Static Indirect Tensile Test
Indirect Tensile Test	
Bulk Specimens (Including Asphalt Mixture and Aggregates)	
Moisture Content Determination	
Texas Boiling Test	
Asphalt Extraction	
Aggregate Gradation	
Penetration of Extracted Asphalt	
Viscosity of Extracted Asphalt	
Theoretical Specific Gravity of Mixture	

* Standard – Standard SDHPT test method at 250°F
** Modified-Standard – Standard SDHPT test method at plant temperature
*** Modified (7% air) – Modified SDHPT test method at plant temperature

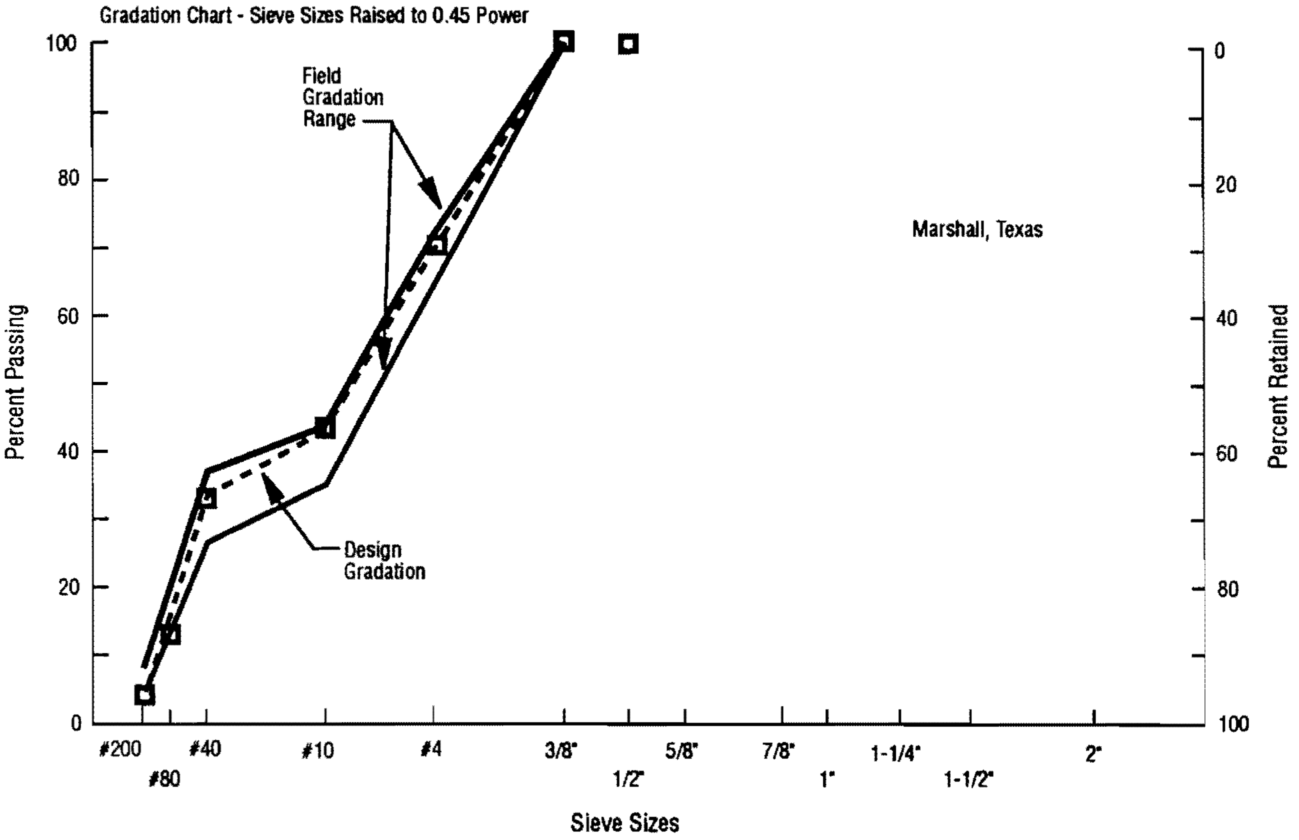

Fig 2(a). Gradation of experimental mixtures, limestone aggregate D.

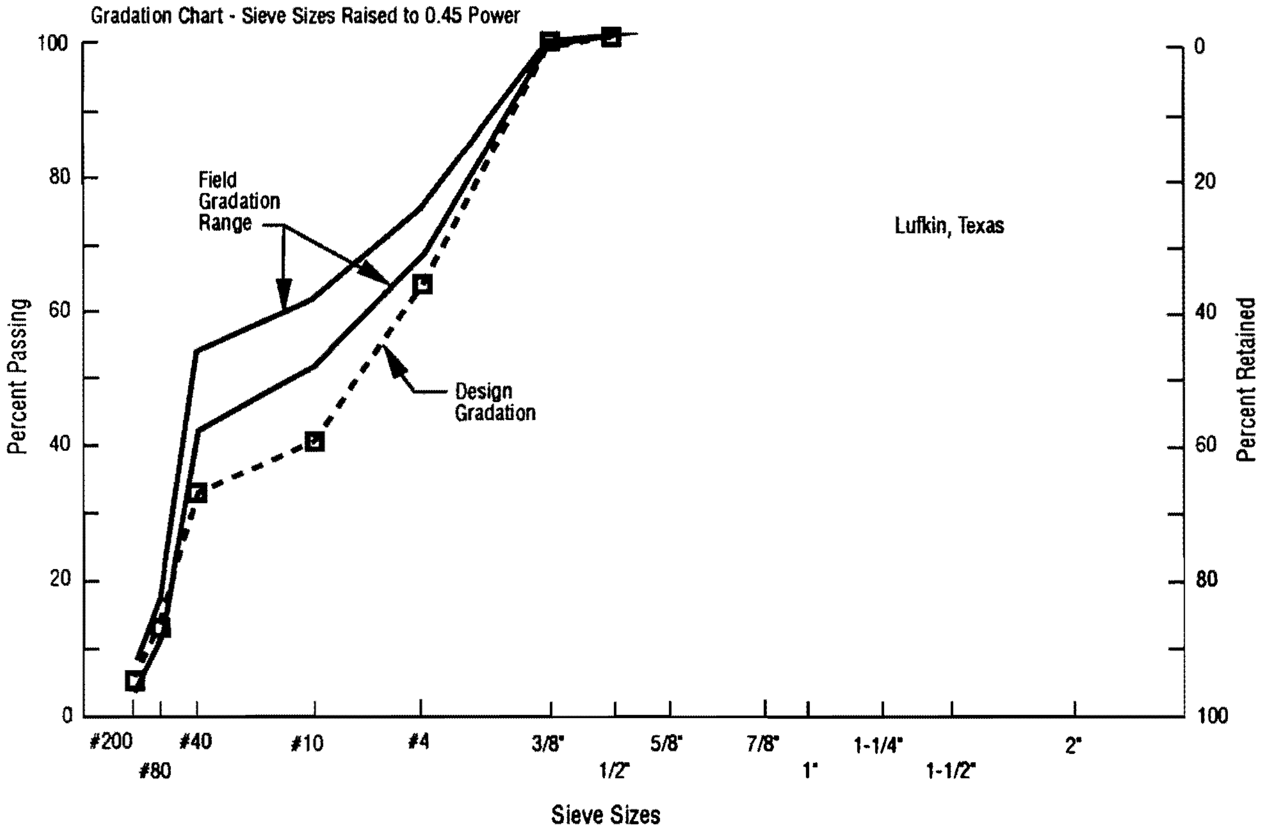

Fig 2(b). Gradation of experimental mixtures, limestone aggregate E.

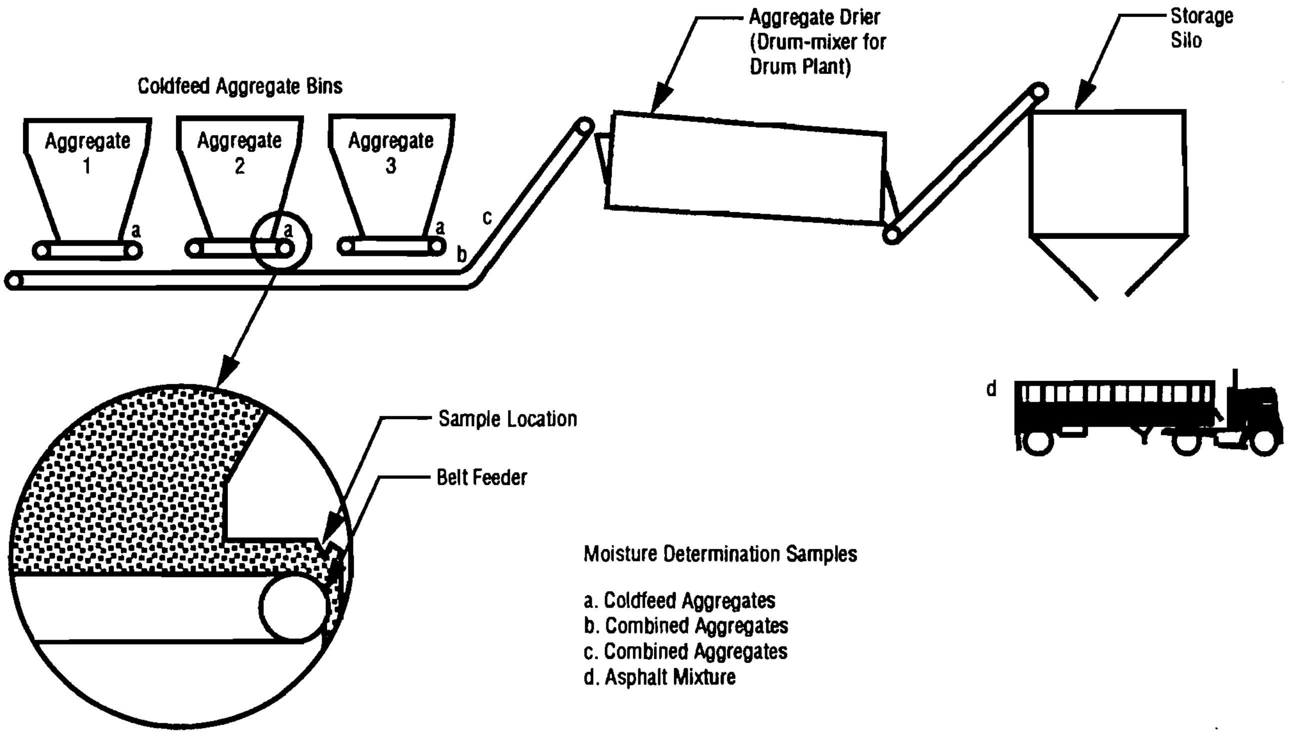

Fig 3. Location of moisture content sampling.

A 300-gram sample of the aggregate-asphalt mixture was boiled for 10 minutes in a 1,000-ml beaker filled with approximately 500 ml of distilled water. After cooling to room temperature and drying, the amount of stripping was determined by a visual rating and expressed in terms of the percent of asphalt retained (Scale 0 to 100 percent retained).*

Other Tests

Other tests used on asphalt mixtures which were conducted according to standard test methods of the Texas State Department of Highways and Public Transportation (Ref 3) and ASTM (Ref 7) included:

- –Asphalt extraction, Tex-210-F, to determine percent asphalt binder.
- –Asphalt recovery by the Abson process, Tex-211-F, to recover extracted asphalt.
- –Asphalt penetration and viscosity, Tex-502-C and Tex-528-C, of the extracted asphalt.
- –Sieve analysis, Tex-200-F, of the aggregate recovered from the asphalt extraction.
- –Theoretical maximum specific gravity, ASTM D2041, of the asphalt-coated aggregate.
- –Bulk specific gravity of compacted specimens, Tex-206-F.
- –Compacting test specimens of asphaltic mixtures, Tex-206-F and a modification of Tex-206-F.

The moisture content of the coated and uncoated aggregate was obtained by drying to constant weight at 250°F.

ENGINEERING PROPERTIES ANALYZED

The testing program was designed to measure the controlled variables to monitor to the extent possible other variables which could not be controlled, and to analyze the dependent properties of these mixtures. The properties analyzed were Hveem stability, indirect tensile strength, resilient modulus of elasticity, static modulus of elasticity, tensile strength ratio, and boiling test values.

Hveem Stability

The equation used to calculate the Hveem stability is:

$$S = 22.2 / (P_hD_2 / P_vP_h) + 0.222 \qquad \text{(Eq 2.1)}$$

where

S = Hveem stability, %, adjusted for height of the specimen,
P_v = vertical pressure, psi,
P_h = horizontal pressure, psi, and
D_2 = displacement of specimen, tenths of an inch.

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*Procedure is a modification of the procedure currently specified by SDHPT, Test Method Tex-530-C.

Tensile Strength

Tensile strength is the maximum tensile stress which the specimen can withstand. The indirect tensile strength for the 4-inch-diameter specimens was calculated using the following relationship:

$$S_T = 0.156P / t \qquad \text{(Eq 2.2)}$$

where

S_T = tensile strength, psi,
P = the maximum load carried by the specimen, lb, and
t = thickness or height of the specimen, in.

Tensile Strength Ratio

The tensile strength ratio was used to evaluate the moisture susceptibility of the experimental asphalt mixtures. The tensile strength ratio, TSR, is defined as follows:

$$TSR = S_T\text{wet} / S_T\text{dry} \qquad \text{(Eq 2.3)}$$

where

$S_T$wet = tensile strength of the wet-conditioned specimen, psi, and
$S_T$dry = tensile strength of the dry-conditioned specimen, psi.

Resilient Modulus of Elasticity

The resilient modulus of elasticity was calculated using the resilient, or instantaneously recoverable, horizontal and vertical deformation after 300 applied load cycles. Resilient modulus was calculated using the following relationship:

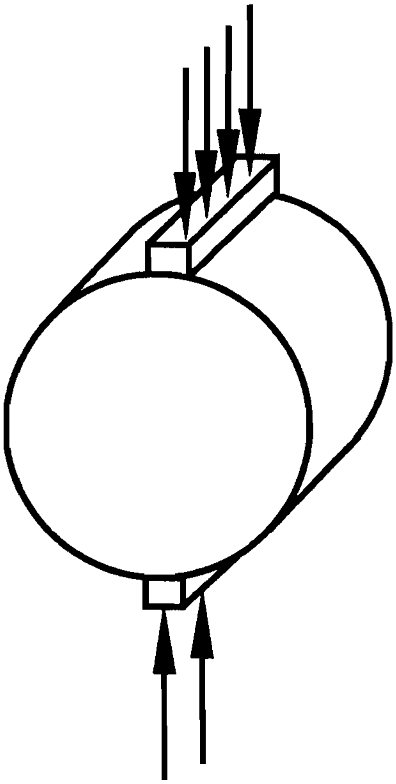
$$E_R = P_R / tH_R (0.27 + Nu_r) \qquad \text{(Eq 2.4)}$$

where

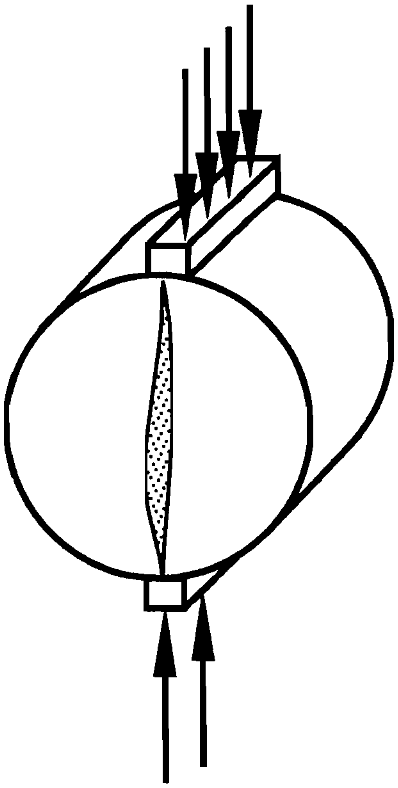
E_R = resilient modulus of elasticity, psi,
P_R = the applied repeated load, lb (Fig 5),
t = specimen thickness,
H_R = horizontal resilient deformation, and
Nu_r = resilient Poisson's ratio, assumed to be 0.35.

Static Modulus of Elasticity

The static modulus of elasticity was calculated using the horizontal deformations over the linear portion of the load-deformation relationships (Fig 6) and the following relationship (Eq 2.5):



(a) Compressive load being applied.



(b) Specimen failing in tension.

Fig 4. Indirect tensile test loading and failure.

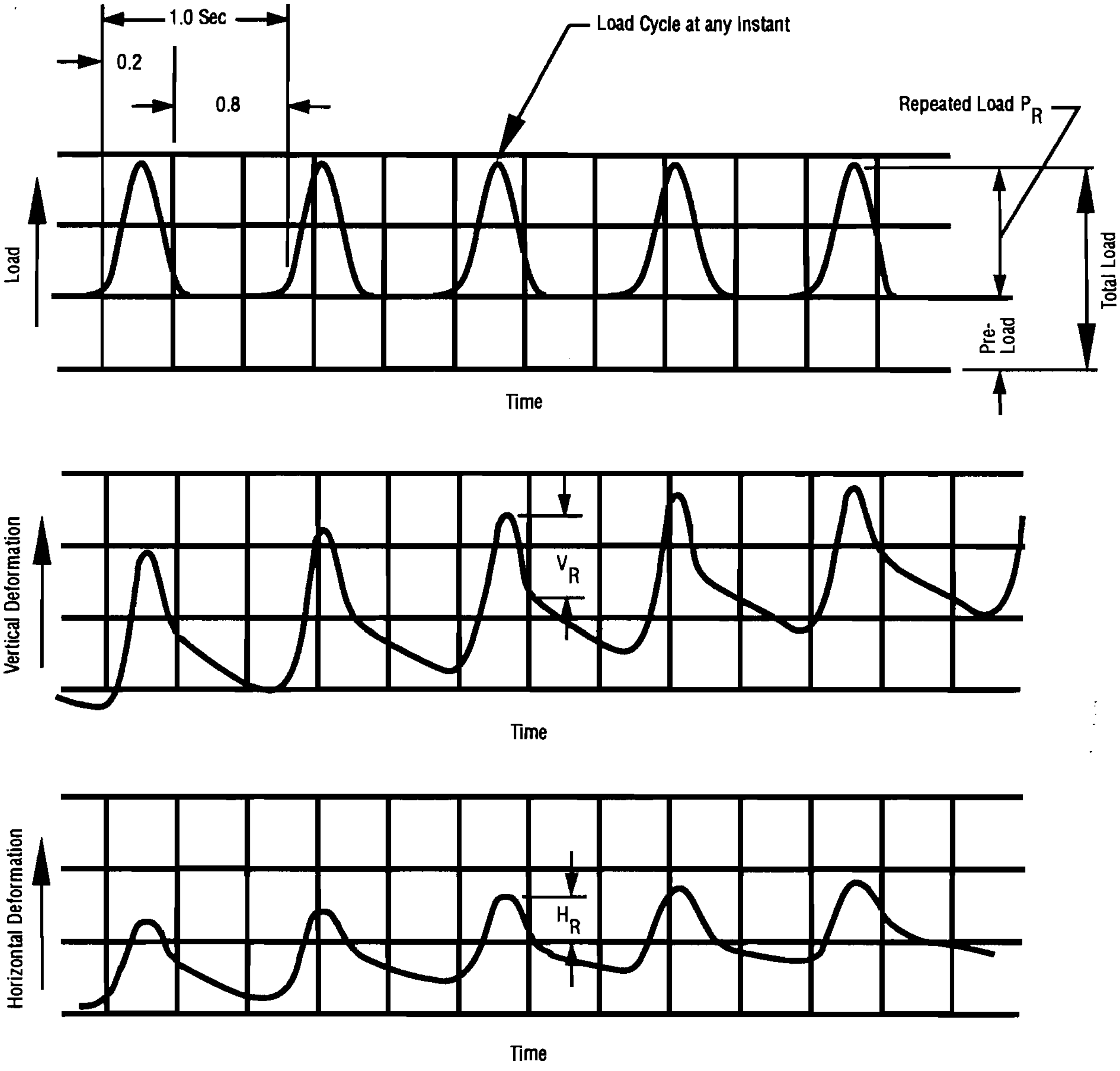
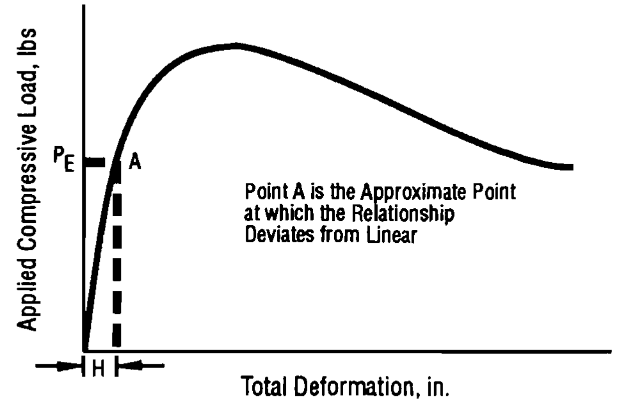


Fig 5. Typical load pulse and deformation-time relationships for the repeated-load indirect tensile test.

$$E_S = (P_E / tH)\ (0.27 + Nu_r) \qquad \text{(Eq 2.5)}$$

where

E_S = static modulus of elasticity, psi,
P_E = the applied load (Fig 6), lb,
t = specimen thickness, in.,
H_S = elastic horizontal deformation, in., and
Nu_r = static Poisson's ratio, assumed to be 0.35.



Point A is the Approximate Point at which the Relationship Deviates from Linear

Fig 6. Generalized characterization of load-deformation data.

CHAPTER 3. EXPERIMENTAL RESULTS

This portion of the overall study was conducted as a continuation of the previous studies involving three aggregates, the findings from which were reported in Research Report 358-1 (Ref 2). Since the primary objective of these studies was to determine the effects of mixing temperature and stockpile moisture content on the engineering properties of asphalt mixtures, only the mixing temperature and stockpile moisture condition were varied in the experiment design. However, other variables which could not be controlled did vary. Statistical analyses of variance with covariants were used to examine the effects of controlled and uncontrolled variables on engineering properties of asphalt mixtures. The results of these analyses indicated a great deal of variation, inconsistent results between projects, and probably a significant effect produced by the uncontrolled variables.

UNCONTROLLED VARIABLES

The uncontrolled variables were those factors which cannot be measured or controlled to an exact value but vary due to either inherent qualities of the material or acceptable variations in the production process.

Stockpile Moisture Content

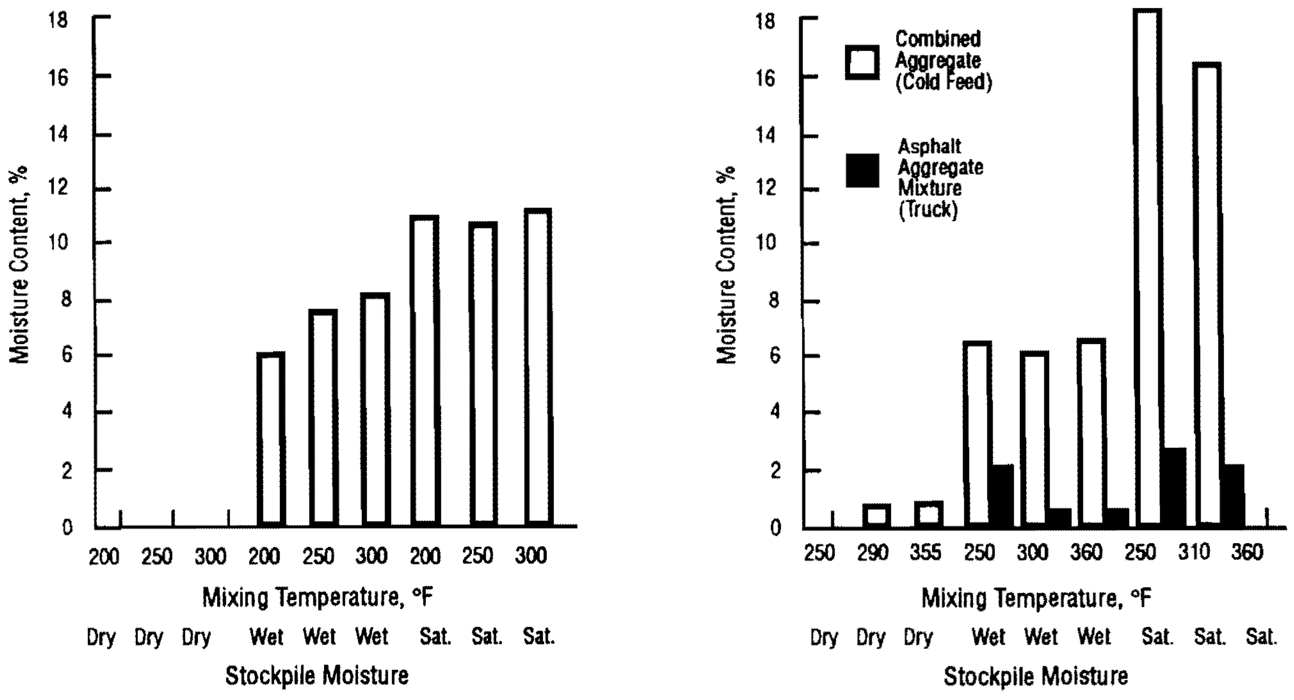
Although the stockpile moisture contents were controlled qualitatively as dry, wet, and saturated, the actual moisture contents were dependent on the type of aggregate, the atmospheric conditions, the time required to construct the test sections, and the techniques used to introduce the moisture.

The indicated stockpile moisture content of each experimental mixture (Fig 7) is the moisture content of the combined aggregates entering the drum mixer. Tables A9 and B9 in the Appendices contain the moisture content data for the limestone aggregate (D) and lightweight aggregate (E), respectively.

Within each aggregate type the moisture contents for the three stockpile moisture conditions were relatively uniform. The lightweight aggregates tended to have a higher stockpile moisture content due to the higher porosity of the aggregate.

Moisture in the Asphalt Mixture

The moisture content of the asphalt mixtures varied significantly for the two aggregates. For mixtures containing the limestone aggregate (D) the moisture content of the final mixture was essentially zero regardless of the mixing temperature and stockpile moisture content, while the lightweight aggregate mixtures (E) had significantly higher moisture content because of the higher aggregate porosity and possibly the void structure.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 7. Moisture cocntents of experimental runs.

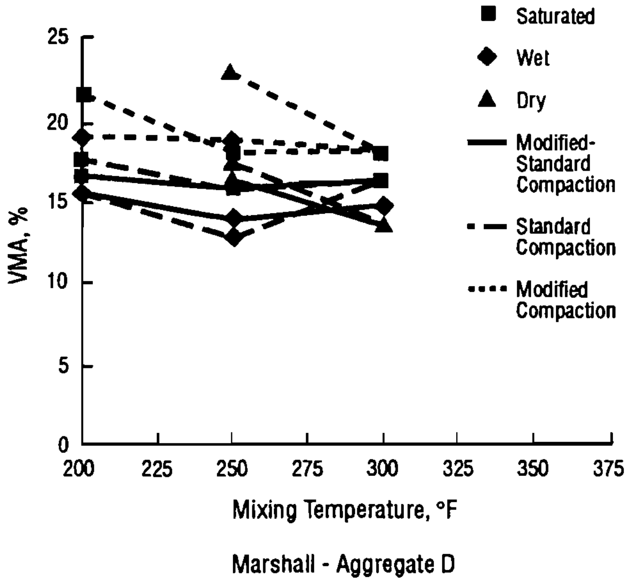


Fig 8. Relationship between mixing temperature and void in mineral aggregate, limestone.

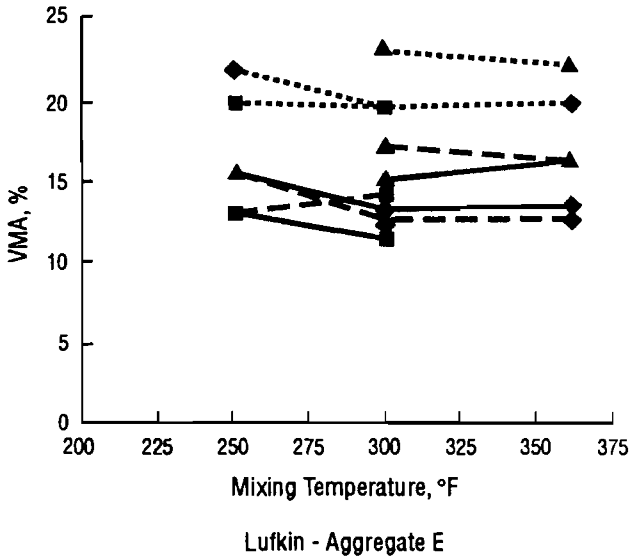


Fig 9. Relationship between mixing temperature and void in mineral aggregate, lightweight.

Density

Density was measured in terms of voids in the mineral aggregate and air voids.

Voids in Mineral Aggregates. Density was evaluated in terms of voids in mineral aggregates (VMA) since the aggregate-specific gravities and asphalt contents were different for each aggregate. The method used to calculate the VMA was as follows:

$$\text{VMA} = 100 - \text{GmbPs} / \text{Gsb}$$

where

Gmb = bulk gravity of compacted mixture,
Ps = percent aggregate by total wt. mix, and.
Gsb = bulk gravity of aggregates

The relationships between average VMA and mixing temperature for the various stockpile moisture contents and compaction procedures are shown in Figs 8 and 9. These relationships suggest that VMA may have decreased slightly with increased mixing temperature; however, the differences are of no practical significance. In addition, it can be concluded that the densities of the specimens are essentially equal as measured by VMA. Variations in VMA were also relatively insignificant for each compaction procedure; therefore, the variations noted in the density probably did not have a significant effect on the various engineering properties.

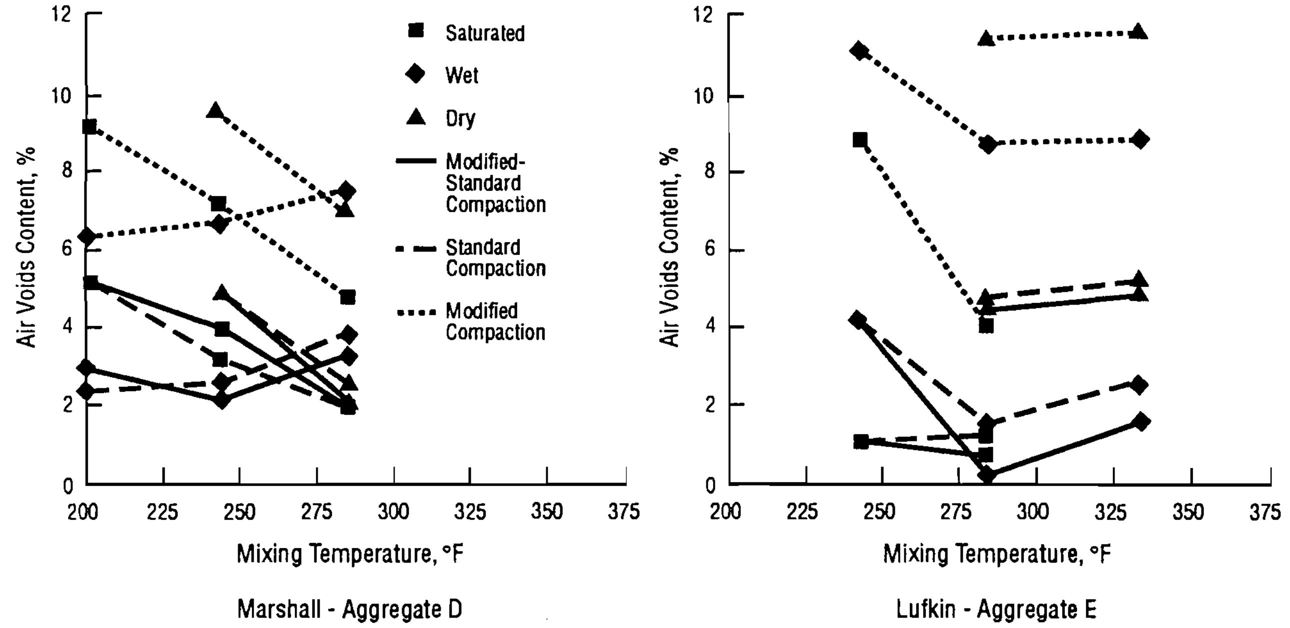
Air Voids. Air voids for each specimen were calculated using the bulk specific gravity of the specimen and the theoretical specific gravity of the asphalt-aggregate mixture as determined by the test method for Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures (Rice Method), ASTM D2041 (Ref 7).

The relationships between mixing temperature and air voids are shown in Fig 10. A general or systematic relationship between mixing temperature and air voids is not evident, although there is a general tendency for air voids to decrease as the mixing temperature increased.

Asphalt Content

An attempt was made to maintain the asphalt content at the specified design value for all experimental runs. The stockpile moisture contents were measured in order to calculate the weight of dry aggregate which is the basis of the asphalt content. The differences between the asphalt content and the design value are illustrated in Fig 11. As shown, there were significant deviations from the design value for the limestone aggregate (D), whereas for the lightweight aggregate (E) the results appear to be much closer.

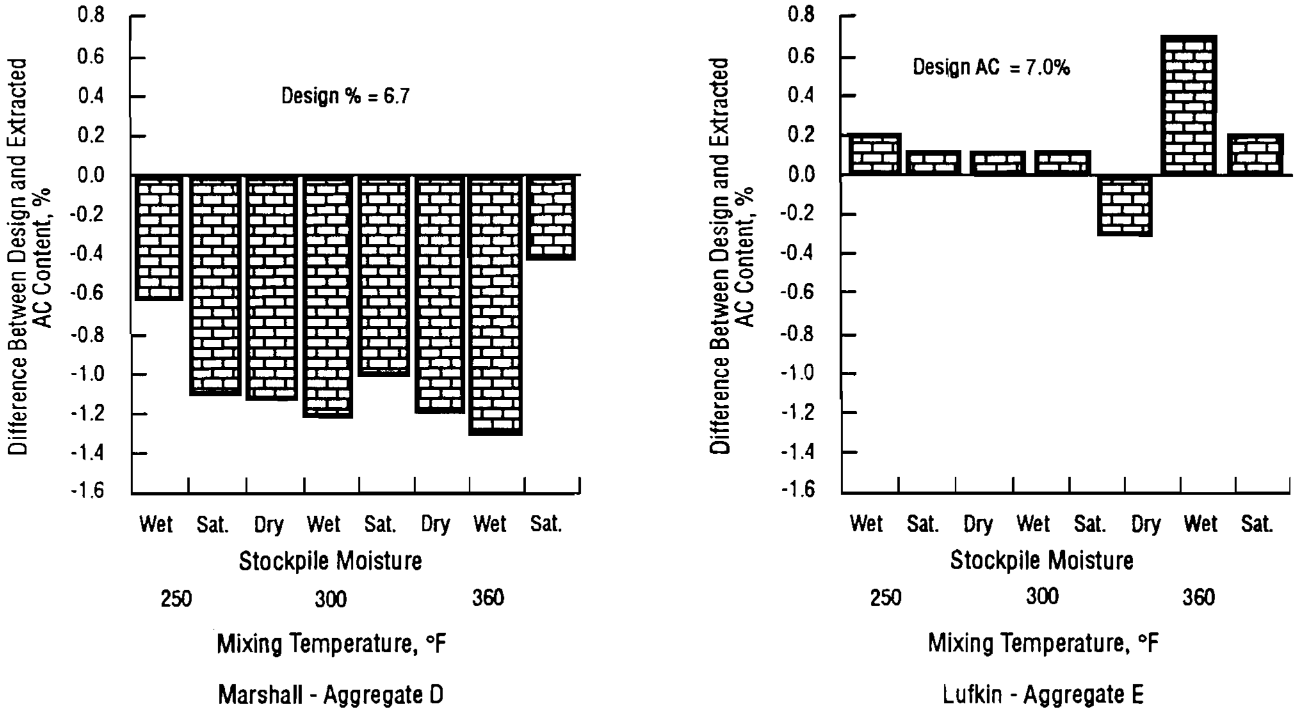
The daily plant testing conducted by Texas SDHPT on the non-experimental mixtures indicated that the asphalt contents varied ±0.1 percent (Ref 2) from the design value. Thus, it is felt that the plant was accurately supplying the proper amount of asphalt. The variation probably is due to fluctuations of moisture content of the aggregate on the cold feed charger conveyor. Another cause is possible transition effects in the plant silo. Experimental mixtures were produced within 10 minutes after changing the mixing temperature. A comparison was made between the design asphalt contents and extracted asphalt contents for experimental studies conducted at normal plant operations temperature for wet (existing) stockpile aggregates (Table 4).



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 10. Relationship between mixing temperature and air void content.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 11. Asphalt content variations in experimental runs.

$\overline{D} = -0.12\%$

$n = 5$

$S = 0.554\%$

where

n = number of observations,
$\overline{D}$ = mean of differences between design and extracted asphalt content, and
S = standard deviation of the differences between design and extracted asphalt content.

Hypotheses

H_0 (null hypothesis): $\mu = 0$
(for the entire population the mean of differences will be equal to zero)
H_A (alternate hypothesis): $\mu \neq 0$
(for the entire population the mean of differences will not be equal to zero)

$t + \overline{D} - 0 = 0.484$ with 4 degrees of freedom

where

$$t = (\overline{D} - 0) / S/\sqrt{n} = -0.484$$

At the 95 percent confidence level the null hypothesis is not rejected. Thus variations in asphalt content are assumed to be due to unstable plant conditions in the transition period.

As a result of this analysis, additional time was allowed for plant operations to stabilize before mixture samples were obtained for the lightweight aggregate (E) study. A comparison of asphalt contents for the light mixtures showed less variability. Throughout the following analyses of experimental results, asphalt content was treated as a constant.

TABLE 4. DESIGN AND EXTRACTED ASPHALT CONTENTS FOR NORMAL PLANT OPERATIONS

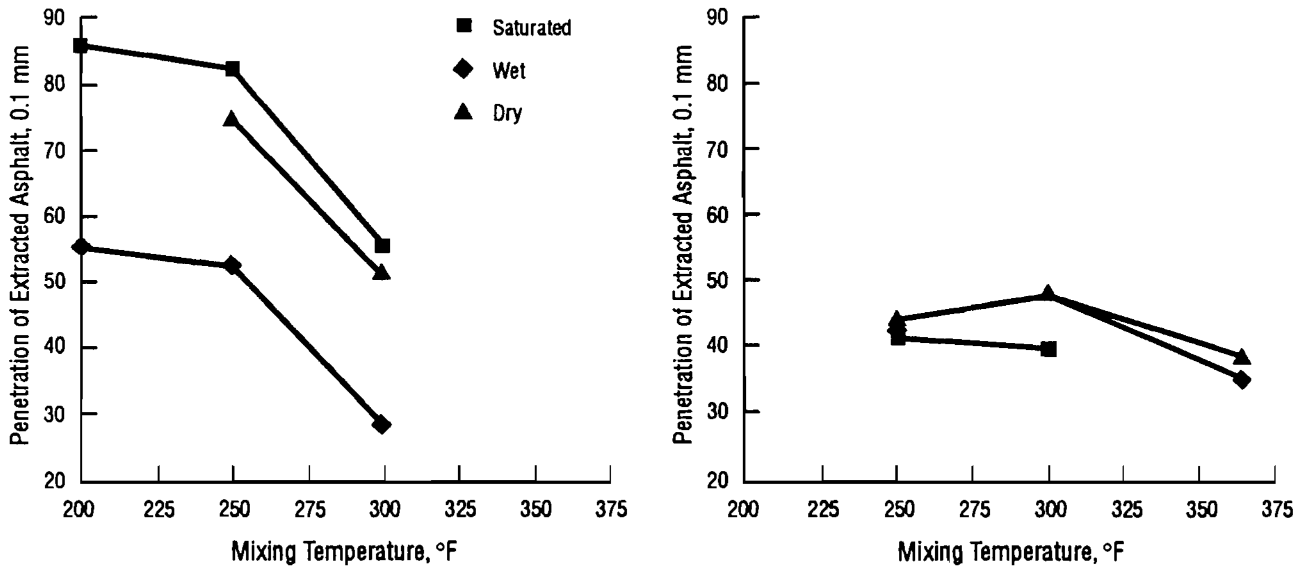
Aggregate	Normal Operations Temp, °F	Extracted Asphalt Content, %	Design Asphalt Content, %	Extracted A.C. –Design A.C., % (D)
A (Batch)*	300	4.5	5.5	-1.0
A (Drum)*	275	5.3	5.5	-0.2
B (Batch)*	300	5.9	5.9	0
C (Drum)*	275	6.2	6.1	0.1
D (Drum)	275	5.5	6.0	0.5

*Data from Reference 2

Extracted Asphalt Penetration

Oxidative hardening of the asphalt cement was evaluated in terms of the penetration of the extracted asphalt. The asphalt cement in both aggregate-asphalt mixtures decreased in penetration (hardened more) when the mixing temperature was increased (Fig 12). The same trend had been observed for the previously studied aggregates (Ref 2).

The degree of hardening of the asphalt cement appeared to decrease and then increase as the stockpile moisture content increased for the limestone (D) mixtures. In the case of the lightweight aggregate (E) mixtures there was no effect (Fig 12). Thus there was no consistent trend for the two mixtures.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 12. Effects of mixing temperature on asphalt hardening.

CONTROLLED VARIABLES

Controlled variables in the experiment were mixing temperature, general classification of stockpile moisture, and compaction procedures.

Effects of Mixing Temperature

The effects of mixing temperature on Hveem stability, tensile strength, resilient modulus of elasticity, static modulus of elasticity, tensile strength ratio, and asphalt retained in the boiling test are shown in Figs 13 through 18 for the limestone and lightweight aggregates. Test results for the limestone (D) and lightweight (E) are summarized in Tables 5 through 10.

Hveem Stability. Figure 13 illustrated the effects of mixing temperature on Hveem stability. As shown, Hveem stability generally was not influenced by mixing temperature; however, the compaction procedure did have an effect on Hveem stability. Modified-standard and standard compaction procedures generally produced mixtures or samples exhibiting essentially equal Hveem stabilities. This result indicates that for a given compactive procedure, compaction temperature did not have a significant effect on Hveem stability. This is possibly due to the fact that the procedure does not impart a constant compactive effort.

Tensile Strength. Effects of mixing temperature on tensile strength are shown in Fig 14. For the limestone aggregate (D), there was no significant change in tensile strength with a change in mixing temperature. For the lightweight aggregate (E), however, tensile strength tended to increase slightly as the mixing temperature increased; however, the changes would have little if any practical significance. Density appeared to be a primary factor affecting tensile strength. The tensile strengths for each compaction procedure generally were within distinctive bands.

Resilient Modulus of Elasticity. The effects of mixing temperature on the resilient modulus of elasticity are shown in Fig 15. For both aggregates the resilient modulus varied with mixing temperature; however, these variations were not consistent or systematic. Thus, based on these two projects, it would be concluded that mixing temperature had no effect on resilient modulus, but it is recognized that uncontrolled variables may have masked the effect.

Static Modulus of Elasticity. Figure 16 shows the effects of mixing temperature on the static modulus of elasticity for both aggregate-asphalt mixtures. As shown, an increase in mixing temperature caused an increase in the static modulus of elasticity for both aggregates in the dry and wet conditions. In the saturated state, however, there was no consistent relationship.

The compaction procedure did not seem to have an effect on the static modulus of elasticity since the modified-standard and the standard compaction specimens had comparable static moduli of elasticity.

Tensile Strength Ratio. The effects of mixing temperature on the tensile-strength ratio are shown in Fig 17. The tensile-strength ratio, used as a measure of moisture resistance, increased with an increase in mixing temperature. This is essentially the same as the effect observed in the previous study (Ref 2).

Asphalt Retained After Boiling Test. The relationship between mixing temperature and asphalt retained after boiling test is shown in Fig 18. Increased mixing temperature generally caused an increase in the amount of asphalt retained for both aggregate-asphalt mixtures. Thus both the TSR values and boiling test results indicate improved moisture and stripping resistance with increased mixing temperatures.

Effects of Stockpile Moisture Condition

The effects of stockpile moisture condition on Hveem stability, tensile strength, resilient modulus of elasticity, static modulus of elasticity, tensile strength ratio, and asphalt retained after boiling test are illustrated in Figs 19 through 24.

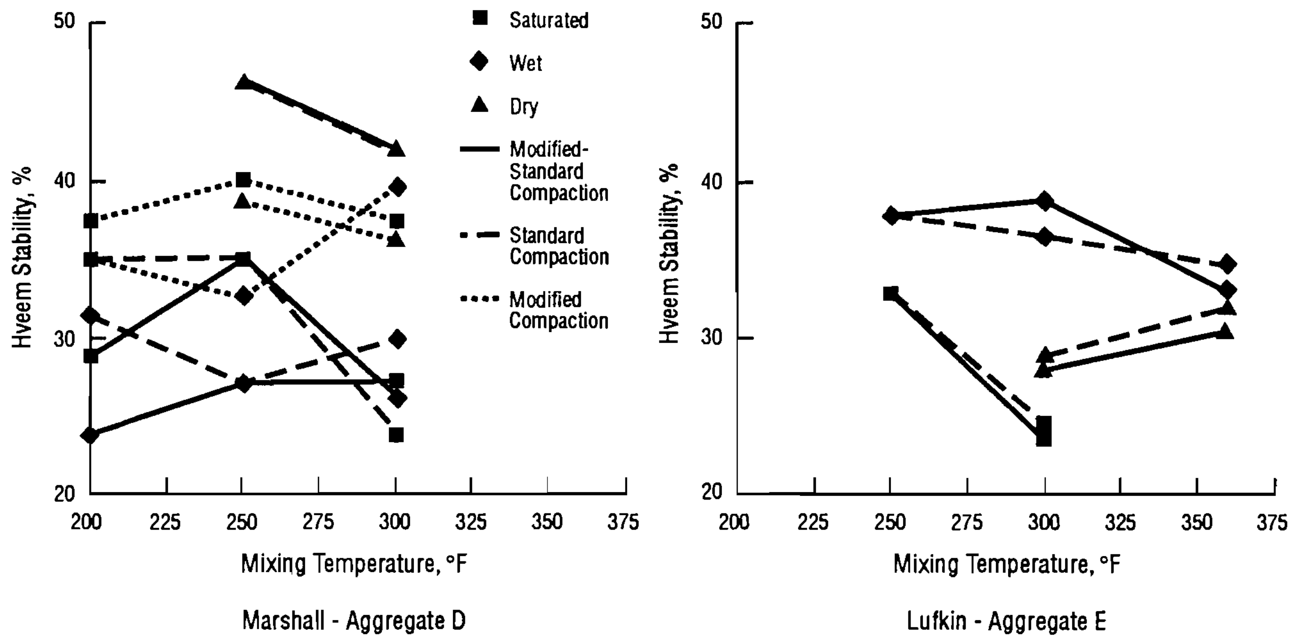
Hveem Stability. The effects of stockpile moisture content on Hveem stability are shown in Fig 19. As shown in this figure, the Hveem stability of the limestone mixtures when compacted by both the standard and modified-standard procedures decreased and then increased as the stockpile moisture condition increased. For the lightweight aggregate stabilities increased and then decreased. Thus while there was a pronounced effect, the effect was project- or aggregate-dependent.

Tensile Strength. Figure 20 shows the effects of stockpile moisture condition on tensile strength. Tensile strength increased significantly as the stockpile moisture content increased for the lightweight aggregate (E) mixture; however, there was little if any effect for the limestone aggregate (D) mixture.

Compaction procedure appeared to be the more important factor affecting the tensile strength for both aggregates, since the tensile strength for each compaction procedure fell within distinctive bands.

Resilient Modulus of Elasticity. Effects of stockpile moisture on the resilient modulus of the asphalt-aggregate mixtures are shown in Fig 21. For both aggregates, the resilient modulus of elasticity increased as the stockpile moisture condition increased from dry to saturated; however, the increase was relatively small for the lightweight aggregate (E) mixtures.

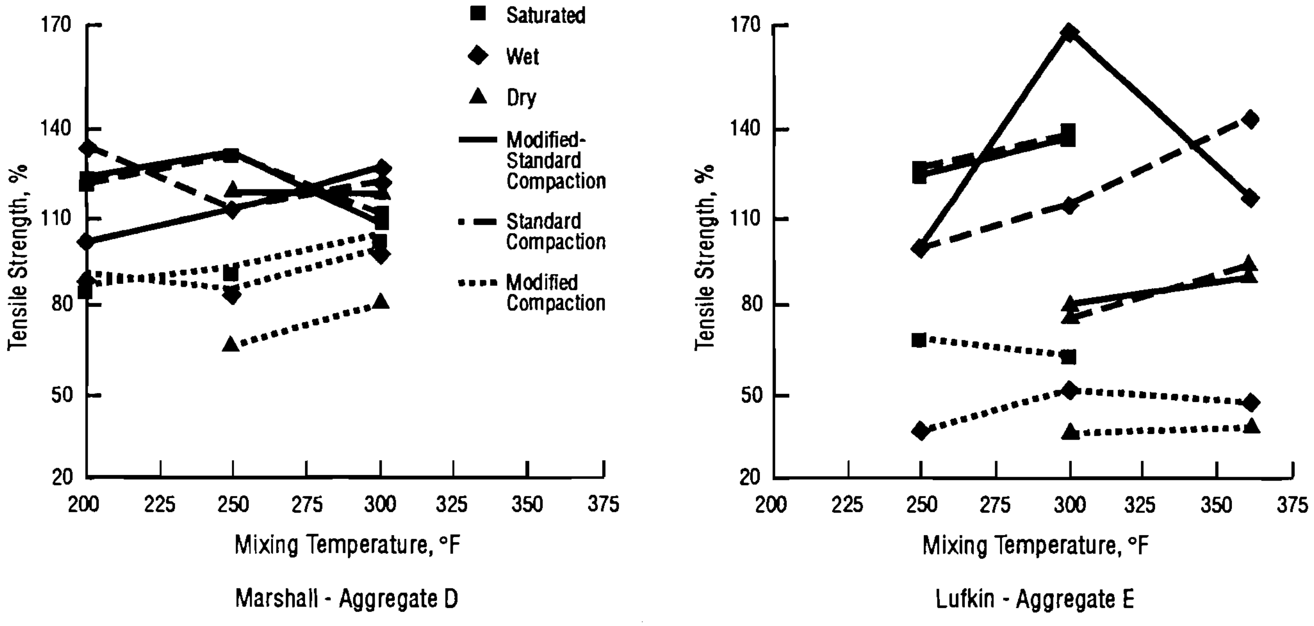
Static Modulus of Elasticity. Figure 22 shows the effects of stockpile moisture condition on the static modulus of elasticity for both aggregate-asphalt mixtures. The static modulus of elasticity tended to increase and then decrease with increased stockpile moisture content. However, a complete range of moisture contents was not available.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 13. Relationship between Hveem stability and mixing temperature.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 14. Relationship between mixing temperature and tensile strength.

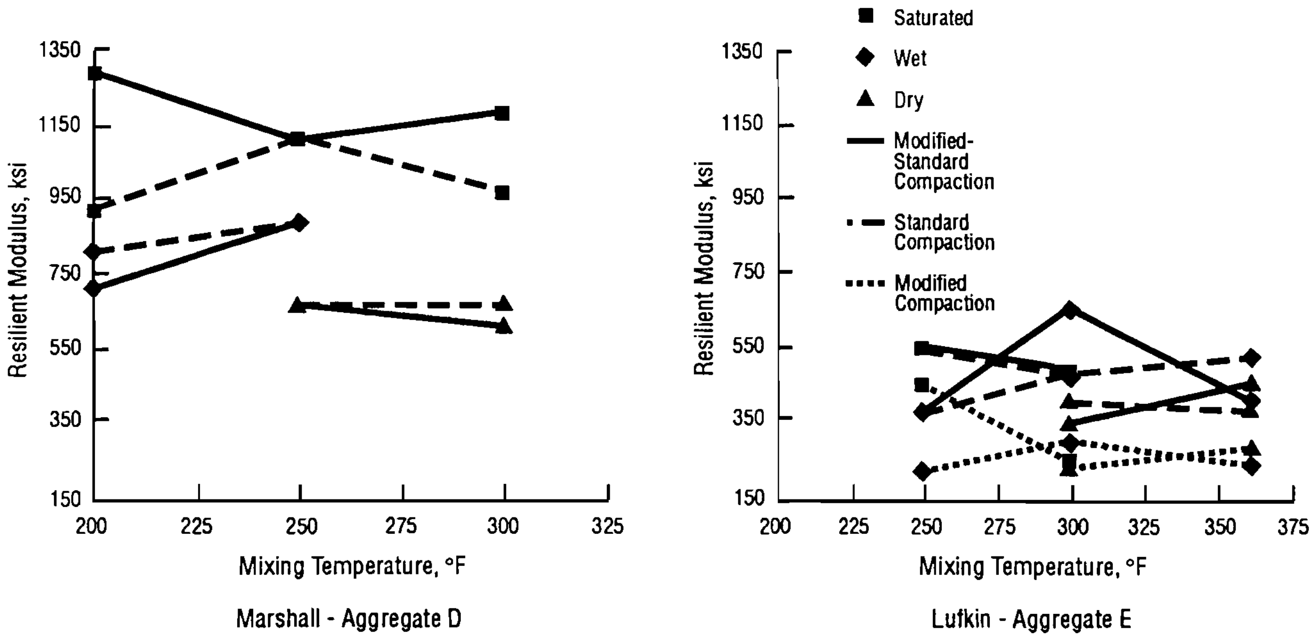


Fig 15. Relationship between mixing temperature and resilient modulus of elasticity.

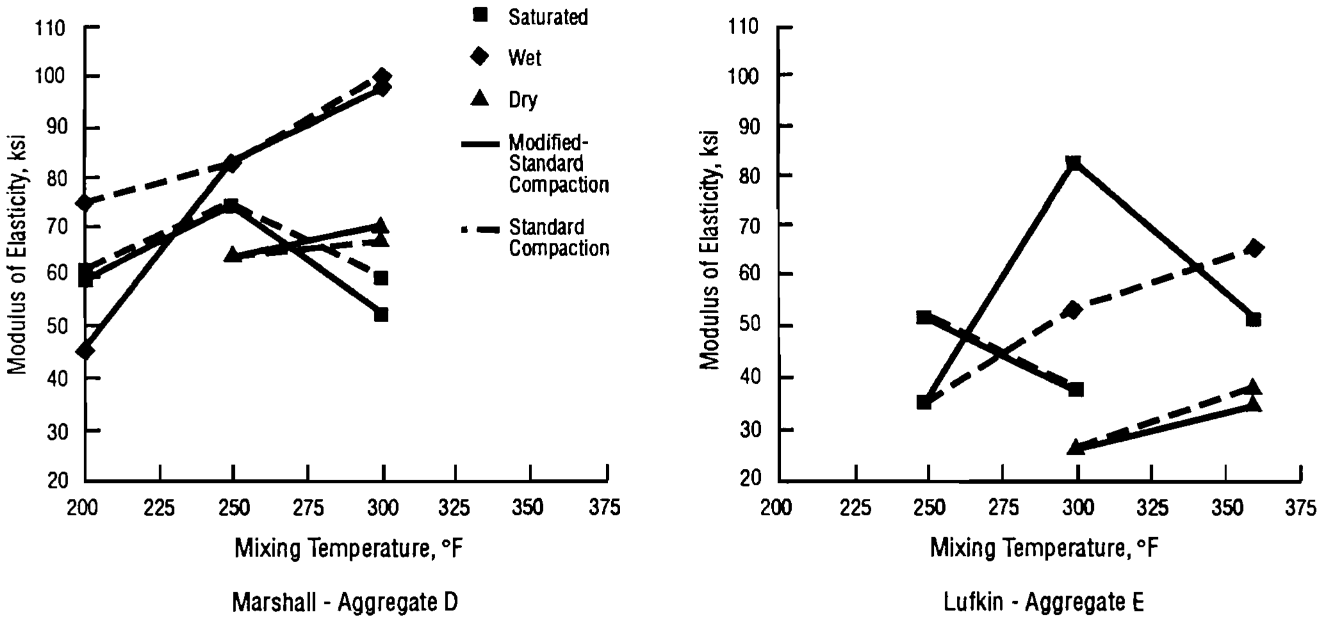
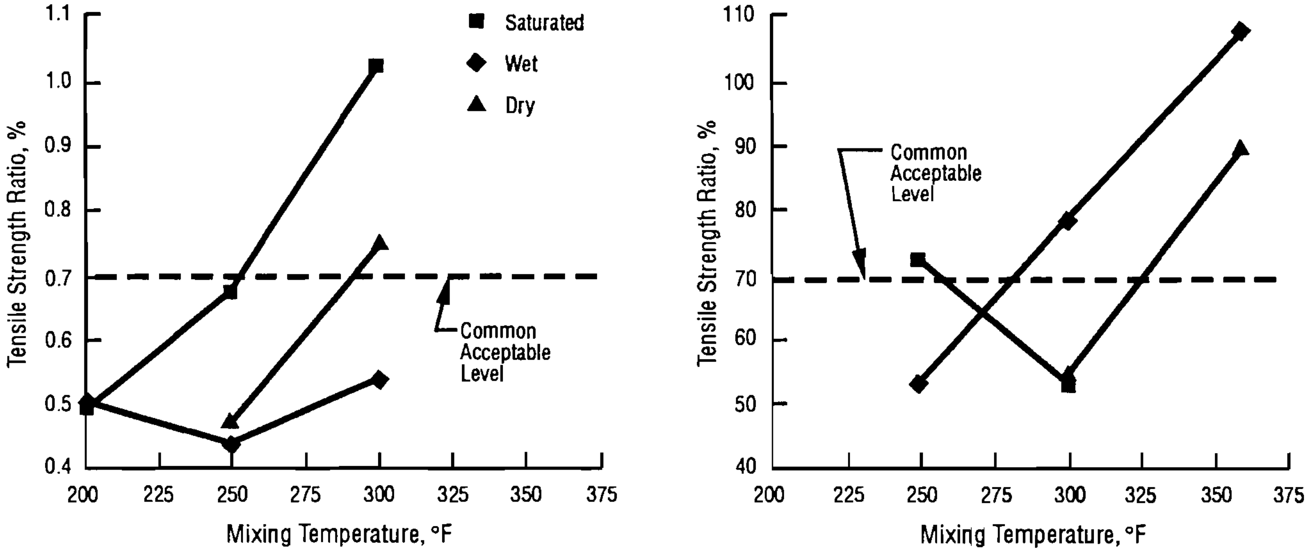


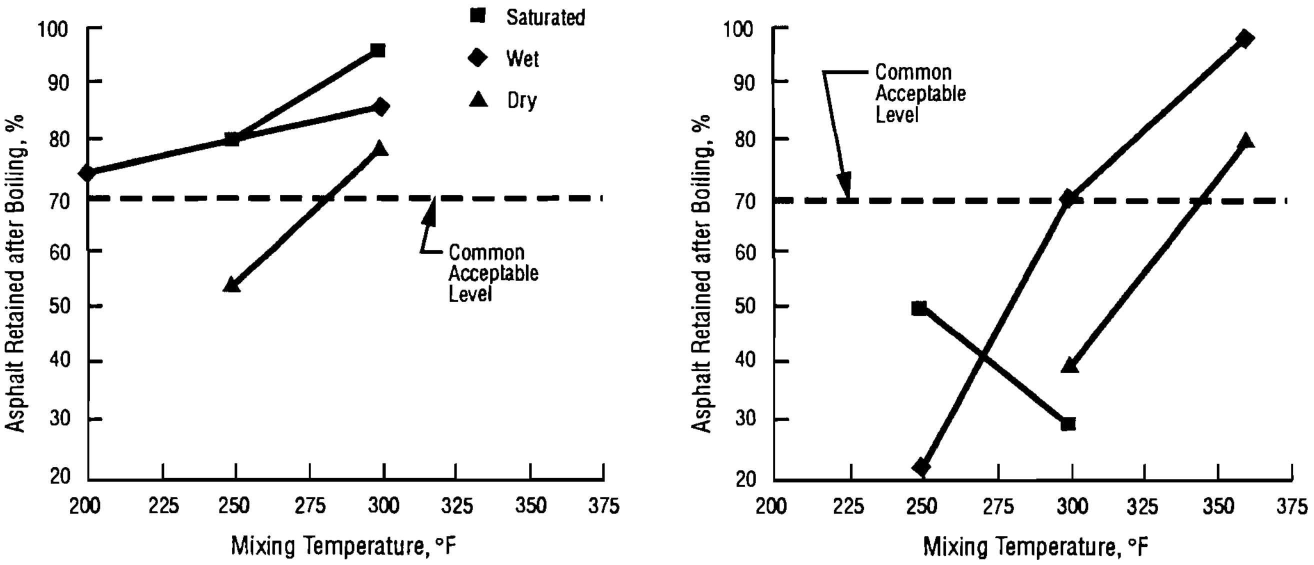
Fig 16. Relationship between mixing temperature and static modulus of elasticity.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 17. Relationship between mixing temperature and tensile strength ratio.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 18. Relationship between mixing temperature and asphalt retained after boiling test.

TABLE 5. SUMMARY OF HVEEM STABILITIES

	Nominal Mix Temp, °F	Hveem Stability, %								
		Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
					Stockpile Condition					
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Marshall – District 19										
Drum Plant										
(Aggregate D)	200	-	31	34	-	23	29	-	37	37
	250	46	28	34	46	28	34	39	32	40
	300	42	30	23	44	28	27	36	39	37
Lufkin – District 11										
Drum Plant										
(Aggregate E)	250	-	38	32	-	38	32			
	300	29	37	24	30	39	25			
	360	32	35	-	33	34	-			

Aggregate D – 55% limestone, 20% limestone screening, 25% field sand

TABLE 6A. SUMMARY OF TENSILE STRENGTHS, AGGREGATE D

	Nominal Mix Temp, °F	Indirect Tensile Strength, psi								
		Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
					Stockpile Condition					
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Marshall – District 19										
Drum Plant										
(Aggregate D)	200	-	136	126	-	101	127	-	90	89
		-	(106)	(112)	-	(91)	(112)	-	(45)	(45)
	250	117	112	133	117	112	133	72	85	92
		(71)	(102)	(113)	(71)	(102)	(113)	(33)	(36)	(64)
	300	118	119	111	117	122	107	79	96	99
		(116)	(107)	(124)	(120)	(108)	(120)	(59)	(51)	(100)

Numbers in parentheses are for specimen subjected to freeze-thaw.

TABLE 6B. SUMMARY OF TENSILE STRENGTHS, AGGREGATE E

	Nominal Mix Temp, °F	Indirect Tensile Strength, psi								
		Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
					Stockpile Condition					
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Lufkin – District 11										
Drum Plant										
(Aggregate E)	250	-	103	122	-	101	127	-	90	89
		-	-	-	-	(91)	(112)	-	(45)	(45)
	300	77	116	140	117	112	133	72	85	92
		(71)	(102)	(113)	(71)	(102)	(113)	(33)	(36)	(64)
	360	100	143	-	117	122	107	79	96	99
		(116)	(107)	(124)	(120)	(108)	(120)	(59)	(51)	(100)

Numbers in parentheses are for specimen subjected to freeze-thaw.

TABLE 7. SUMMARY OF RESILIENT MODULUS OF ELASTICITY

	Nominal Mix Temp, °F	Resilient Modulus of Elasticity, ksi								
		Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
		Stockpile Condition								
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Marshall – District 19										
Drum Plant										
(Aggregate D)	200	-	810	930	-	730	1300	-	-	-
	250	690	900	1100	690	900	1100	-	-	-
	300	690	-	9800	640	-	1200	-	-	-
Lufkin – District 11										
Drum Plant										
(Aggregate E)	250	-	371	563	-	730	1300	-	-	-
	300	405	463	476	690	900	1100	-	-	-
	360	397	525	-	640	-	1200	-	-	-

TABLE 8. SUMMARY OF MODULUS OF ELASTICITY

	Nominal Mix Temp, °F	Modulus of Elasticity, ksi								
		Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
		Stockpile Condition								
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Marshall – District 19										
Drum Plant										
(Aggregate D)	200	-	75	60	-	45	58	-	44	40
	250	68	84	75	68	84	75	43	36	44
	300	69	100	59	71	99	53	38	42	51
Lufkin – District 11										
Drum Plant										
(Aggregate E)	250	-	36	52	-	36	52	-	-	-
	300	26	53	38	26	83	38	-	-	-
	360	39	66	-	37	52	-	-	-	-

TABLE 9. SUMMARY OF MODULUS OF TENSILE STRENGTH RATIO

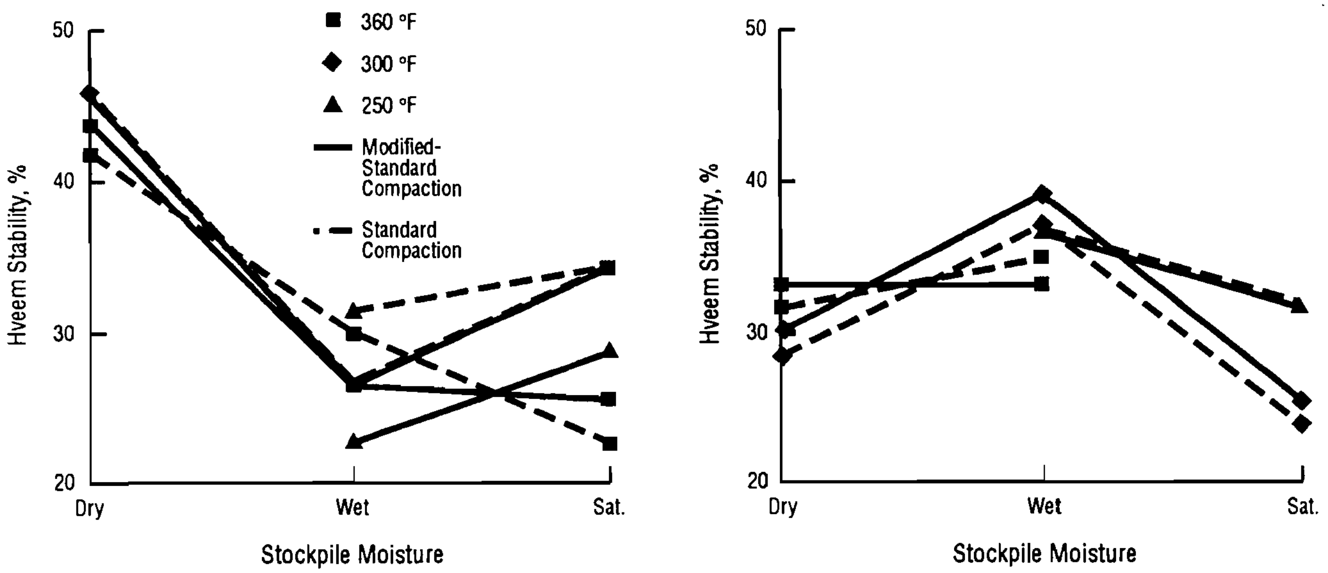
	Nominal Mix Temp, °F	Compaction, Standard			Compaction, Modified-Standard			Compaction, Modified		
		Stockpile Condition								
		Dry	Wet	Sat.	Dry	Wet	Sat.	Dry	Wet	Sat.
Marshall – District 19										
Drum Plant										
(Aggregate D)	200	-	.78	.89	-	.90	1.13	-	.51	.51
	250	.61	.91	.85	.61	.91	.85	.46	.42	.69
	300	.98	.90	1.13	1.03	.89	.88	.75	.53	1.02
Lufkin – District 11										
Drum Plant										
(Aggregate E)	250	-	-	-	-	-	-	.53	1.05	-
	300	-	-	-	-	-	-	.54	.79	.54
	360	-	-	-	-	-	-	.91	1.06	-

TABLE 10. SUMMARY OF MODULUS OF BOILING TEST RESULTS

	Nominal Mix Temp, °F	Retained Asphalt, %		
		Stockpile Condition		
		Dry	Wet	Sat.
Marshall – District 19				
Drum Plant				
(Aggregate D)	200	-	75	75
	250	55	80	80
	300	80	85	95
Lufkin – District 11				
Drum Plant				
(Aggregate E)	250	-	20	50
	300	40	70	30
	360	80	97	-

Tensile Strength Ratio. The effects of stockpile moisture condition on tensile strength ratio are shown in Fig 23. Tensile strength ratio generally tended to increase as the stockpile moisture condition increased from dry to saturated; however, the results were erratic. This is similar to previous results (Ref 2) and is difficult to explain.

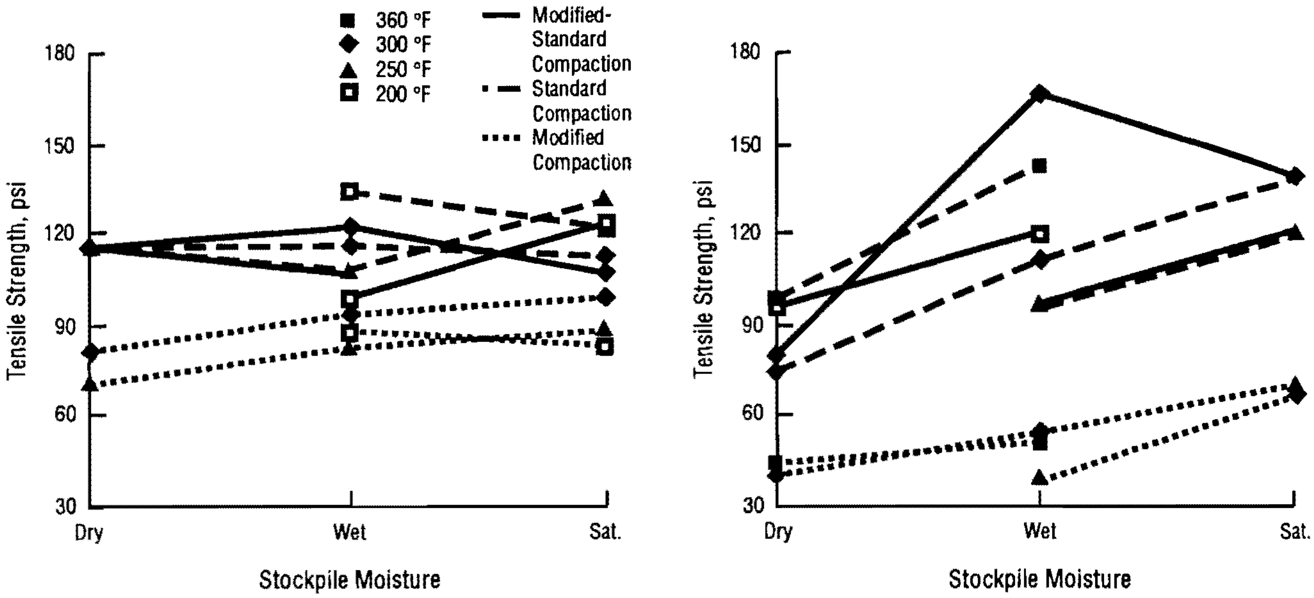
Asphalt Retained After Boiling. Effects of stockpile moisture condition on percent asphalt retained after boiling test are shown in Fig 24. The amount of asphalt retained tended to increase as the stockpile condition changed from dry to saturated. Again, these results are difficult to explain and may be due to confounding with uncontrolled variation.



Marshall - Aggregate D

Lufkin - Aggregate E

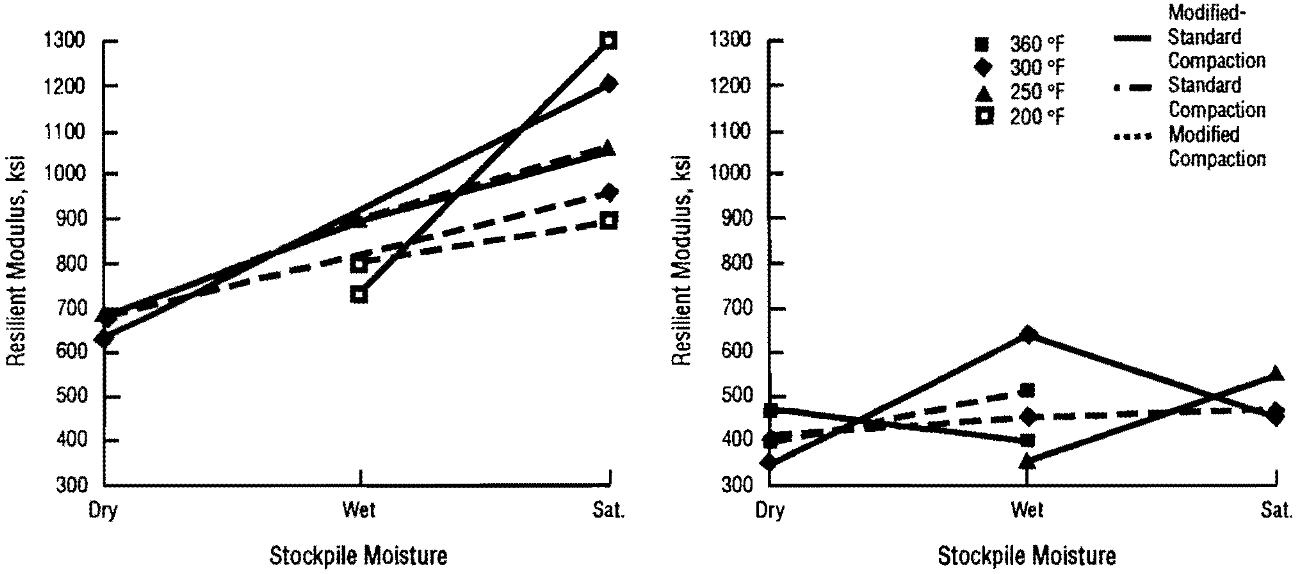
Fig 19. Relationship between stockpile moisture and Hveem stability.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 20. Relationship between stockpile moisture and tensile strength.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 21. Relationship between stockpile moisture condition and resilient modulus.

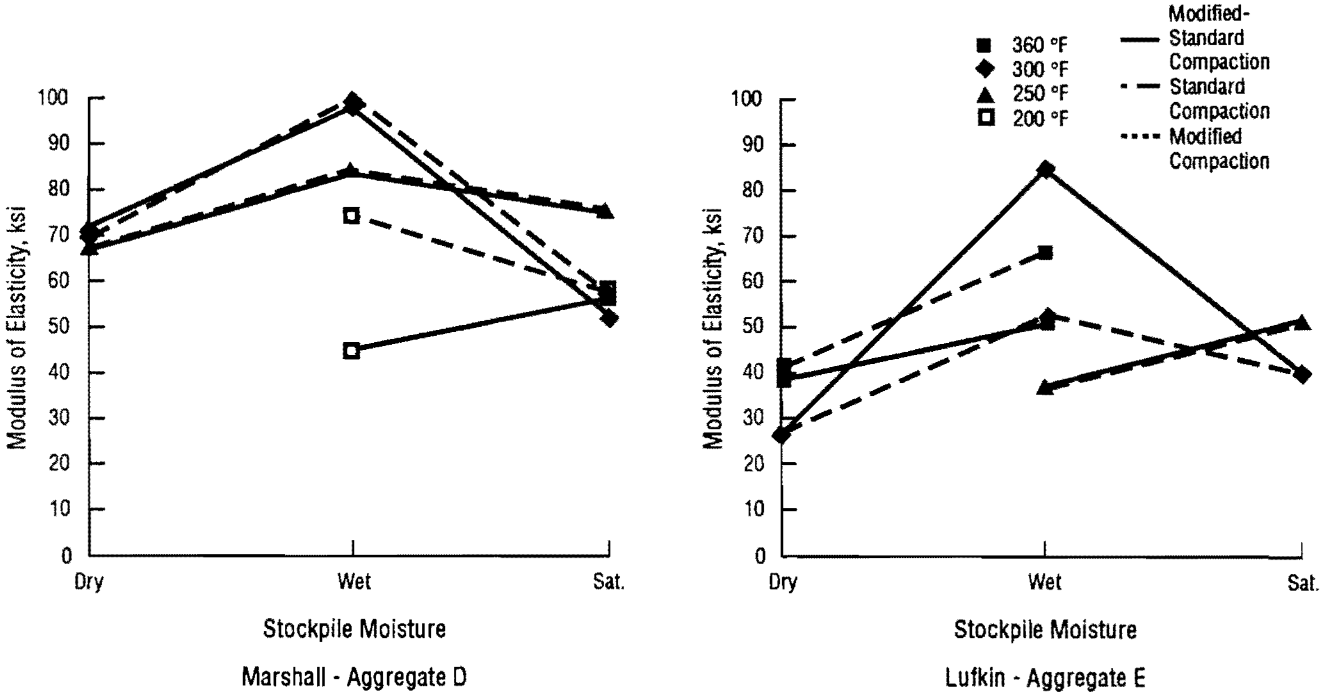


Fig 22. Relationship between stockpile moisture condition and static modulus elasticity.

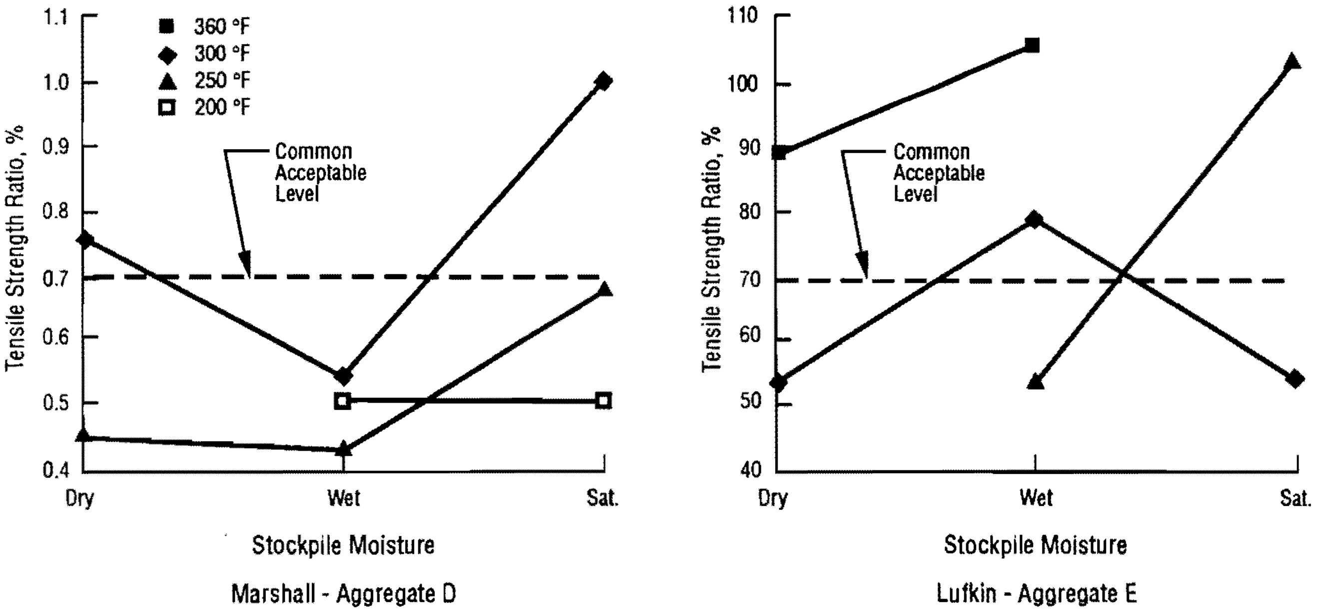
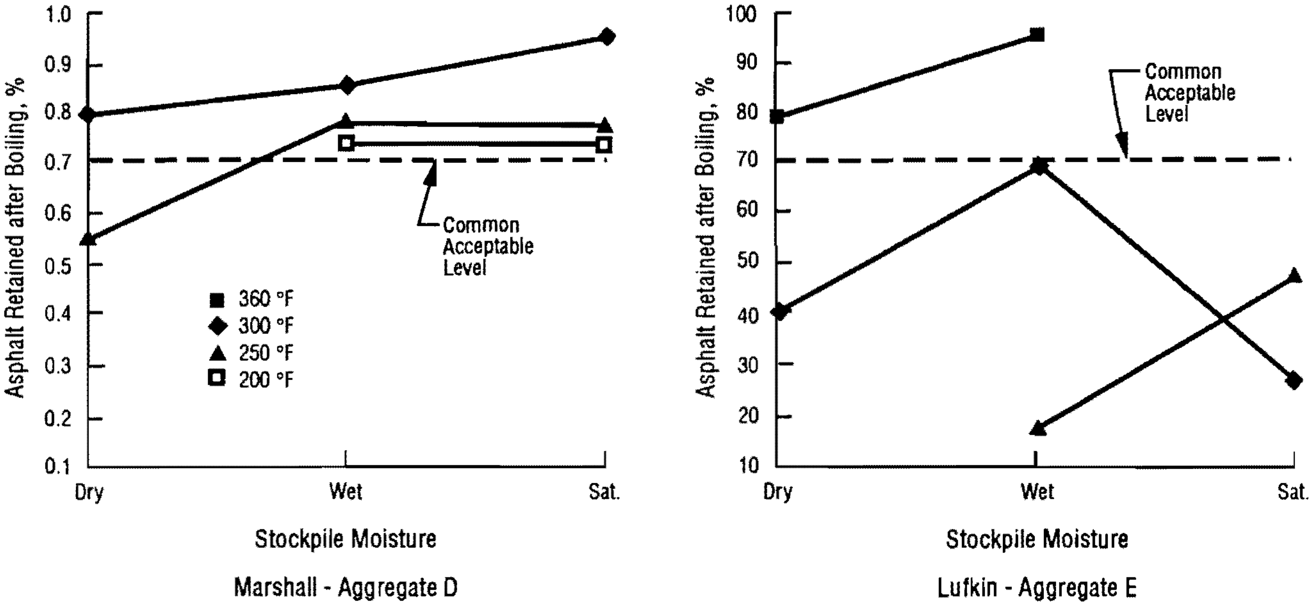


Fig 23. Relationship between stockpile moisture condition and tensile strength ratio.



Marshall - Aggregate D

Lufkin - Aggregate E

Fig 24. Relationship between stockpile moisture condition and asphalt retained after boiling test.

CHAPTER 4. CONCLUSIONS

The primary objective of this research project was to study the effects of mixing temperature and stockpile moisture condition on the engineering properties of asphalt mixtures. Findings of this research project are summarized in this chapter and pertain only to the mixtures studied and the conditions of the projects. Generally, it is felt that the uncontrolled variables probably masked or caused many of the observed effects.

GENERAL CONCLUSIONS

1. Variations in some of the uncontrolled variables in this study were significant and probably could have produced a significant effect on the engineering properties of the two mixtures.
2. Compaction was found to be the major factor affecting the measured engineering property.

SPECIFIC CONCLUSIONS

Effects of Mixing Temperature

1. Mixing temperature had no effect on Hveem stabilities of the two asphalt-aggregate mixtures evaluated.
2. Tensile strength possibly increased slightly as mixing temperature increased; however, this increase in tensile strength would have little, if any, practical significance.
3. Mixing temperatures had little, if any, effect on the resilient modulus of elasticity.
4. The static modulus of elasticity had a tendency to increase with increased mixing temperature; however, the results were very erratic.
5. Resistance to moisture damage measured by tensile strength ratio and asphalt retained after boiling test increased significantly as mixing temperature increased.
6. Asphalt hardening (as indicated by penetration) significantly increased for the limestone mixtures. For the lightweight aggregate mixtures the effect was minimal as the mixing temperature increased.

Effects of Stockpile Moisture Condition

1. Stockpile moisture content appeared to have had a pronounced effect on Hveem stability; however, the effect was project-dependent. Hveem stability generally tended to decrease and then increase as the stockpile moisture content increased for the limestone-aggregate mixtures, while for the lightweight mixtures stability decreased and then increased.
2. The effects of the stockpile moisture condition on the tensile strength of the mixture were dependent on the aggregate type. The tensile strength of the limestone-aggregate (D) mixtures was generally unaffected by stockpile moisture condition, while increased stockpile moisture content produced an increase in tensile strength for the lightweight aggregate (E) mixtures.
3. The resilient modulus of elasticity increased significantly for the limestone aggregate (D) as the stockpile moisture content increased. The lightweight aggregate (E) was generally unaffected by stockpile moisture conditions.
4. The static modulus of elasticity tended to increase and then decrease as the stockpile moisture condition increased; however, there was not a complete range of moisture contents.
5. The resistance to moisture damage, indicated by the tensile strength ratio and the asphalt retained after the boiling test, increased as the stockpile moisture condition changed from dry to saturated.
6. Asphalt hardening was found to decrease as the stockpile moisture content changed from dry to saturated.

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APPENDIX A. AGGREGATE D—LIMESTONE AGGREGATE USING A DRUM MIX ASPHALT PLANT

The limestone asphalt mixture (Aggregate D) was produced by Madden Contracting Company. The plant, located 15 miles east of Marshall, Texas (Figs A1 and A2), consisted of a mobile drum mixer, stockpiles of aggregates, asphalt tanks, and other related equipment. The aggregates were trucked to the plant site and loaded into the cold feed bins with a rubber-tired loader. The sources of the aggregates are listed in Table A1.

Asphalt Mix Design

Each of the aggregate gradations and the combined mix gradation are shown in Table A2. Prior to the start of the experiment, a field change increased the design asphalt content from 6.1% to 6.7%. Table A3 contains theoretical specific gravities for each aggregate and the theoretical specific gravity of the mixture when combined with various percentages of asphalt. Listed in Table A4 are the relative

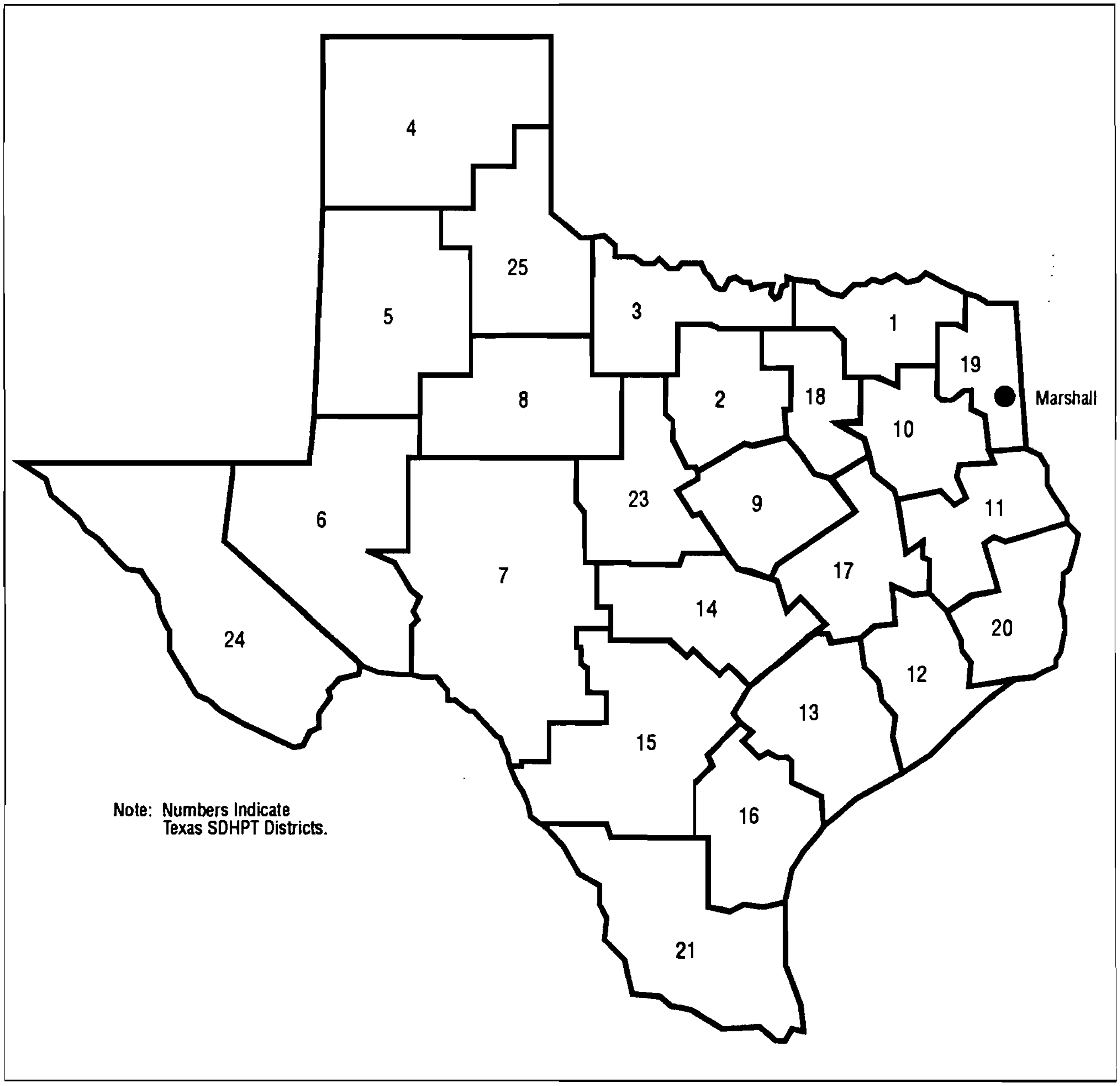

Fig A1. Location of limestone experiment.

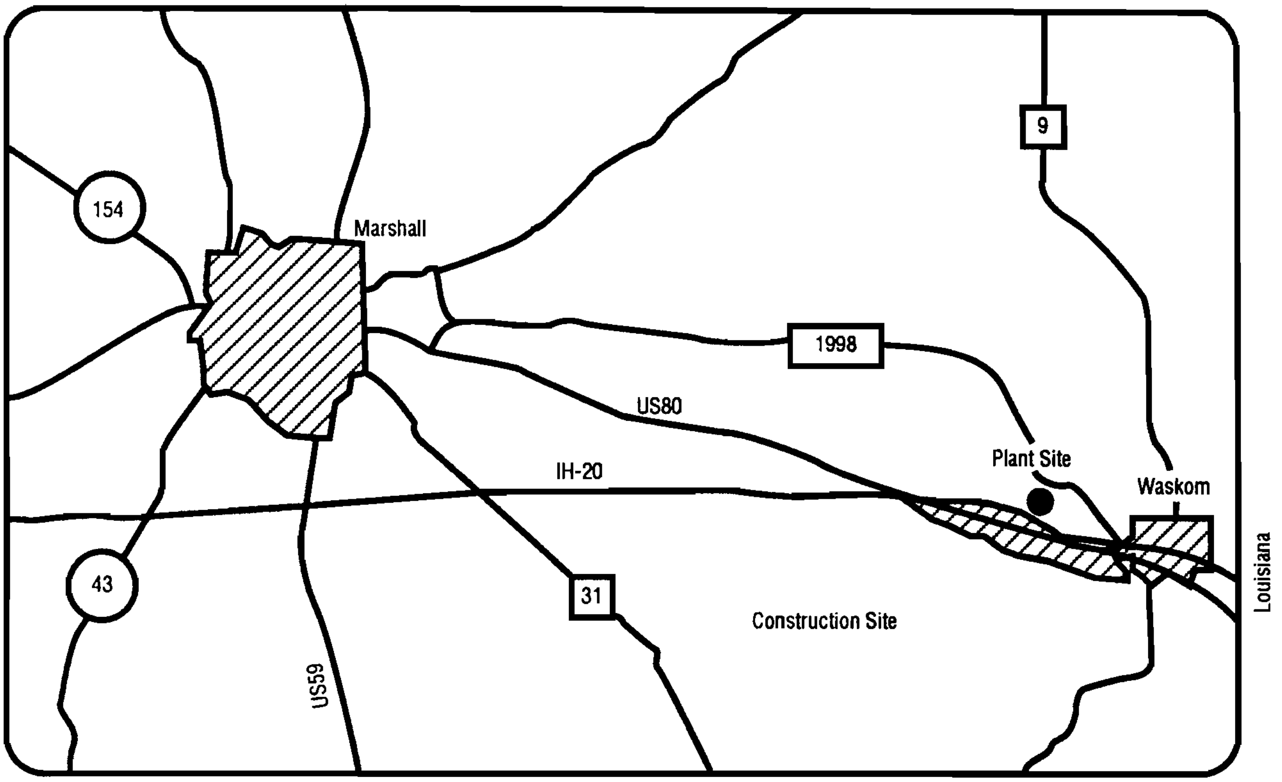

Fig A2. Vicinity of experimental sections and plant site.

TABLE A1. LIMESTONE AGGREGATE (D) MATERIAL

Material	Material Source
Limestone	Texas Crushed Stone Georgetown, Texas
Limestone Screening	Texas Crushed Stone Georgetown, Texas
Field Sand	Vaughn Materials Marshall, Texas
AC 20 Asphalt Cement	Dorchester Asphalt Mt. Pleasant, Texas

TABLE A2. LIMESTONE AGGREGATE (D) DESIGN GRADATION

Sieve Size	Aggregate Type, %			
	Limestone	Limestone Screenings	Field Sand	Aggregate Mixture*
1/2" - 3/8"	0.0	0.0	0.0	0.0
3/8" - #4	51.0	0.3	0.0	28.2
#4 - #10	46.3	15.2	0.0	28.5
+ #10	97.3	15.5	0.0	56.7
#10 - #40	1.6	44.9	1.3	10.1
#40 - #80	0.2	14.2	66.2	19.5
#80 - #200	0.3	12.2	26.9	9.3
+ #200	0.6	13.3	5.6	4.4

* Combined aggregates composed of 55% limestone, 20% limestone screenings, and 25% field sand

TABLE A3. LIMESTONE AGGREGATE (D) DESIGN THEORETICAL SPECIFIC GRAVITIES

Aggregate	Specific Gravity*
Limestone	2.362
Limestone Screenings	2.525
Field Sand	2.642
Aggregate Mixture	2.459
Aggregate Mixture with 5.0% Asphalt	2.300
Aggregate Mixture with 6.0% Asphalt	2.271
Aggregate Mixture with 7.0% Asphalt	2.242
Aggregate Mixture with 8.0% Asphalt	2.214
Aggregate Mixture with 9.0% Asphalt	2.187

* The specific gravities of the aggregates are measured bulk specific gravities and the specific gravities of the mixtures are calculated.

TABLE A4. LIMESTONE AGGREGATE (D) DESIGN RELATIVE DENSITIES AND HVEEM STABILITIES

Asphalt Content, %	Relative Density,* %	Hveem Stability, %
5.0	95.5	58
6.0	98.5	59
7.0	101.5	54
8.0	102.8	30

*Percent theoretical specific gravity of the asphalt mixture densities and Hveem stabilities from which the design asphalt content was determined (Fig A3).

Compaction Effort Study

A laboratory study was conducted to determine the compactive effort required to produce specimens with 7 percent air voids at each of the experiment temperatures. These procedures were later used in the field to produce modified compaction specimens.

Oven-dried samples of the individual aggregates were sieved to individual sizes, then recombined to form the gradation in Table A2. Asphalt was added to produce the design mix. By trial and error, the compactive effort which would produce 7 percent air voids in the specimen was determined.

Field Sample Preparation and Testing

The experimental runs were usually done in the midmorning after the first group of trucks had departed. The following method was used.

(1) The asphalt mixture storage silo was emptied.

(2) The asphalt plant was restarted and the burner control set for the desired temperature. The production rate of the plant was not altered except for the experimental runs in which the high stockpile moisture content required a slowing of the production rate to achieve the desired temperature.

(3) The material was discharged into a truck and the temperature was measured. Corrections were made until the desired temperature was obtained.

(4) A sample of approximately 200 pounds of the mixture was placed in a covered metal container and taken to a field laboratory on site.

(5) Additional samples of the mixture and the aggregate were obtained for moisture determination. The individual aggregates were sampled from the belt feeders on the bottom of the cold feed bins. Combined aggregates were sampled from the gathering conveyor and the moisture content was determined on the job site.

(6) In the field laboratory modified compaction specimens were made with material taken directly from the bulk sample. The temperature change of the material in the container prior to compaction was approximately 10°F.

(7) The mixture for the standard compacted specimens was weighed into pans and placed in a small electric oven to produce a mix temperature of 250°F. Control on this oven was ±10°F.

(8) After all specimens were compacted, a 30-pound sample was retained for an asphalt extraction, theoretical specific gravity determination, and other miscellaneous tests and transported to The University of Texas Asphalt Laboratories for testing.

Test Results

The results of all tests performed during this experiment are tabulated in Tables A5 to A9. The values listed are for the individual test specimens. Tensile strength, static and resilient modulus of elasticity, and Hveem stability are listed in Table A5 for the standard compaction specimens and in Table A6 for the modified compaction specimens. Table A7 lists the moisture damage susceptibility parameters and Table A8 contains aggregate gradation and extracted asphalt data. These gradations are plotted in Fig A4. Moisture contents of the asphalt mixtures and cold feed aggregates are listed in Table A9.

The experimental mixtures were placed and compacted as part of the highway contract using routine construction procedures.

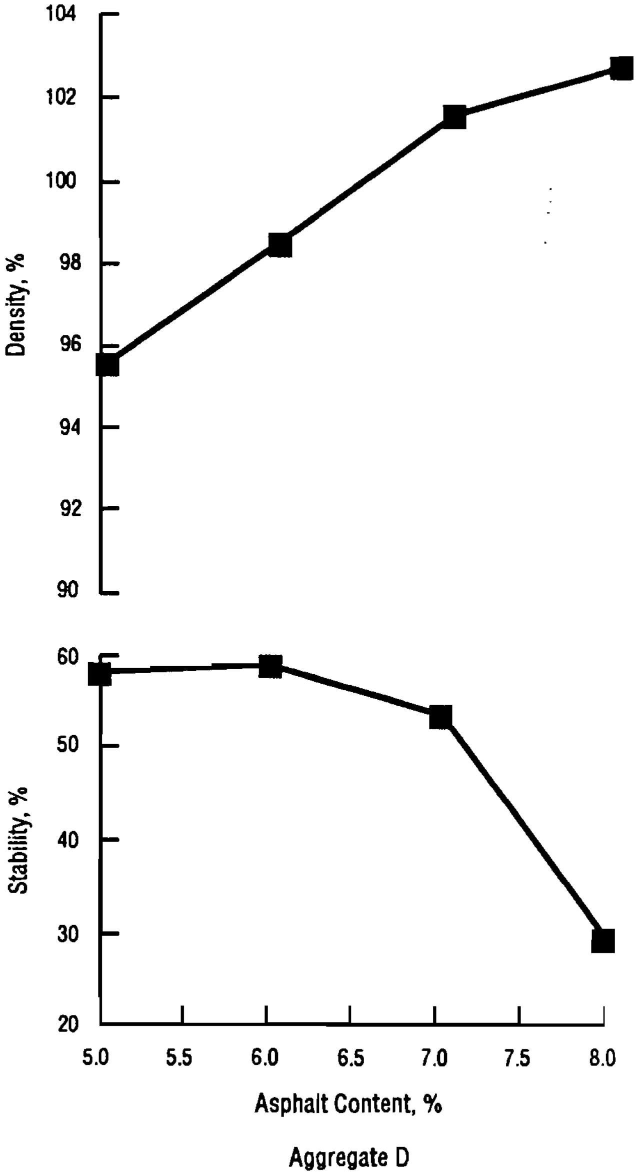

Fig A3. Density-stability design curves.

TABLE A5. LIMESTONE AGGREGATE (D) RESULTS OF INDIVIDUAL STANDARD COMPACTION SPECIMEN TESTS

		Dry Conditioning				Freeze-Thaw Conditioning
Stockpile Moisture	**Mixing Temp, °F**	**Tensile Strength, psi**	**Static Modulus, ksi**	**Resilient Modulus, ksi**	**Hveem Stability, %**	**Tensile Strength, psi**
Dry	200	-	-	-	-	-
	250	115	62	790	46	68
		120	75	580	45	74
	300	114	70	800	42	113
		123	68	580	42	120
Wet	200	124	67	930	26	107
		148	83	690	36	105
	250	107	77	860	28	99
		116	92	940	27	105
	300	117	93	-	34	101
		120	107	-	25	113
Saturated	200	127	58	909	37	112
		126	63	943	31	113
	250	136	77	1082	36	120
		129	73	1180	31	107
	300	108	63	1100	23	122
		113	55	850	22	127

TABLE A6. LIMESTONE AGGREGATE (D) RESULTS OF INDIVIDUAL MODIFIED COMPACTION

		Modified-Standard Specimens*					Modified Specimens**			
		Dry Conditioning				Freeze-Thaw Conditioning	Dry Conditioning			Freeze-Thaw Conditioning
Stockpile Moisture	Mixing Temp, °F	Tensile Strength, psi	Static Modulus, ksi	Resilient Modulus, ksi	Hveem Stability, %	Tensile Strength, psi	Tensile Strength, psi	Static Modulus, ksi	Hveem Stability, %	Tensile Strength, psi
Dry	200	-	-	-	-	-	-	-	-	-
	250	115	62	790	46	68	74	48	40	34
		120	75	580	45	74	71	39	38	33
	300	115	71	570	44	125	79	38	37	60
		119	72	700	43	114	78	39	35	58
Wet	200	100	59	770	23	89	92	42	38	39
		101	58	680	23	93	88	38	36	52
	250	107	77	860	28	99	89	45	30	36
		116	73	940	27	105	81	43	35	36
	300	120	55	-	25	110	98	56	38	53
		123	52	-	32	106	95	46	40	50
Saturated	200	126	47	1158	31	108	88	47	37	41
		129	44	1485	27	116	89	42	37	49
	250	136	77	1082	36	120	94	35	40	57
		129	92	1180	31	107	90	37	40	70
	300	106	94	1100	28	124	98	41	38	107
		107	105	1200	25	117	99	44	35	94

* Compacted to standard compaction procedure endpoint at mixing temperature

** Compacted to 7% air voids at mixing temperature

TABLE A7. LIMESTONE AGGREGATE (D) MOISTURE SUSCEPTIBILITY PARAMETERS

Stockpile Moisture	Mixing Temp, °F	Standard Compaction Tensile Strength Ratio*	Modified Standard Compaction Tensile Strength Ratio*	Modified Compaction Tensile Strength Ratio*	Boiling Test Retained Asphalt %
Dry	200	-	-	-	-
	250	61	60	46	55
	300	98	103	75	80
Wet	200	78	90	51	75
	250	91	91	42	80
	300	90	89	53	85
Saturated	200	89	113	51	75
	250	85	85	69	80
	300	113	88	102	95

*Tensile strength ratio computed from the average tensile strength of the freeze-thaw conditioned specimens divided by the average tensile strength of the dry conditioned specimens

TABLE A8. LIMESTONE AGGREGATE (D) EXPERIMENTAL GRADATION AND ASPHALT DATA

Stockpile Moisture	Mixing Temp, °F	Gradation, % Passing								Extracted Asphalt			Theoretical Specific Gravity*
		3/8"	#4	#8	#16	#30	#50	#100	#200	Content, %	Penetration, 0.1mm	Viscosity, poises	
Dry	200	-	-	-	-	-	-	-	-	-	-	-	-
	250	100	72	44	38	35	33	12	5	5.6	75	4368	2.360
	300	100	66	37	32	30	28	11	4	5.5	50	8752	2.330
Wet	200	100	68	40	35	32	30	12	7	6.1	55	7043	2.330
	250	100	65	37	33	31	29	13	8	5.5	53	10011	2.333
	300	100	68	37	32	29	27	13	6	5.4	53	10022	2.368
Saturated	200	100	72	46	40	36	34	14	9	5.6	85	3269	2.380
	250	100	68	42	36	33	31	14	8	5.7	82	3395	2.348
	300	100	68	40	36	34	32	14	8	6.3	54	7401	2.331

*Rice theoretical specific gravity of asphalt-aggregate combination.

TABLE A9. LIMESTONE AGGREGATE (D) EXPERIMENTAL MOISTURE RUN CONTENTS

Stockpile Moisture	Mixing Temp, °F	Moisture Content, %				
		Limestone	Limestone Screenings	Field Sand	Cold Feed Aggregate Mixture	Asphaltic Mixture
Dry	200	-	-	-	-	-
	250	5.7	7.1	9.2	0.0	0.0
	300	5.7	7.1	9.2	0.0	0.0
Wet	200	4.5	7.3	9.6	6.0	0.1
	250	4.5	7.3	9.6	7.2	0.0
	300	4.5	7.3	9.6	7.9	0.0
Saturated	200	5.1	7.3	6.1	10.6	0.0
	250	5.1	7.3	9.9	10.5	0.0
	300	6.2	6.1	9.3	11.0	0.0

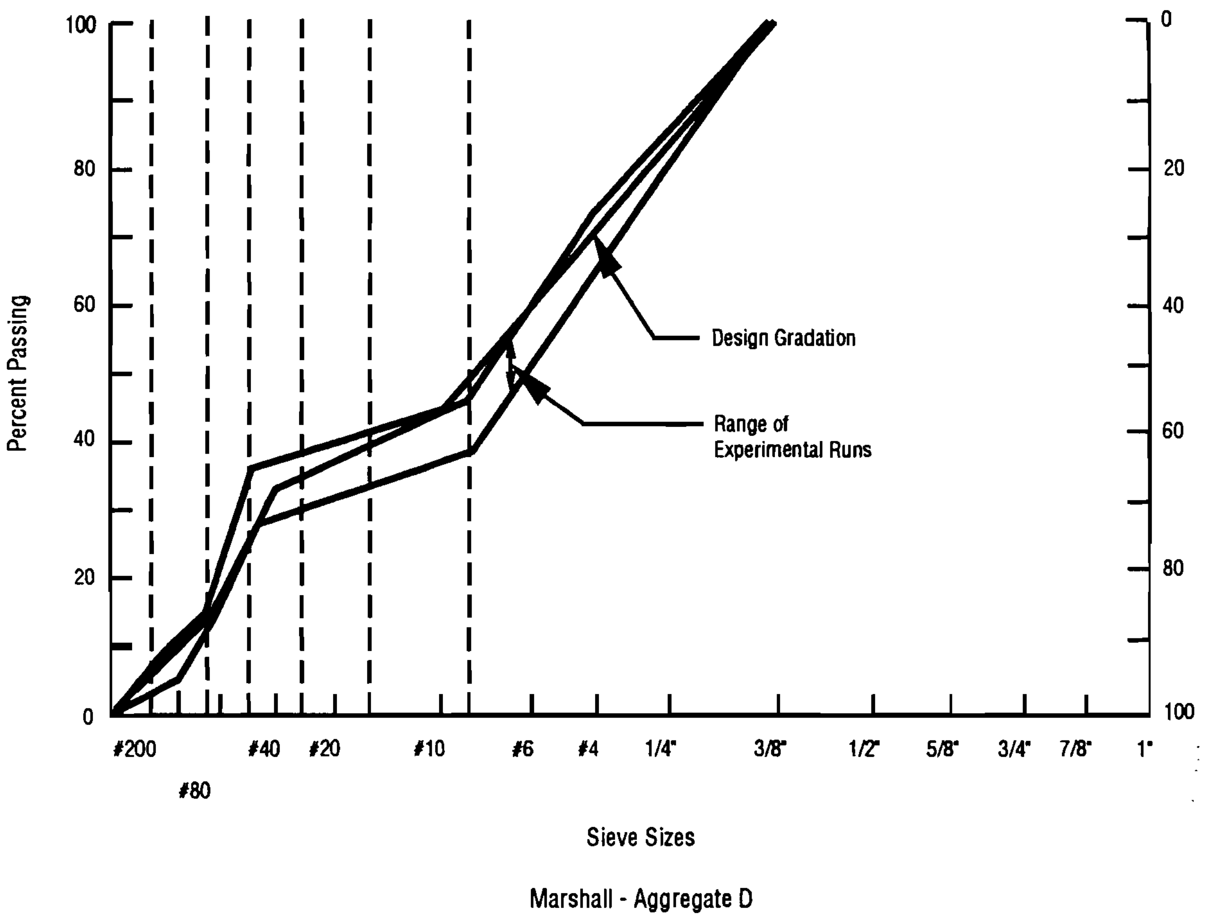

Fig A4. Aggregate D gradation limits of experimental runs.

APPENDIX B. AGGREGATE E—LIGHTWEIGHT MANUFACTURED AGGREGATE USING A DRUM MIX ASPHALT PLANT

The lightweight manufactured aggregate-asphalt mixture was produced by East Texas Asphalt of Lufkin. The plant site in Lufkin, Texas (Figs B1 and B2), consisted of a permanent drum mix plant, stockpiles of aggregate, asphalt storage tanks, and other related equipment. The aggregates were trucked to the plant and loaded into the cold feed bins with a rubber tire loader. The source of the aggregates is listed in Table B1.

The asphalt plant was not modified for the experimental project. The mixing temperature of the asphalt mixture was controlled by altering the burner fuel control. The angle of the drum was not changed throughout the experiment. Hence, retention time in the drum and also mixing time remained constant.

Asphalt Mix Design

The gradations of both the individual and the combined aggregates are given in Table B2. The theoretical specific gravities of the individual aggregates, the combined aggregates and the aggregate-asphalt combinations are shown in Table B3. The results of the density and stability tests for the various asphalt contents are given in Table B4. These results, plotted in Fig B3, were used to determine the design asphalt content.

Compaction Effort Study

A laboratory study was conducted to determine the compactive effort required to produce molded specimens with 7 percent air voids. These procedures were then used in the field to compact modified compaction specimens.

Oven-dried samples of the individual aggregates were sieved, then recombined to form the gradations shown in Table B2. Asphalt was added to produce the design mix. By trial and error, the compactive effort which would produce 7 percent air voids in the specimen was determined.

Field Sample Preparation and Testing

The experimental sections were constructed and sampled as described below:

(1) One of the storage silos was emptied while the other was in use.

(2) The temperature control for the drum mixer was set at the desired temperature and the production was switched to the empty silo.

(3) The material was discharged into a truck, its temperature was measured, and the drum temperature was adjusted until the desired mixing temperature was obtained.

(4) A sample of approximately 200 pounds of the mixture was placed in a covered metal container.

(5) Additional samples of the mixture and aggregate were obtained for moisture determination.

(6) The individual aggregates were sampled from the belt; the feeders and the combined aggregates were sampled from the gathering conveyor cold feed belt.

(7) Modified compaction specimens were made with material taken directly from the bulk sample. The temperature loss of this material during transport was 5 to 10°F.

(8) Eight standard compaction specimens were compacted using material which had been heated to 250°F in an oven.

(9) A 30-lb bulk sample was retained for an asphalt extraction, theoretical specific gravity, and other miscellaneous tests, and transported to The University of Texas Asphalt Laboratories for testing.

Test Results

The results of all tests performed during this experiment are tabulated in Tables B5 to B9. The results are listed for each of the individual test specimens. Tensile strength, static and resilient modulus of elasticity, and Hveem stability are listed in Table B5 for the standard compaction specimens and in Table B6 for the modified compaction specimens. Table B7 lists the moisture damage susceptibility parameters and Table B8 contains gradation and extracted asphalt data. The gradations are shown in Fig B4. Moisture contents of the asphalt mixture and the cold feed aggregates are listed in Table B9.

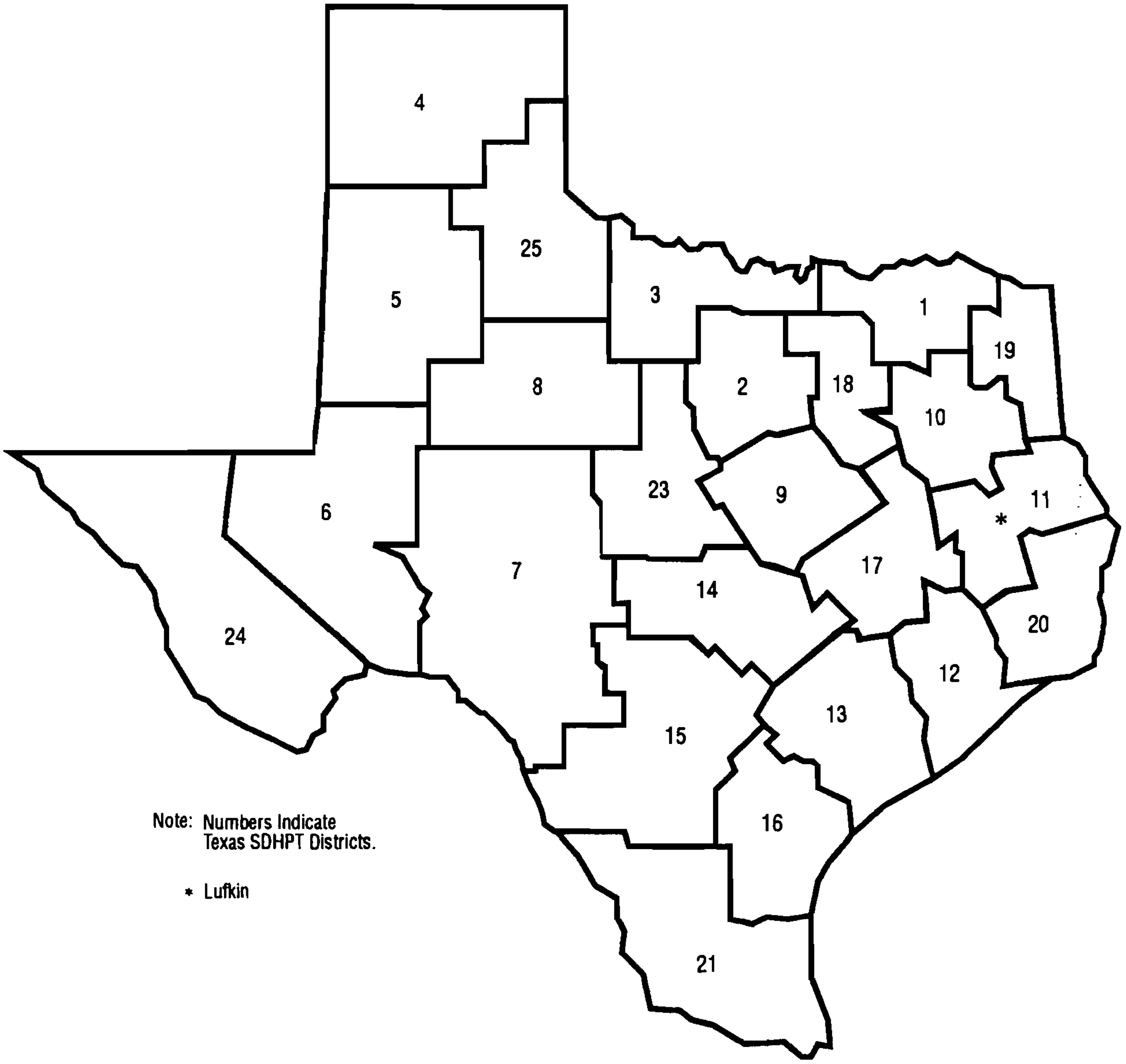

Fig B1. Location of lightweight aggregate experiment.

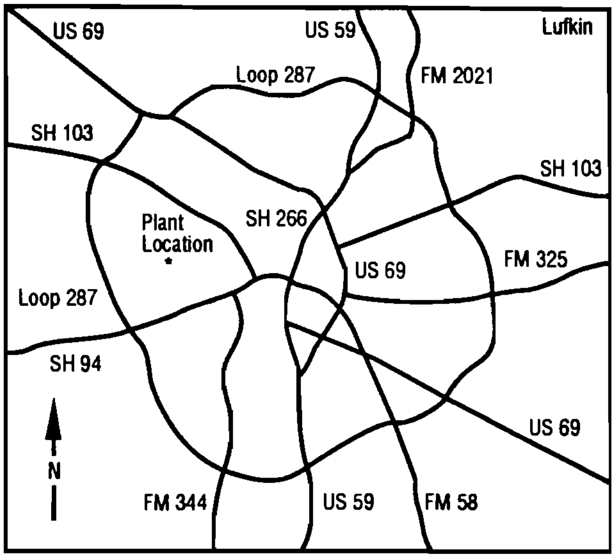

Fig B2. Vicinity of experimental sections on Loop 287 and plant site.

TABLE B1. LIGHTWEIGHT AGGREGATE (E) MATERIAL SOURCES

Material	Material Source
Lightweight Limestone	Texas Industries, Streetman, Texas
Fine Sand	East Texas Asphalt, Eason Lake, Lufkin, Texas
Coarse Sand	East Texas Asphalt, Smith Pit, Lufkin, Texas
AC 20 Asphalt Cement	Texaco, Corpus Christi, Texas

TABLE B2. AGGREGATE E DESIGN GRADATION

Sieve Size	Light Weight	Fine Sand	Coarse Sand	Aggregate Mixture*
1/2" - 3/8"	2.7	0.0	0.0	1.7
3/8" - #4	59.9	0.0	0.0	37.1
#4 - #10	32.1	0.0	0.0	19.9
+ #10	94.7	0.0	0.0	58.7
#10 - #40	1.8	2.5	24.5	8.0
#40 - #80	0.8	27.7	48.6	16.7
#80 - #200	0.9	52.2	14.0	10.1
+ #200	1.8	17.6	12.4	6.5

* Combined aggregates composed of 62% lightweight, 11% fine sand, 27% coarse sand by volume

TABLE B3. AGGREGATE B DESIGN THEORETICAL SPECIFIC GRAVITIES

Material	Specific Gravity*
Lightweight	1.446
Fine Sand	2.642
Coarse Sand	2.611
Aggregate Mixture	1.885
Aggregate Mixture with 5.0% Asphalt	1.810
Aggregate Mixture with 6.0% Asphalt	1.795
Aggregate Mixture with 7.0% Asphalt	1.781
Aggregate Mixture with 8.0% Asphalt	1.767
Aggregate Mixture with 9.0% Asphalt	1.754

* The specific gravities of the aggregates are measured bulk specific gravities and the specific gravities of the mixtures are calculated.

TABLE B4. AGGREGATE E THEORETICAL SPECIFIC RELATIVE DENSITIES AND SPECIFIC GRAVITIES

Asphalt Content, %	Relative* Density, %	Hveem Stability, %
5.5	90.2	42
6.0	93.4	39
6.5	95.8	41
7.0	97.6	44
8.0	98.8	34

*Based on Rice specific gravity

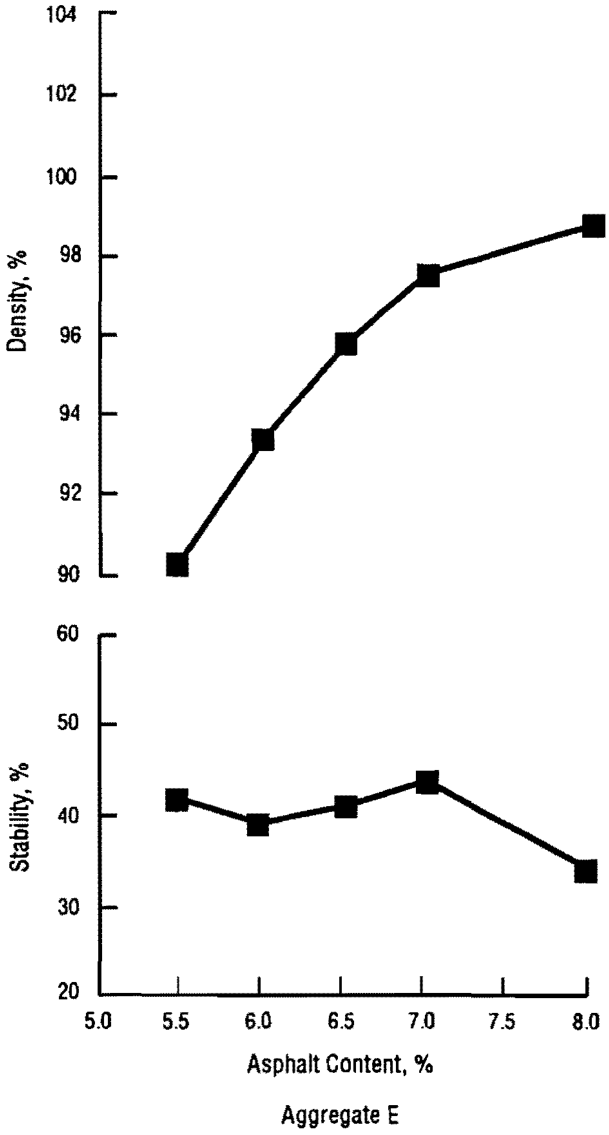

Fig B3. Density-stability design curves.

TABLE B5. AGGREGATE E RESULTS OF INDIVIDUAL STANDARD COMPACTION SPECIMEN TESTS

		Dry Conditioning			
Stockpile Moisture	**Mixing Temp, °F**	**Tensile Strength, psi**	**Static Modulus, ksi**	**Resilient Modulus, ksi**	**Hveem Stability, %**
Dry	250	-	-	-	-
	290	78	26.2	452	29
		76	25.2	358	30
	355	100	38.1	348	31
		100	39.9	446	33
Wet	250	103	38.5	380	38
		103	34.2	362	38
	300	113	-	460	37
		119	53	467	38
	360	143	69	549	36
		144	62	502	35
Saturated	250	123	48	601	29
		122	56	524	36
	310	143	38	454	23
		137	38	497	24
	350	-	-	-	-
		-	-	-	-

TABLE B6. AGGREGATE E RESULTS OF INDIVIDUAL MODIFIED COMPACTION SPECIMENS

		Modified-Standard Specimens*					Modified Specimens**		
		Dry Conditioning				Freeze-Thaw Conditioning	Dry Conditioning		Freeze-Thaw Conditioning
Stockpile Moisture	**Mixing Temp, °F**	**Tensile Strength, psi**	**Static Modulus, ksi**	**Resilient Modulus, ksi**	**Hveem Stability, %**	**Tensile Strength, psi**	**Tensile Strength, psi**	**Resilient Modulus, ksi**	**Tensile Strength, psi**
Dry	250	-	-	-	-	-	-	-	-
	290	81	27	313	30	-	40	48	34
		79	24	399	31	-	41	39	33
	355	101	36	449	32	-	79	38	60
		94	37	466	35	-	78	39	58
Wet	250	103	39	380	38	-	92	42	39
		103	34	362	38	-	88	38	52
	300	184	92	618	38	-	89	45	36
		151	74	658	39	-	81	43	36
	360	116	48	413	34	-	98	56	53
		127	56	411	34	-	95	46	50
Saturated	250	123	48	601	29	-	88	47	41
		122	56	524	36	-	89	42	49
	310	138	37	513	25	-	94	35	57
		141	39	440	24	-	90	37	70
	360	-	-	-	-	-	98	41	107
		-	-	-	-	-	99	44	94

* Compacted to standard compaction procedure endpoint at mixing temperature

** Compacted to 7% air voids at mixing temperature

TABLE B7. AGGREGATE E MOISTURE DAMAGE SUSCEPTIBILITY PARAMETERS

Stockpile Moisture	Mixing Temp, °F	Modified Compaction Tensile Strength Ratio*	Boiling Test Retained Asphalt, %
Dry	250	-	-
	290	54	40
	355	91	80
Wet	250	53	20
	300	79	70
	360	106	97
Saturated	250	105	50
	310	54	30
	360	-	-

*Tensile strength ratio computed from the average tensile strength of the freeze-thaw conditioned specimens divided by the average tensile strength of the dry conditioned specimens

TABLE B8. AGGREGATE E EXPERIMENTAL RUN GRADATION AND ASPHALT DATA

		Gradation, % Passing						Extracted Asphalt			
Stockpile Moisture	Mixing Temp, °F	3/8"	#4	#10	#40	#80	#200	Content, %	Penetration, 0.1mm	Viscosity, poises	Theoretical Specific Gravity*
Dry	250	-	-	-	-	-	-	-	-	-	-
	290	99	68	61	54	16	4	6.9	47	7813	1.877
	355	99	67	57	49	17	4	6.3	39	8606	1.879
Wet	250	99	71	51	42	13	3	6.8	44	6353	1.787
	300	99	70	54	44	18	7	6.9	47	7711	1.748
	360	99	75	57	45	18	7	6.8	37	10659	1.773
Saturated	250	99	68	54	42	17	7	6.9	43	6117	1.802
	310	99	67	52	41	17	7	7.3	41	7388	1.735
	360	-	-	-	-	-	-	6.3	-	-	-

*Rice theoretical specific gravity of asphalt-aggregate combination

TABLE B9. AGGREGATE E EXPERIMENTAL RUN MOISTURE CONTENTS

		Moisture Content	
Stockpile Moisture	Mixing Temp, °F	Cold Feed Aggregate Mixture	Asphaltic Mixture
Dry	250	-	-
	290	0.5	0.0
	355	0.5	0.0
Wet	250	6.3	1.8
	300	5.7	0.3
	360	6.3	0.3
Saturated	250	17.9	2.3
	310	16.0	1.5
	360	-	-

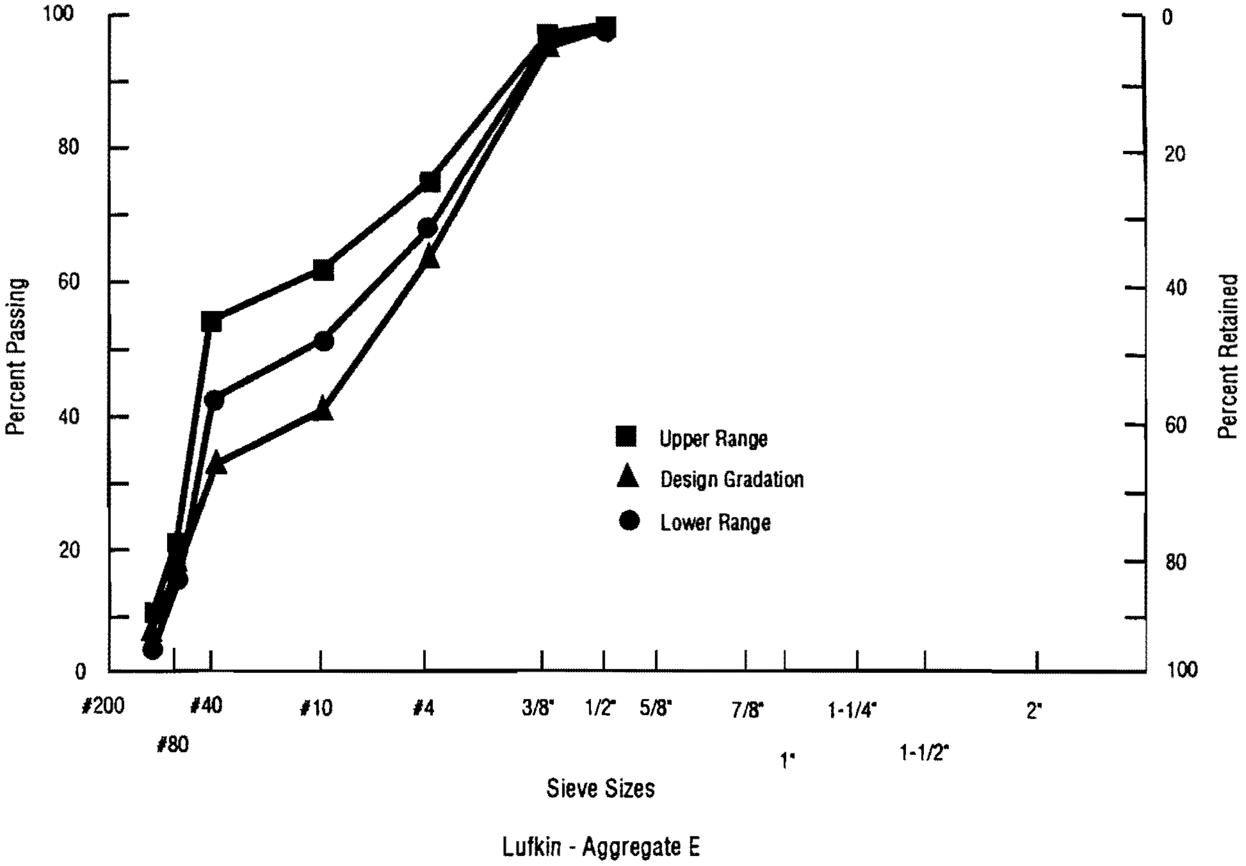

Fig B4. Aggregate E gradation limits of experimental runs.