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Effect of variations in compaction on asphaltic concrete

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EFFECT OF VARIATIONS IN

COMPACTION ON ASPHALTIC CONCRETE

by

Mohammad Abdullah El-Ali

A Thesis Submitted to the Faculty of the

DEPARTMENT OF CIVIL ENGINEERING
AND ENGINEERING MECHANICS

In Partial Fulfillment of the Requirements
For the Degree of

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WITH A MAJOR IN CIVIL ENGINEERING

In the Graduate College

THE UNIVERSITY OF ARIZONA

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Professor of Civil Engineering

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ABSTRACT

In this report the influence of several variables including asphalt content, mixing temperature, compaction temperature and compaction energy on void content, voids-in-the-mineral-aggregate (VMA), density and stability of asphaltic concrete mixtures was established.

Straight lines were obtained on double logarithmic paper for each asphalt content when the logarithm of Marshall stability values as ordinate were plotted versus the logarithm of the corresponding number of blows of a Marshall compactor as the abscissa. The straight lines were very nearly parallel and therefore, it was possible to develop a single empirical formula expressing the relationship between stability at any compactive effort, within the range of 20 to 110 blows per face, in terms of the standard stability at 75 blows per face of specimen.

Results indicate that void content, VMA, density and stability were significantly affected by compaction temperature, asphalt content, compactive effort and mixing temperature.

CHAPTER 1

INTRODUCTION

Since motorized traffic has greatly increased since World War I and there has been a greater demand for more and better roads, the search for low cost and high performance roadway design and construction procedures has been extensively pursued. Today, incontrovertible documentary evidence exists that bituminous pavements, if properly designed and constructed, are stable, durable and thrifty, providing the public with economical, smooth, safe and anti-skid road surfaces.

Recently, increased volume of traffic and loads has resulted in efforts to explore methods for improving performance of flexible pavements. It has been generally agreed that for a better design of asphaltic paving mixtures, a balance among various mixture properties must be achieved.

Public and private agencies have expressed a need for reliable engineering data in order to instruct their design and construction personnel in the use of current hot-mix design methods, allowing them to predict whether or not a mixture will perform satisfactorily.

Knowledge of the effects on mixture properties of compactive effort, compaction temperature, asphalt content and mixing temperature are necessary to develop maximum strength of asphaltic concrete mixtures.

J. J. Lingle(14), in a 1956 study of the importance of thorough compaction of bituminous test mixtures stated:

1. "The Structural strength of the compressed mixture, or its ability to carry loads is mainly dependent upon the mineral aggregate which constitutes the entire framework and three-fourths of the absolute volume of the structure. The asphalt imparts cohesiveness and tensile strength to the mixture, and at the same time a certain degree of plasticity. It also fills most of the voids in the mineral aggregate framework and waterproofs the entire structure. The unfilled voids or air spaces, at first thought, might appear undesirable or at least useless, but actually are of value in providing a reservoir within the structure to care for increase in volume of asphalt at hot summer temperatures due to its high coefficient of expansion, as compared with that of the mineral aggregate."

2. "Resistance to displacement under traffic and durability are the two primary requisites of a satisfactory compressed asphalt paving mixture. No matter how carefully and scientifically the mixture is designed, it will be lacking in both of these properties if it is not thoroughly compressed. For any properly designed mixture, resistance to displacement has been found to be almost a direct function of its degree of compression."

These statements, taken from a paper presented at the Engineer's Club in Philadelphia in February, 1930 by Mr. Prevost Hubbard were used by J. J. Lingle to illustrate that thorough compaction accomplishes the following:

1. Determines the mix volume available as storage space for asphalt, thereby providing a scientific basis for the selection of proper asphalt content.
2. Causes a displacement and orientation of the aggregate into a condition of interlock of the larger particles, producing a unit

structure thoroughly bound together by the bitumen-fines mortar, thereby developing the maximum test stability of which the mixture is capable.

3. Results in test data that is coherent, orderly, and obeys theory, enabling the designer to interpret and evaluate test results according to intended pavement use.

Lingle's discussion and supporting data suggest a need for a revision of the published test procedures to include higher than specified mixing and compaction temperatures. Lingle himself used a mixing temperature of 300°F and a compaction temperature of 280°F.

In the design of asphaltic concrete mixtures, a number of desirable mix properties must be considered. Two of the essential properties of bituminous paving mixtures are stability and durability. The temperature to which an asphalt-aggregate combination may be exposed during its processing, without detrimental effects on stability and durability remains a controversial matter among designers of bituminous mixtures.

A major requirement in the design of a sound asphalt paving mixture is stability, i.e. resistance to displacement or deformation and to tensile, compressive, and shear stresses that cause failure in a pavement surface. Stability is considered to be the property of primary importance in relation to resistance of the mixture to the destructive effects of traffic. Stability is influenced by the gradation, shape, size, and surface texture of the aggregate, the percent of bitumen in the mix, and the degree of compaction of the pavement.

Durability has been defined as the resistance to disintegration caused by weathering or abrasive action of traffic. In general, good durability requires high asphalt content and dense, well-compacted, impervious mixtures.

The provision of adequate durability requires the correct evaluation of the air voids and the voids-in-the-mineral-aggregates (VMA) of the bituminous mixtures. Unless the VMA is large enough, the mixture will be deficient in asphalt or air voids or both. Pavements low in bitumen become brittle and crack early in life. Subsequently, serious ravelling may occur under traffic. There is a minimum amount of air voids necessary for proper asphalt performance. Without sufficient voids, free asphalt will be flushed or pushed out of the mixture as a result of densification of the mix during use or due to expansion of the asphalt during high temperatures. This can result in loss of stability and excessive deformation of the pavement surface. High amounts of air voids, on the other hand, results in high permeability. Varying the amounts of air voids allows the permeability to be varied when it is considered important that a mixture be relatively impermeable or in other cases, when it becomes important to allow water or water vapors to pass through freely.

Most of the constructed pavements have appreciable variation in their void content, which could range from about 3 percent in an old, heavily trafficked pavement to about 20 percent in an improperly designed and/or compacted new pavement (1).

High bitumen content results in thick films, which are most resistant to hardening and a reduction of the air voids, which minimize the entry of air and water. They also provide the mix with tensile strength so that tractive or abrasive forces of traffic may be resisted.

High void content permits free access of air and leads to rapid oxidation of the asphalt, with resultant loss in flexibility (2). High void content also permit water to enter the pavement freely, which can result in stripping of the asphalt, particularly where aggregates with an acidic surface reaction are concerned (2).

Air voids and the asphalt content of an aggregate are interrelated. There must be voids in the aggregate to allow room for the asphalt and there must be voids in the final compacted mix to allow room for densification but there must be sufficient asphalt in the mix to make the pavement durable. The amount of voids in the final compacted mix can be controlled by altering the asphalt content but, if this is done, generally a lean and unsturdy pavement would result. Therefore, for a satisfactory mixture, the aggregate must have enough voids to permit the addition of sufficient asphalt to provide a comparatively thick film of asphalt around the aggregate but without filling all of the voids of the aggregate.

Density is a measure of compaction either in the laboratory or in the field. Compaction, in simple terms, is forcing the particles closer together resulting in a higher unit weight. The compaction process is actually much more complex. The degree of compaction is dependent on the type of material being compacted and the type and amount of compactive effort being applied. There are three principal types of compaction: that obtained in the field by construction equipment, that obtained in the laboratory, and that resulting from exposure of the pavement to traffic.

Density and void content of the pavement are very much dependent on each other. The percent voids will, in general, vary in proportion to the variation in density for any given mixture. Therefore, if test specimens are prepared using different compactive efforts which produce different unit weights the percent voids will not be the same. The air voids vary inversely as the density. Therefore, the higher the density, the lesser the percent air voids in the total mix.

This study was undertaken to investigate the effects of compactive effort, compaction temperature, asphalt content and mixing temperature on void content, VMA, density and stability of asphalt mixtures.

In preparing the test specimens, the Marshall method of mix design was selected for proportioning of the mixtures mainly because of its rather wide scale use throughout the world. Different amounts of compactive effort were applied at different compaction temperatures, different asphalt contents and different mixing temperatures in order to obtain the effects of these variables on void content, VMA, density and stability of asphaltic concrete mixtures. Compactive efforts used in the study were 20, 75, and 110 blows per face of specimen with a Marshall hammer. Compaction temperatures used were 212°, 250°, and 285°F. Mixing temperatures were 250°, 285°, and 325°F. Asphalt contents were 4.5, 5.0, 5.5, and 6.0 percent by weight of total mix.

Experimental results for all test specimens include Marshall stability and flow values and density-voids analysis, and they are tabulated and plotted.

It may be noted here that there is much less need to consider the effect of variations in mix composition on flow value since this quantity is dependent almost entirely on the binder (asphalt plus filler) content of the mix (3,4) and to a minor degree on the other mix variables which exert a profound influence on void content, VMA, density and stability.

CHAPTER 2

REVIEW OF LITERATURE

In the literature, investigations concerning variables affecting void content, VMA, density and stability are reported. For instance, Lingle (14) studied the importance of thorough compaction of bituminous test mixtures. Routine Marshall data was used to illustrate that higher than specified mixing and compaction temperatures were needed for a satisfactory asphalt paving mixture.

It is generally recognized that compaction is important in asphaltic concrete design. In some instances it is believed that variance in the allowable time for compaction has led to failure of asphaltic concrete because insufficient compaction eventually led to the problems generally associated with high voids content and low densities.

The amount of the compactive effort have a significant influence on the void space remaining in the mixture. As the compactive effort is increased, the void space is reduced because of aggregate embedment.

Large temperature range effects on compaction has been studied often in the laboratory. Parker (5,8) showed the importance of compacting at high temperatures i.e. 225°F or above. The effect of compaction temperature on mixture properties was studied extensively by Parker (5) and figures 1 and 2 are from his report. In the figures it is assumed that 100 percent compaction was obtained at 275°F. Figure 1 shows that there is little, if any, increase in density when compaction occurs at temperatures higher than 275°F.

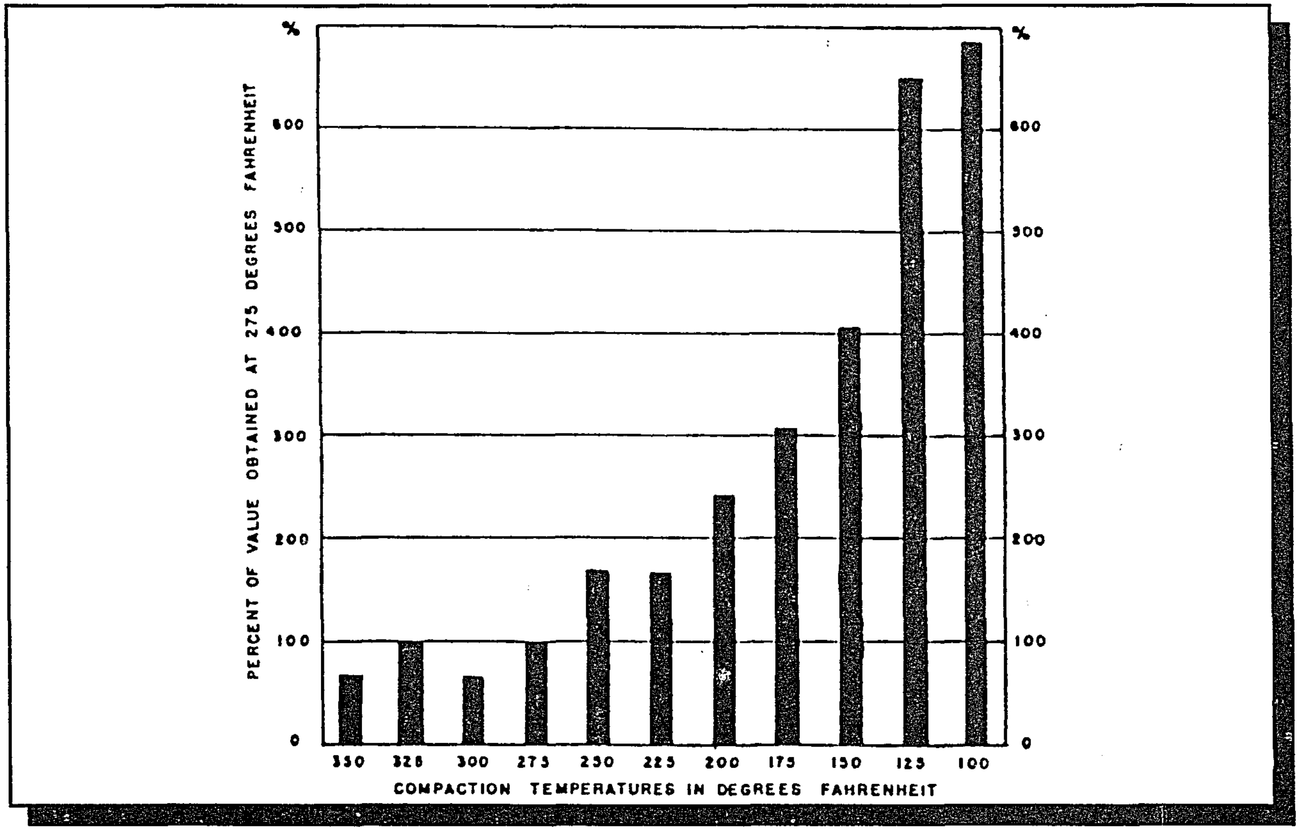

FIGURE 1. Effect of temperatures at compaction (Marshall method) on percent voids of bituminous concrete wearing course (after Parker, 5).

However, density decreases rapidly when compaction occurs at lower temperatures. For example, at 150°F, there is an increase in voids of more than 400 percent.

Temperature also affects other characteristics. For example, Figure 2 shows how stability using the Marshall test procedure decreases as the compaction temperature decreases. As Figure 2 shows, there is some increase in stability when compaction occurs at temperatures higher than 275°F; however, there is a marked decrease in stability when compaction occurs at lower temperatures, especially below 200°F. According to Parker (5), compacting a particular mixture of asphalt and aggregate at 200°F. gave an air voids of 2.4 times larger than that obtained when the mixture was compacted at 275°F. Similarly compaction at 175°F. gave air voids 4 times larger than that obtained at 275°F. Parker used the Marshall compaction procedure (50 blows on the top and bottom of the sample) in his investigation, and the temperature range studied was 100° to 350°F.

In comparing the conclusions drawn by Parker (5,8) with the results of this research thesis there is concurrence. However, the temperature range studied by Parker was different from the temperature range studied in this research paper.

Fink and Lettier (3) investigated the influence of the type and consistency of the bituminous binder on the Marshall stability values of a dense graded asphaltic concrete measured at temperatures above the softening point (100°F) and at a high deformation rate. They concluded the following:

(1) The stability value is strongly influenced by the viscous resistance of the binder.

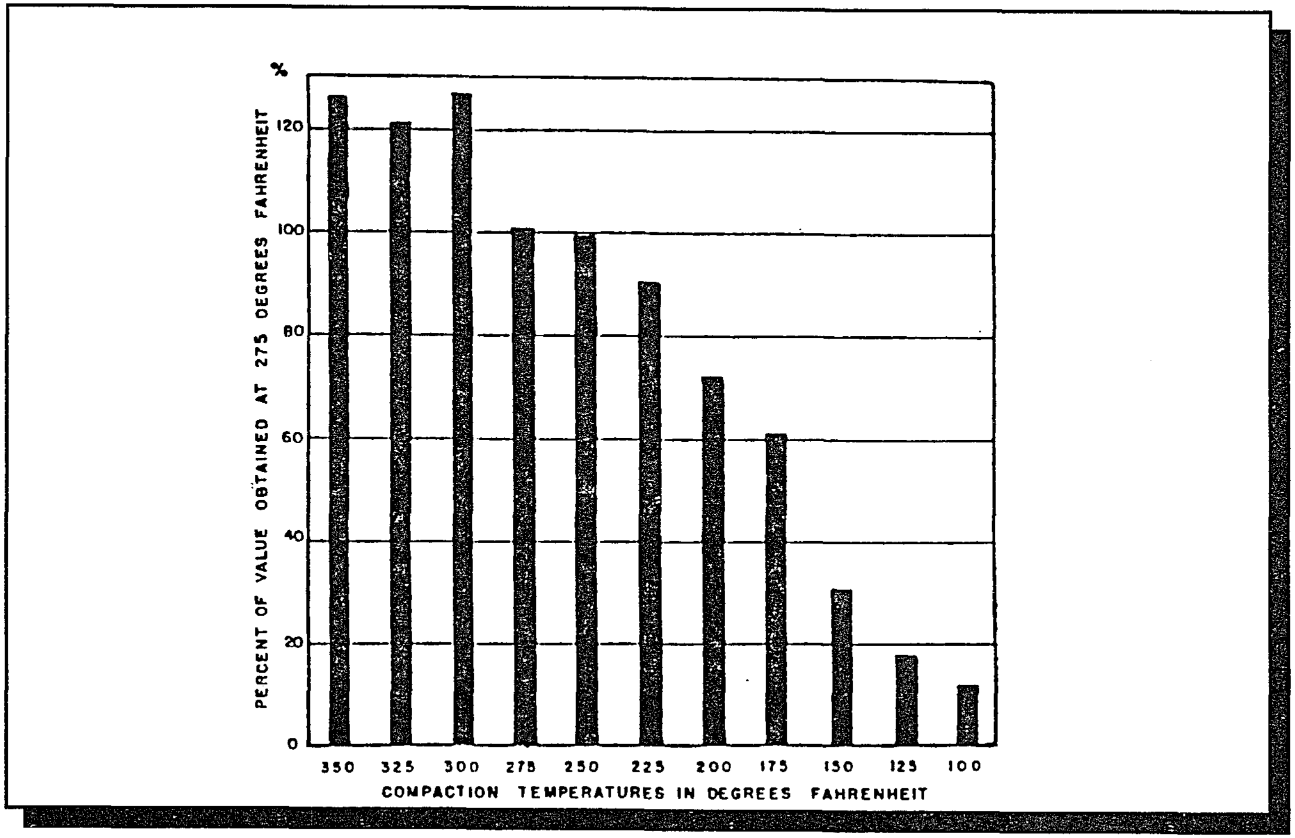

FIGURE 2. Effect of temperatures at compaction on Marshall stability of bituminous concrete wearing course (after Parker, 5).

(2) For comparable asphalt contents, varying the compaction temperature had a very little effect on the measured density.

(3) Considerably higher stability values were obtained as the compaction temperature was increased particularly at the lowest asphalt content as shown in Figure 3.

(4) At higher asphalt contents the flow value was increased somewhat when the compaction temperature was raised.

The conclusion by Fink and Lettier (3) that varying the compaction temperature had very little effect on the measured density is in complete agreement with the conclusions drawn by Parker (5,8) for temperatures higher than 275°F. It is further indicated that higher stability values were obtained as the compaction temperature was increased which concurs with the conclusions drawn by Parker and this research as well.

Kiefer (6), using the Hveem kneading compactor in his study of the influence of compaction temperature on density of a low-viscosity paving mixture, obtained an increase in density from 146.3 to 148.4 lb. per cu. ft. when the compaction temperature was increased from 150° to 270°F. This increase in density is not significant. Kiefer's work embraced a temperature range of 150° to 350°F. Varying the compaction temperature from 150° to 270°F had very little effect on the measured density.

The effect of mixing temperature on the properties of bituminous mixtures has been studied for many years. However, with the exception of viscosity effects on the hardening of the asphalt during mixing, few clear cut conclusions have been reached.

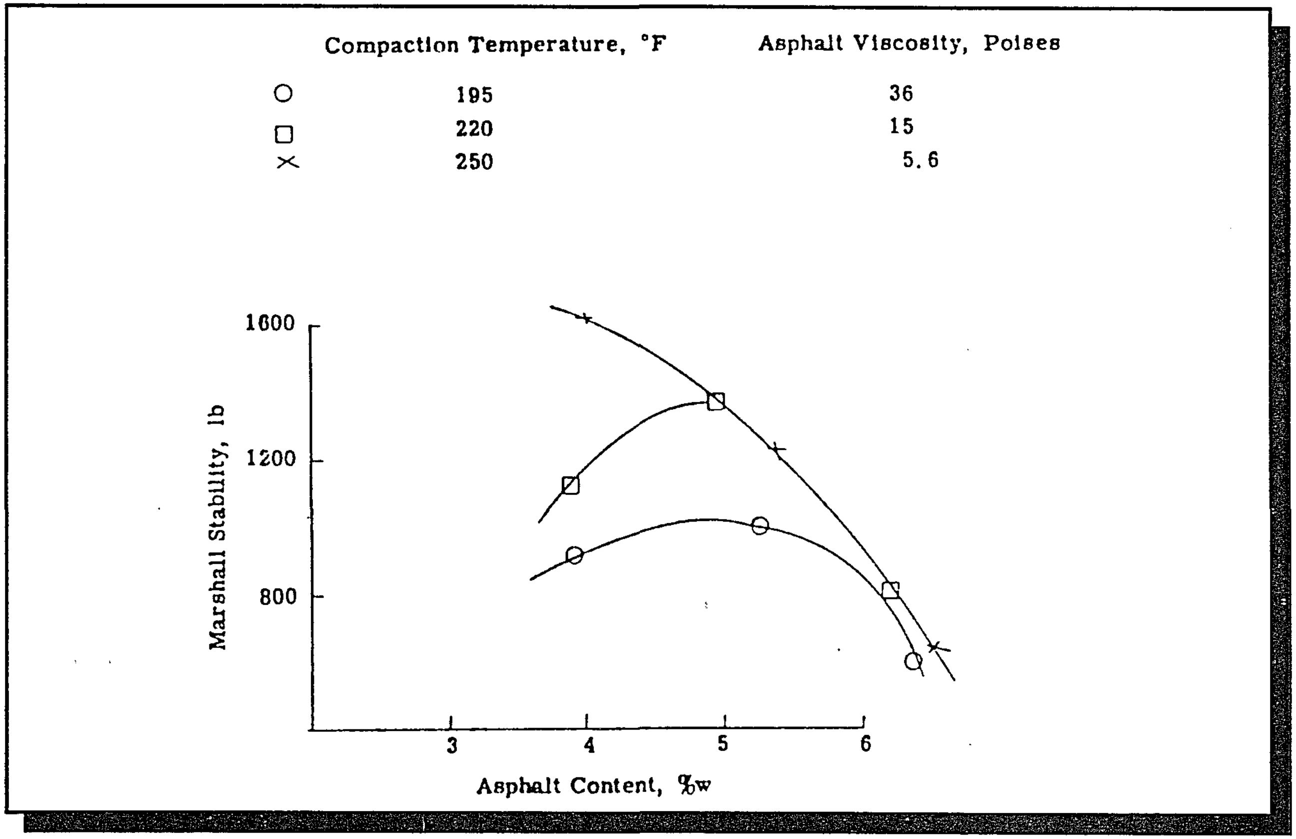

FIGURE 3. Effect of Compaction Temperature on Marshall Stability (after Fink and Lettier,3).

The effect of mixing temperatures on hardening was investigated by Bright and Reynolds(7) and the references of that paper provide a good background of the hardening effect.

Gallaway (9) showed little change in density on roads made of bituminous mixes laid at 250°F to 310°F. This conclusion is in agreement with the finding of this research because there was no significant increase in density when the compaction temperature was increased from 250° to 325°F.

Heithaus and Izatt (12) investigated the effect of certain variables of paving mix composition on Marshall stability. These variables were:

(1) Compactive effort.

(2) Compaction temperature.

(3) Asphalt content and viscosity.

The results of their investigation were the following:

(1) Increasing compactive effort increases stability. This is illustrated Figure 3.

(2) Increasing compaction temperature increases stability at low asphalt contents.

(3) Decreasing asphalt content increases stability provided that an increase in compactive effort or other means of stability improvement be employed.

(4) Higher viscosity leads to greater stability.

The conclusions drawn in this thesis are in complete agreement with the conclusions of Heithaus and Izatt. Stability increased when compaction temperature

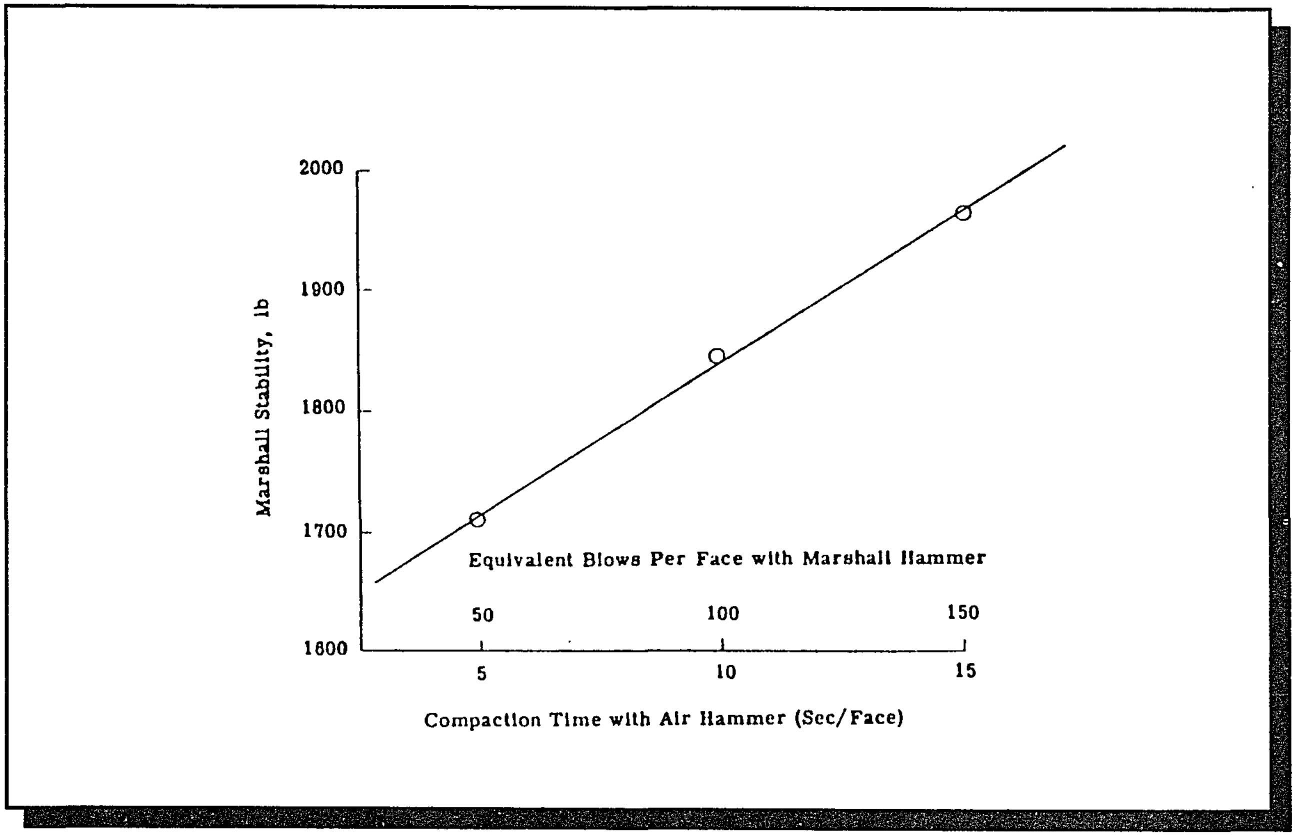

FIGURE 4. Effect of Compactive Effort on Stability (after Heithaus and Izatt, 12).

was increased at low asphalt contents; the results of this research indicated an increase in stability at low (as well as high) asphalt contents, also.

Williams and Kimble (13) studied the effects of variation in compaction temperatures on field density. Compaction temperatures were varied between 250°F and 325°F in 25° increments. Three types of aggregate combinations and two nominal maximum particle sizes were used in the investigation.

The effect of compaction temperature was investigated for limestone, limestone-sand mixtures with nominal maximum particle size of 3/4" for a mixture designed to have 50 percent retained on the No. 6 sieve. The asphalt cement used was 70 - 80 penetration grade asphalt.

The results of their study show the following:

(1) Density at time of construction increased as compaction temperature increased.

(2) Differences between densities obtained by laboratory and by field compaction were nearly eliminated after a short period of use and at the end of 17 months the density difference appeared to be completely eliminated from the high traffic count surface.

3) Compaction temperatures should be raised whenever density at construction is critically low and cannot be corrected by subsequent traffic compaction before exposure to freezing atmospheres.

Williams and Kimble concluded that density increased as compaction temperature increased. This is not in agreement with the tests and research conducted for this paper.

This report investigates the effect of compactive effort, compaction temperature, mixing temperature and asphalt content on void content, VMA, density and stability of asphaltic concrete mixtures. The next chapter deals with the description of the materials used in this investigation.

CHAPTER 3

MATERIALS USED AND THEIR PROPERTIES

The objectives of this study, as presented earlier, were to investigate the influence of asphalt content, mixing temperature, compaction temperature and compactive effort on void content, VMA, density and stability of asphaltic concrete mixtures. Accordingly, an experimental plan consisting of sixty five specimen sets (two replicates of each) was developed as set up in Table 1 on page 18.

The materials used for this study were a previously mixed asphaltic concrete, four separate aggregates, and AC-20 asphalt cement.

Asphaltic Concrete

The asphaltic concrete mixtures investigated contained 3/4 inch and 3/8 inch maximum size aggregates. Hereinafter, they will be referred to as Mix A and Mix B respectively.

Mix A was mixed in the laboratory using the Marshall method of mix design (15). This method was selected for proportioning of the mixtures mainly because of its rather wide scale use throughout the world. Mix B was provided by the Tanner Companies located at Interstate 10 and Orange Grove Road, Tucson, Arizona and brought to the asphalt laboratory in sealed five gallon pails. The asphaltic concrete mixture was from regular plant production.

The pails of mixtures were heated to 200°F one at a time and divided into 1200 gram portions which were stored in paper bags until time of use. All of the mixture that was heated at any one time was either weighed for samples or discarded to avoid

TABLE 1 EXPERIMENTAL PLAN

MIXTURE	A																				B		
ASPH. CONTENT	L	M									M + 0.5%									H	M		
MIXING TEMP.	M	L			M			H			L			M			H			M	M		
COMPACTION TEMP.	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	M	L	M	H
COMPACTIVE EFFORT 20		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*
75	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
110		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*

* = a pair

L = Low
M = Medium
H = High

Asphalt content: M = Design Value

Mixing Temperatures: L = 250°F
M = 285°F
H = 325°F

Compaction Temperatures: L = 212°F
M = 250°F
H = 285°F

repeated heating of the material.This procedure was followed for the preparation of samples to avoid the changes in mixture properties that result from long duration of elevated temperatures and to achieve uniformity among specimens.

Two samples were prepared for asphalt content and aggregate gradation analysis. Each of these two samples were extracted in a reflux extractor in accordance with AASHTO Test Method T-164, Method B (18). Methylene chloride was used as a solvent to remove the asphalt cement. The extracted aggregates were then oven dried and the asphalt content determined by the difference in weight of the unextracted and extracted samples.

The particle size distribution of each of the two samples of dried aggregates was then determined by sieving through a nest of sieves in accordance with AASHTO Test Method T-30 (18). The amount passing the No. 200 sieve was also determined.

The asphalt content recorded for the mix was the average of the two results. These test results are shown in Table A.1 of Appendix A. Similarly the average aggregate gradation was determined and recorded as shown in Tables 2,3 and Figure 5. The mixture was further analyzed by the Marshall test procedure, AASHTO T-245 (18).

Aggregates

Four separate aggregates were used for Mix A. The aggregates came from Tanner Companies plant in Tucson. Large quantities were obtained and stored in fifty five gallon containers. Gradations of each of these aggregates were determined in accordance with AASHTO Test Method T-27 and are reported in Table 2.

The specifications selected to govern the composition of the test specimens were those of the Asphalt Institute (10). These specifications present excellent criteria

TABLE 2 GRADATIONS OF AGGREGATES

Aggregate Type	I	II	III	IV
Sieve Size	Percent Passing, By Weight			
1 in.	100			
3/4 in.	75	100		
1/2 in.	10	86	100	
3/8 in.	1	21	96	
No. 4	1	2	29	100
No. 8			1	90
No. 16				67
No. 30				42
No. 50				25
No. 100				12
No. 200				8

for determining the composition of eight mix types which cover the range of normal mixes from macadam types through the graded aggregate types to sand and sheet asphalt types.

The mix type used for this investigation was a dense graded asphaltic concrete which is designated as Mix No. IVC by the Asphalt Institute (25).

The following aggregate gradation limits are specified.

Sieve size	Total % passing by weight
1 in.	100
3/4 in.	80-100
3/8 in.	60-80
No. 4	48-65
No. 8	35-50
No. 30	19-30
No. 50	13-23
No. 100	7-15
No. 200	0-8

Mineral filler is considered to be that portion of the aggregate blend which passes a No. 200 sieve. The grading of the filler below the No. 200 sieve is not normally controlled by specification requirements even though particle size distribution is important because filler is mainly used to decrease the voids in a mixture. Since portland cement has well distributed particle sizes below the No. 200 sieve, it was selected for the mineral filler as is general practice.

A tabulation and a plot showing the gradation of the blend are shown in Table 3 and Figure 5.

Asphalt Cement

AC-20 viscosity graded original asphalt cement was used in this study. The Arizona Department of Transportation (ADOT) specifications for this asphalt are shown in Table 4.

TABLE 3 GRADATIONS OF ASPHALTIC CONCRETE MIXTURES

Sieve Size	Percent Passing Mix A	Mix B
1 in.	100	100
3/4 in.	94	100
1/2 in.	76	100
3/8 in.	62	85
No. 4	51	63
No. 8	43	47
No. 16	33	31
No. 30	21	18
No. 50	14	8
No. 100	8	4
No. 200	6	1.5

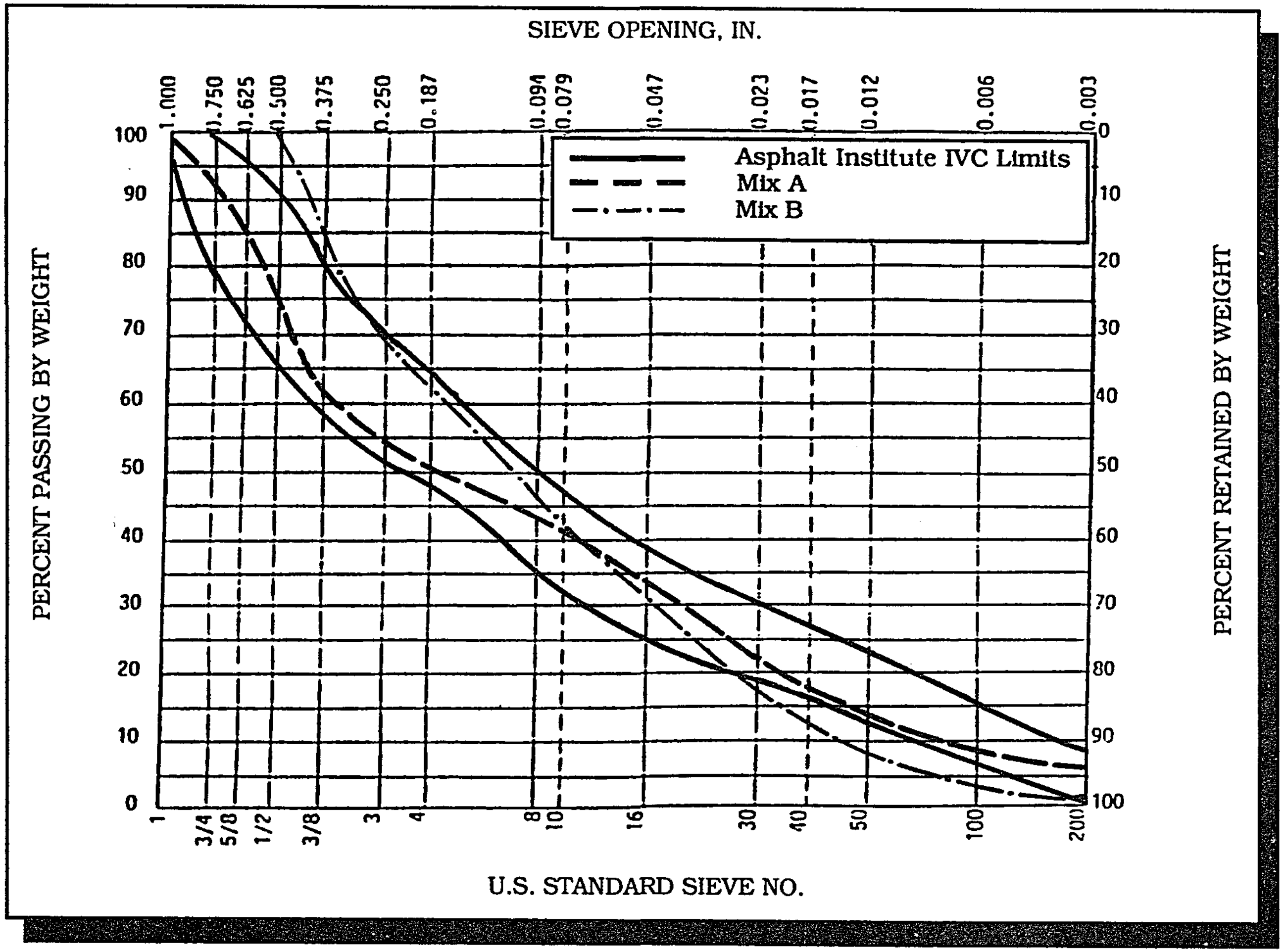

FIGURE 5 Aggregate Gradation Curves

TABLE 4 ARIZONA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR THE (AC-20)

Item	Number
Viscosity, 140 degrees F., poises, range	1600-2400
Viscosity, 275 degrees F., antistokes, minimum	210
Penetration, 77 degrees F., 100 grams, 5 seconds, minimum	60
Flash point, Pensky-Martens closed tester, degrees F., minimum	450
Solubility in Trichloroethylene, percent, minimum	99
Ductility, 77 degrees F., centimeters, minimum	75

CHAPTER 4

SPECIMEN PREPARATION AND TEST PROCEDURE

In preparing the test specimens, the Marshall method of mix design was used (15). Specimens 4 inches in diameter by 2-1/2 inches high were prepared in duplicate for different asphalt contents. To provide adequate data, triplicate test specimens are usually prepared for each asphalt content used. However, for this investigation only two specimens were prepared for each asphalt content. It was felt that this was justified on the basis of the extreme care taken to obtain the batch mix for individual specimens. Therefore, the total number of specimens required for this investigation was equal to 130 (refer to Table 1). Different amounts of compactive effort were applied at different compaction temperatures and different mixing temperatures in order to obtain the effects of these variables on void content, VMA, density and stability.

Compactive efforts used in this study were 20, 75, and 110 blows per face of specimen. Compaction temperatures were 212°, 250°, and 285°F. Mixing temperatures were 250°, 285°, and 325°F. Asphalt contents were 4.5, 5.0, 5.5, and 6.0 percent by weight of total mix.

It was necessary that a mixture design be performed prior to any testing of Mix A (the mixture prepared in the laboratory). The procedures used to perform this work are discussed in this chapter.

Mixture Design

Designing an asphaltic concrete paving mixture involves the preparation of a series of test specimens with different asphalt contents. Before establishing the range of asphalt contents, it is necessary to estimate the optimum asphalt content. A new procedure for establishing an initial asphalt content for the design of Mix A was used.

A basic thought in this new procedure is that the mixture will be viewed with the potential of having certain properties approaching those of the pavement surface after it has been in service for a period from 4 to 5 years (16).

Table 2 is a copy of a computer printout of a program written by Jimenez (16) to obtain the total asphalt content by weight of mixture, VMA, surface area and the asphalt film thickness that corresponds to a variable amount of air voids.

The required material properties are listed as follows:

(1)	gradation of aggregate	3/4 inch blend
(2)	aggregate ESG	2.570
(3)	asphalt SG	1.018
(4)	asphalt absorption(assumed)	1.0 percent

The Jimenez method(16) determines the VMA of the aggregate using the procedure described by Hudson and Davis (11), the surface area of the blend using the California Surface Area Factors (15) and the film thickness using the effective asphalt content.

TABLE 5 OUTPUT OF PROGRAM FOR BASIS OF A MIXTURE DESIGN

TEST DATA

SIEVE SIZE	PERCENT PASSING (P)	R	VOIDAGE REDUCTION FACTOR (F)	AGGREGATE VOIDAGE	SURFACE AREA FACTOR	SURFACE AREA (SQFT/LB)
200.000	6.0	.00	.000	32.00	160.	9.60
100.000	8.0	1.33	.892	28.55	60.	4.80
50.000	14.0	1.75	.933	26.64	30.	4.20
30.000	21.0	1.50	.897	23.90	14.	2.94
16.000	33.0	1.57	.906	21.66	8.	2.64
8.000	43.0	1.30	.894	19.37	4.	1.72
4.000	51.0	1.19	.906	17.54	2.	1.02
.375	62.0	1.22	.904	15.85	0.	2.00
.750	94.0	1.52	.899	14.25	0.	.00
1.500	100.0	1.06	.974	13.89	0.	.00

TOTAL SURFACE AREA = 28.92

AIR VOIDS PERCENT	ASPHALT CONTENT PERCENT	FILM THICKNESS MICRONS
2.00	5.18	7.41
3.00	4.77	6.65
4.00	4.35	5.88
5.00	3.93	5.12
6.00	3.50	4.36

EFFECTIVE SPECIFIC GRAVITY = 2.570
ASPHALT SPECIFIC GRAVITY = 1.018
ASPHALT ABSORPTION VALUE = 1.000

From Table 2, the aggregate gradation yielded a final VMA value of 13.89 percent which is close to the recommended minimum of 14 percent for a 3/4 in. mixture (16).

A general concept in the design of paving mixtures is to use as much asphalt as possible without undue loss of stability (16). Therefore, from the Jimenez mehtod the recommended asphalt content is 5.0 percent which corresponds to a 2.5 percent air void value and 7 microns asphalt film thickness, which is between the recommended values of 6-12 microns (16).

The design asphalt content to be used is generally established through laboratory tests for stability and durability. The Marshall Method of mix design was used to determine the optimum asphalt content for the aggregate combination (15). Specimens 4 inches in diameter by 2-1/2 inches high were prepared for four different asphalt contents of 4.5, 5.0, 5.5, and 6.0 percent by weight of total mix. Compaction was accomplished using the Marshall hammer (impact load) with 75 blows on each end of the specimen, delivered by a 10 lb. weight falling 18 inches. Photographic illustrations of this compaction device are shown in Appendix B.

Mixing

The total weight for an individual test specimen was 1150 grams. For a given asphalt content it was a simple matter to determine the weight of each ingredient in the mixture. For example, for a 5 percent asphalt content the weight of asphalt and aggregate blend for a batch mix (to make 3 speciments) becomes:

Total Batch Weight = 3800 grams

Weight of Asphalt Cement = 0.05 X 3800 = 190 grams

Total Weight of Aggregate blend = 3800 - 190 = 3610 grams

Four batches of the aggregate combination for four different asphalt contents were weighed and placed in a 285°F oven. A can of asphalt cement was heated in a 275°F oven. After reaching the above temperatures, the aggregates were transferred into a preheated mixing bowl and tared on a beam balance. Then the required amount of asphalt was carefully poured onto the aggregates and then mixed using a mechanical mixer. The mixing time was 1-1.5 minutes to obtain complete coating.

After mixing, the mixture was divided into smaller pans, with enough in each to produce the required specimen height. Finally, the smaller pans were placed in a forced draft oven and heated to a temperature of 250° ± 5°F along with twelve compaction molds prior to compaction. It ordinarily took approximately one hour for all components to come to the desired compaction temperature.

Compaction

In preparing the test specimens, the Marshall compaction procedure was carried out as outlined in Reference (15). Compaction was accomplished by using a mechanical compactor with a hammer weighing 10 lb., dropped from a height of 18 inches with 75 blows on each face of the specimen.

Test Procedure

Following compaction, all specimens were extruded from the mold using an extrusion jack. Marshall test specimens were stored at ambient laboratory temperature of approximately 77°F for 24 hours to be ready for testing. Specimens were tested in the manner given in AASHTO Test Method T-245 (18). First, the height and density of each specimen was determined. The specimens were then placed in a 140°F water bath to be brought to test temperature. After 30-45 minutes, a specimen was removed from the water bath and placed in the lower testing head and the upper testing head was placed on top. The flow meter was placed over the guide rod and zeroed. Load was then applied to the specimen until failure. The maximum load at the point of failure was recorded as the Marshall Stability. The flow meter was removed from the guide rod and the specimen deformation was read as flow.

Design Asphalt Content

The stability-flow test coupled with the density-voids analysis provide the necessary data for selecting the optimum asphalt content. Prior to selecting the optimum asphalt content, it was necessary to prepare separate plots for each of the following values:

Percent Voids of Total Mix versus Asphalt Content
Percent VMA versus Asphalt Content
Stability versus Asphalt Content
Density versus Asphalt Content
Flow versus Asphalt Content

All of the plots depicting the results obtained in this investigation are shown in figures 6. The data for the curves shown in this figure are from Tables A.2, A.4, A.7 and A.9.

The recommended optimum asphalt content is determined by assigning criteria to certain of the test properties, selecting the asphalt content that satisfies each individual criterion and averaging the asphalt contents obtained. The average value is the optimum asphalt content. These criteria become part of the specification controlling the design of the mix. The criteria for satisfactory pavement design by the Marshall method were recommended by the Asphalt Institute for their specifications. The design criteria for asphaltic concrete are as follows:

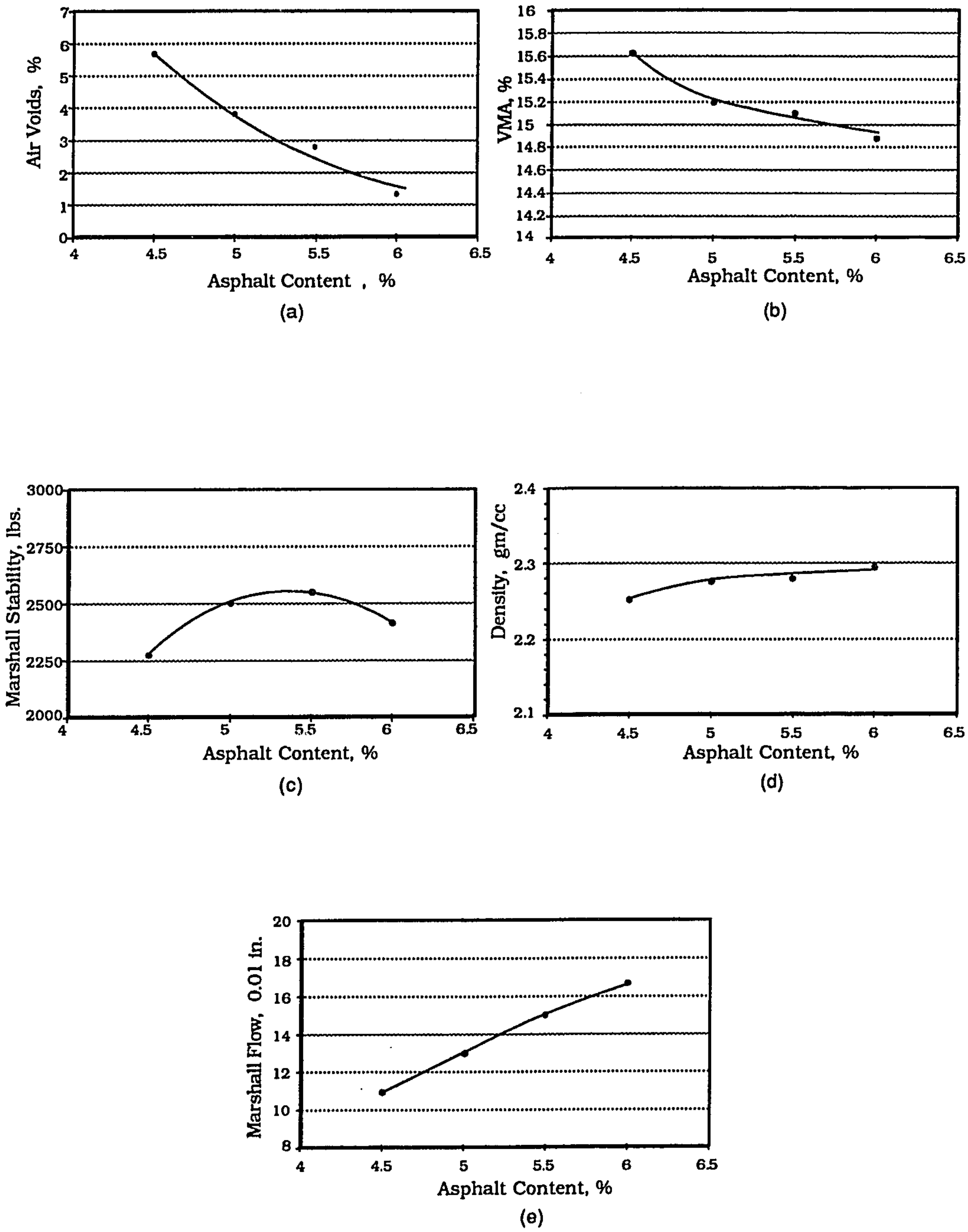

FIGURE 6 Marshall Test Results

Design Criteria for Asphaltic Concrete

Test Property	Limits	Value To Be Used For Selection of Optimum Asphalt Content
Stability	Min. of 1500 pounds	Maximum
Air Voids	3 to 5 percent	4
VMA	Min. of 14 percent	None specified
Density	No limits	Maximum
Flow	8 to 16 0.01 in	None specified

From Figure 6 the optimum asphalt content was as follows:

Asphalt content at maximum stability	5.4 percent
Asphalt content at maximum density	6.0 percent
Asphalt content providing 4 percent air voids in the total mix (median of 3-5 percent range)	4.9 percent
Optimum asphalt content taken as the numerical average of the above three items	5.4 percent

After the optimum asphalt content is determined, it is necessary to evaluate the satisfactoriness of the asphalt mixture with an asphalt content equal to the optimum. The test properties corresponding to the optimum asphalt content are determined and compared with the criteria established for governing the design of the mixture. From Figure 6 the test properties corresponding to the optimum asphalt content of 5.4 percent were as follows:

Stability at optimum asphalt content	2550	pounds
Air voids at optimum asphalt content	2.5	percent
VMA at optimum asphalt content	15.1	percent
Density at optimum asphalt content	2.280	gm/cc
Flow at optimum asphalt content	14.8	0.01 in

Comparison of the above test properties with the design criteria reveals that the stability value exceeds the minimum value of 1500, that the percent VMA value exceeds the minimum of 14, and that the flow value is within the limiting range of 8 to 16.

These three test properties are in reasonable agreement with the criteria, however, the percent air voids in the total mix is below the lower limit of 3. This deviation of 0.5 percent which exists between the percent air voids in the total mix and the lower limit permitted by the design criteria does require a redesign of the mix. Since the aggregate gradation and all other test properties are acceptable, it is impractical to redesign the mix because of this variation. However, the mix could be modified to increase the percent air voids in the total mix by simply reducing the asphalt content or the quantity of mineral filler, or both.

Accordingly, an optimum asphalt content of 5.0 percent was selected following the Jimenez method. From figure 6 the test properties corresponding to the optimum asphalt content of 5.0 percent were as follows:

Stability at optimum asphalt content	2504	pounds
Air voids at optimum asphalt content	3.81	percent
VMA at optimum asphalt content	15.2	percent
Density at optimum asphalt content	2.275	gm/cc
Flow at optimum asphalt content	13	0.01 in

Comparison of the above test properties with the design criteria reveals that the stability value exceeds the minimum value of 1500, that the percent of air voids is within the limiting range of 3 to 5, that the percent VMA value exceeds the minimum of 14, and that the flow value is within the limiting range of 8 to 16.

Comparison of the results obtained in Figure 6 with the general trends in the test properties of asphaltic concrete mixtures observed over a period of time with the Marshall method reveals good agreement with the general trends outlined in

Reference (15). However, of more significance is that the value of the optimum asphalt content obtained by the computer program agrees with the value determined by laboratory testing which is 5.0 percent. This value satisfies all the requirements indicating that the durability of the mix is good and that there won't be any detrimental effects on the pavement. It should be noted as expected that the VMA values obtained by laboratory testing were higher than the value obtained by the computer program.

Loose Mixture Specific Gravity

Using the standard test AASHTO T-209 (18) the maximum specific gravity test was performed. This is commonly referred to as the Rice or voidless density. The effective specific gravity (E.S.G.) of the aggregate was calculated from the Rice specific gravity. The effective specific gravity value results in consideration of the unit aggregate volume excluding the aggregate's pore permeable to asphalt.

$$\text{E.S.G.} = \frac{\%\ \text{Aggregate}}{\dfrac{100}{\text{Rice S.G.}} - \dfrac{\%\ \text{Asphalt}}{\text{Asphalt S.G.}}}$$

Results of this test were as follows:

Mixtures	% Asphalt	Average Rice Specific Gravity(gm/cc)	Average Effective Specific Gravity(gm/cc)
A	4.5	2.387	2.549
A	5.0	2.365	2.542
A	5.5	2.344	2.536
A	6.0	2.320	2.526
B	5.5	2.365	2.564

CHAPTER 5

TEST RESULTS AND DISCUSSION

Several factors affecting asphaltic concrete mixture properties were studied and combinations of these factors were evaluated as to their influence on void content, VMA, density and stability.

These factors included:

(1) Compactive Effort

(2) Compaction Temperature

(3) Mixing Temperature and

(4) Asphalt Content.

In this investigation, the aforementioned factors were varied systematically as shown in Table 1 to obtain a parametric study of the influencing factors.

The discussion of the test results is presented in this chapter in sections entitled:

(a) Effects of Compactive Effort on Mix Properties

(b) Effects of Compaction Temperature on Mix Properties

(c) Effects of Mixing Temperature on Mix Properties

(d) Effects of Asphalt Content on Mix Properties

Tabulations of laboratory test results are shown in Tables A.2 through A.10 of Appendix A. Graphs of selected data will be presented in this chapter.

Effects of Compactive Effort on Mix Properties

In this investigation, the effect of compactive effort on the properties of bituminous mixtures was measured in terms of voids in the aggregate (VMA) of the final compacted mix. Variables that could control the void content of any compacted asphaltic mix are:

(1) asphalt content

(2) mixture temperature at time of compaction

(3) mixing temperature and

(4) compactive effort produced from either long-term traffic densification or the compaction equipment during construction.

Epps and others (1), in their study on the long-term compaction of asphalt concrete, show that 85 percent of the samples examined did not gain the required 95 percent of the laboratory density during the construction period. Also, the void content throughout the test section ranged from about 3 to 18 percent after one week of opening to traffic.

The laboratory investigation for this project was based on three different compactive efforts of 20, 75, and 110 blows per face of Marshall specimen.

The results of the present investigation are listed in the tables of Appendix A are plotted in Figures 7 through 22.

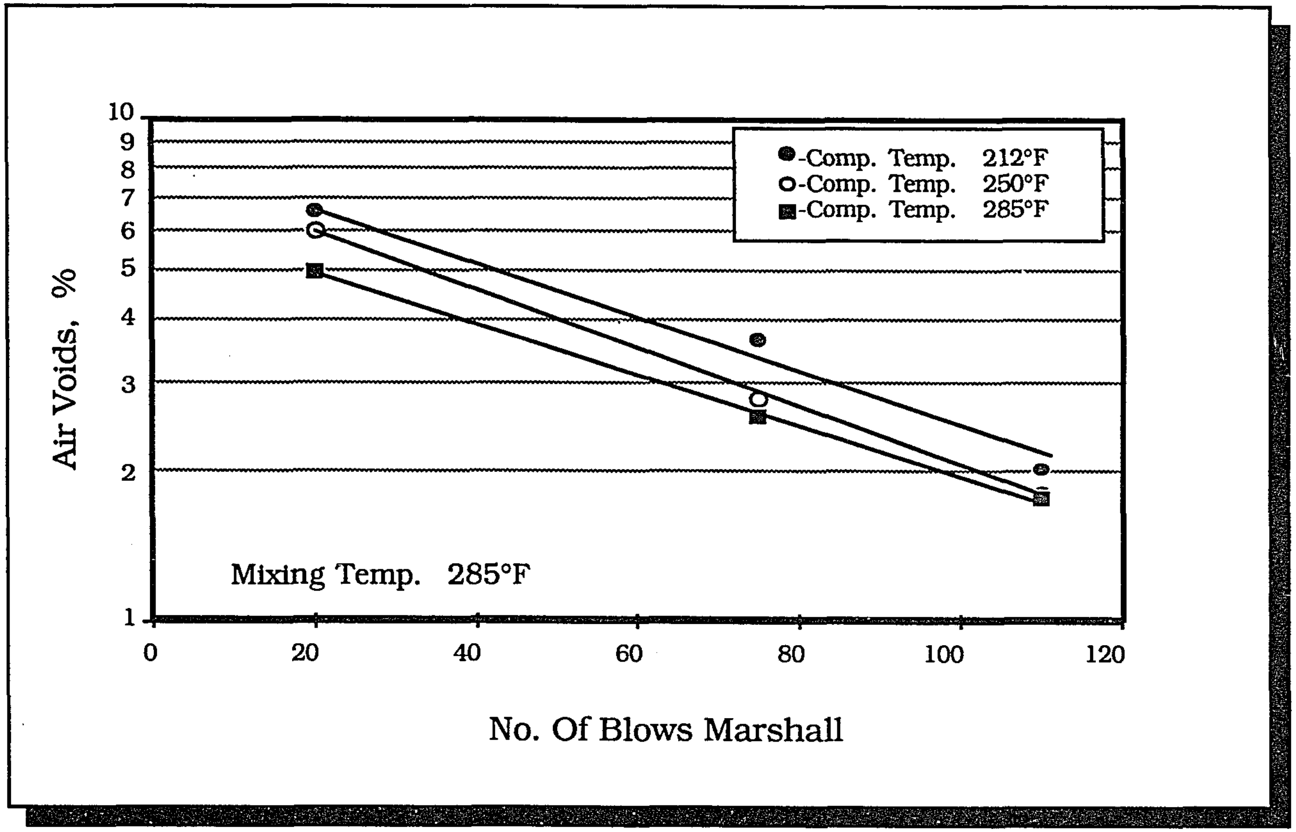

FIGURE 7 Effects of Compactive Effort And Compaction Temperature on Void content.

MIX "A", 5.5% Asphalt

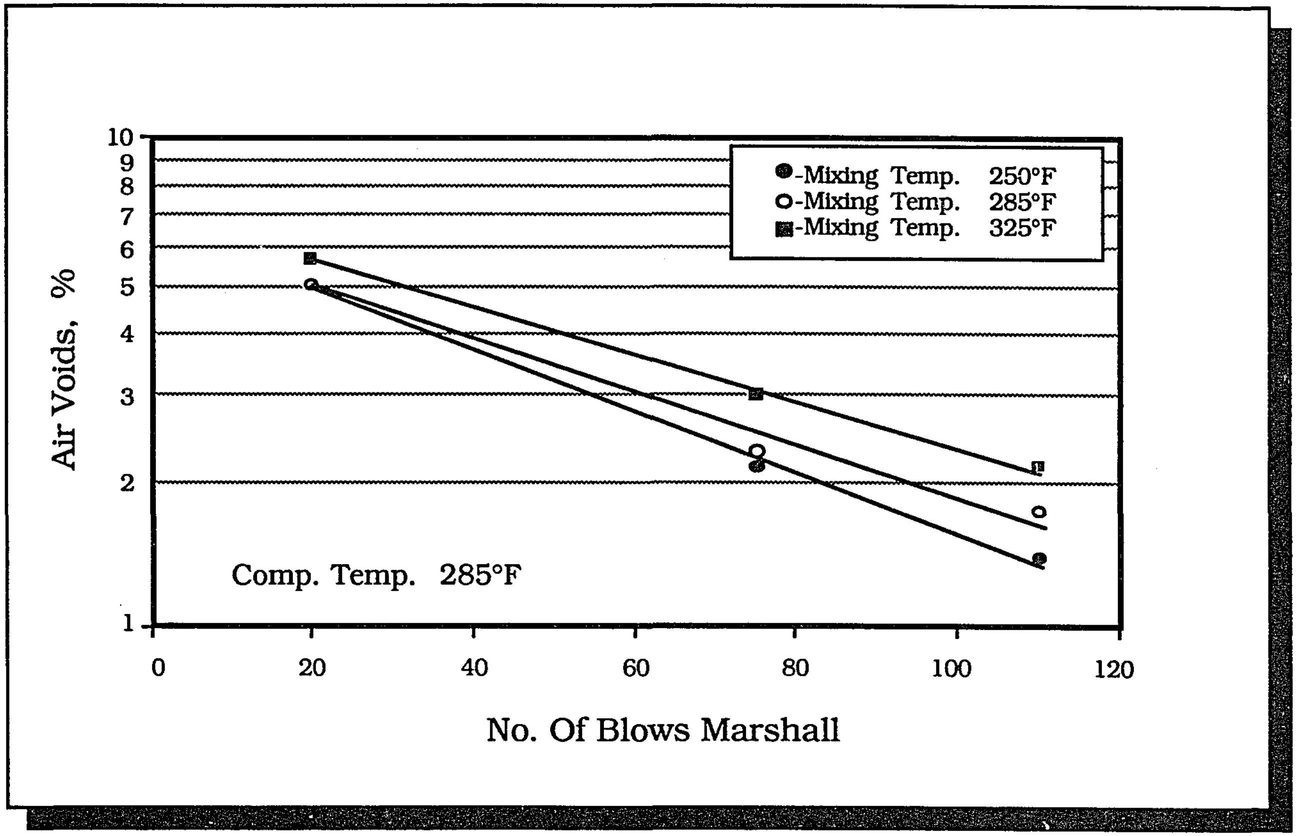

FIGURE 8 Effects of Compactive Effort And Mixing Temperature on Void content.

MIX "A", 5% Asphalt

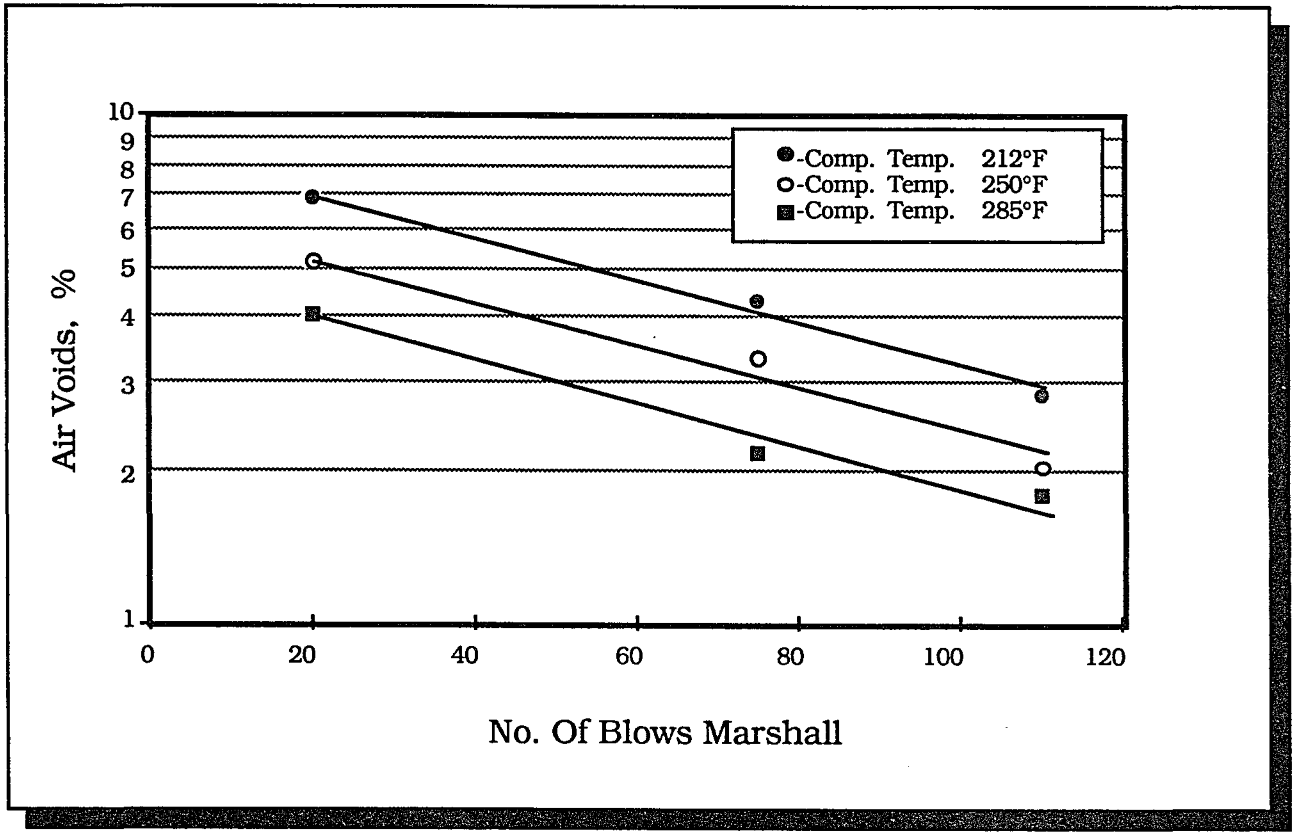

FIGURE 9 Effects of Compactive Effort And Compaction Temperature on Void content.

MIX "B" , 5.5% Asphalt

As shown in Figures 7 to 9, the percent of air voids decreased as the compactive effort increased. These Figures show that a straight line relationship may exist when percent air voids on the logarithmic ordinate is plotted versus the number of Marshall compaction blows as the arithmetic abscissa on a semi-logarithmic chart. Figure 7 is presented to show the effects of compactive effort on void content for Mix A. This figure was plotted for a mixing temperature of 285°F, an asphalt content of 5.5 percent and for different compaction temperatures. A review of the data in Appendix A reveals that similar trends were obtained for all mixing temperatures. For example, for 5.0 percent asphalt content and a compaction temperature of 250°F the percent air voids were as follows:

COMPACTIVE EFFORT B/F	MIXING TEMPERATURE °F		
	250	285	325
20	**5.95**	**6.35**	**6.90**
75	**3.25**	**3.81**	**4.45**
110	**2.24**	**2.35**	**3.10**

It is evident from the above data that similar trends were obtained for all mixing temperatures. Comparison of these results with the data in Figure 7 reveals good agreement which indicates that 5.0 and 5.5 percent asphalt content also gave similar results. Figure 8 demonstrates the increase in percent air voids when compactive effort was decreased for a compaction temperature of 285°F, an asphalt content of 5.0 percent and for different mixing temperatures. Figure 9 is presented to show the decrease in air voids when compactive effort is increased for Mix B. Comparison of this figure with Figure 7 reveals that the two mixtures gave similar trends. For example, the percent air voids obtained for the two mixtures for a compaction temperature of 250°F and 5.5 percent asphalt were as follows:

COMPACTIVE EFFORT B/F	MIXTURE A	MIXTURE B
20	6.01	5.14
75	2.80	3.34
110	1.80	2.05

Similar trends were also obtained for the VMA values, as can be seen from Figures 10 to 12. In these Figures, the VMA values decreased when the compactive effort was increased.

Density increased when compactive effort was increased. This is illustrated in Figures 13 to 16. Figure 13 is plotted for a mixing temperature of 285°F. However, all mixing temperatures gave similar results for varying compaction temperatures. For instance, for 5.0 percent asphalt content and a compaction temperature of 285°F the density values were as follows:

COMPACTIVE EFFORT B/F	MIXING TEMPERATURE °F 250	285	325
20	2.245	2.246	2.231
75	2.315	2.311	2.295
110	2.332	2.323	2.315

It is evident from the data above that density increased as compactive effort was increased. Figure 14 is presented to show the effects of compactive effort on density for a compaction temperature of 250°F and for varying mixing temperatures. This figure shows that a straight line relationship exists when density on the arithmetic ordinate is plotted versus the number of Marshall blows as the arithmetic abscissa. A further examination of Figure 14 indicates that the straight line relationships are parallel. Figure 15 also demonstrates that densities versus number of blows plot as a straight line on semi-logarithmic paper. Densities are represented by the arithmetic ordinate, while the number of blows are plotted as the logarithmic abscissa. This is similar to other sutdies but it is of no advantage for this work. From Figures 13 and 16 it is evident that they show similar trends for mixtures A and B.

Similar trends were also obtained for stability as illustrated in figures 17 to 20. Stability increased when compactive effort was increased. Marshall stabilities versus number of blows by the Marshall double compactor plot as a straight line on double logarithmic paper. Stabilities are represented by the logarithmic ordinate, while the number of blows are plotted as the logarithmic abscissa.

In an attempt to develop a relationship between stability and compactive effort, within the range of concern in this investigation, the data obtained for all asphalt contents were considered rather than just for the optimum asphalt content of 5.0 percent.

Stability was plotted against number of Marshall compaction blows, for each asphalt content on double logarithmic paper. The data for all plots were obtained form Tables A.3 to A.8. In all cases it was possible to draw a straight line through the plotted points. The plots are shown in Figures 17 to 20. A critical

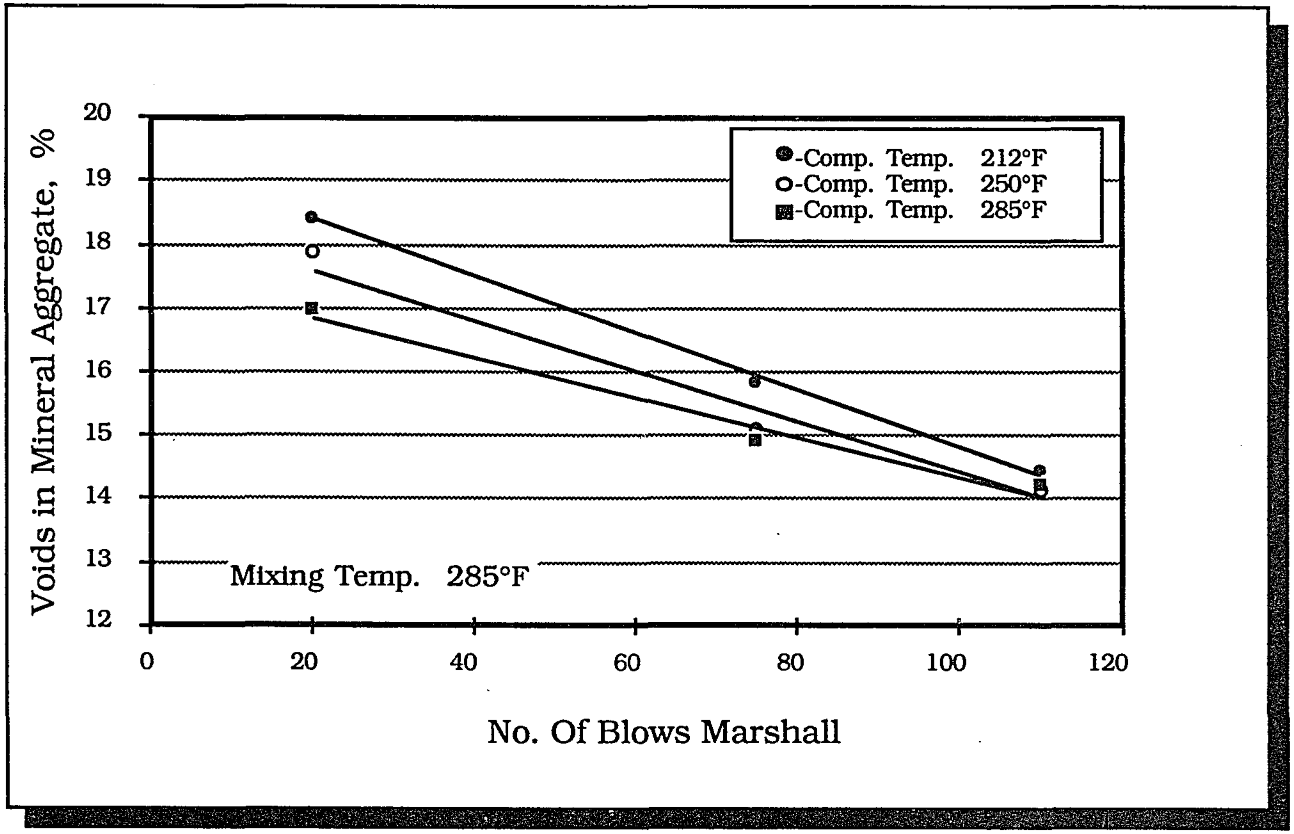

FIGURE 10 Effects of Compactive Effort And Compaction Temperature on VMA

MIX "A", 5.5% Asphalt

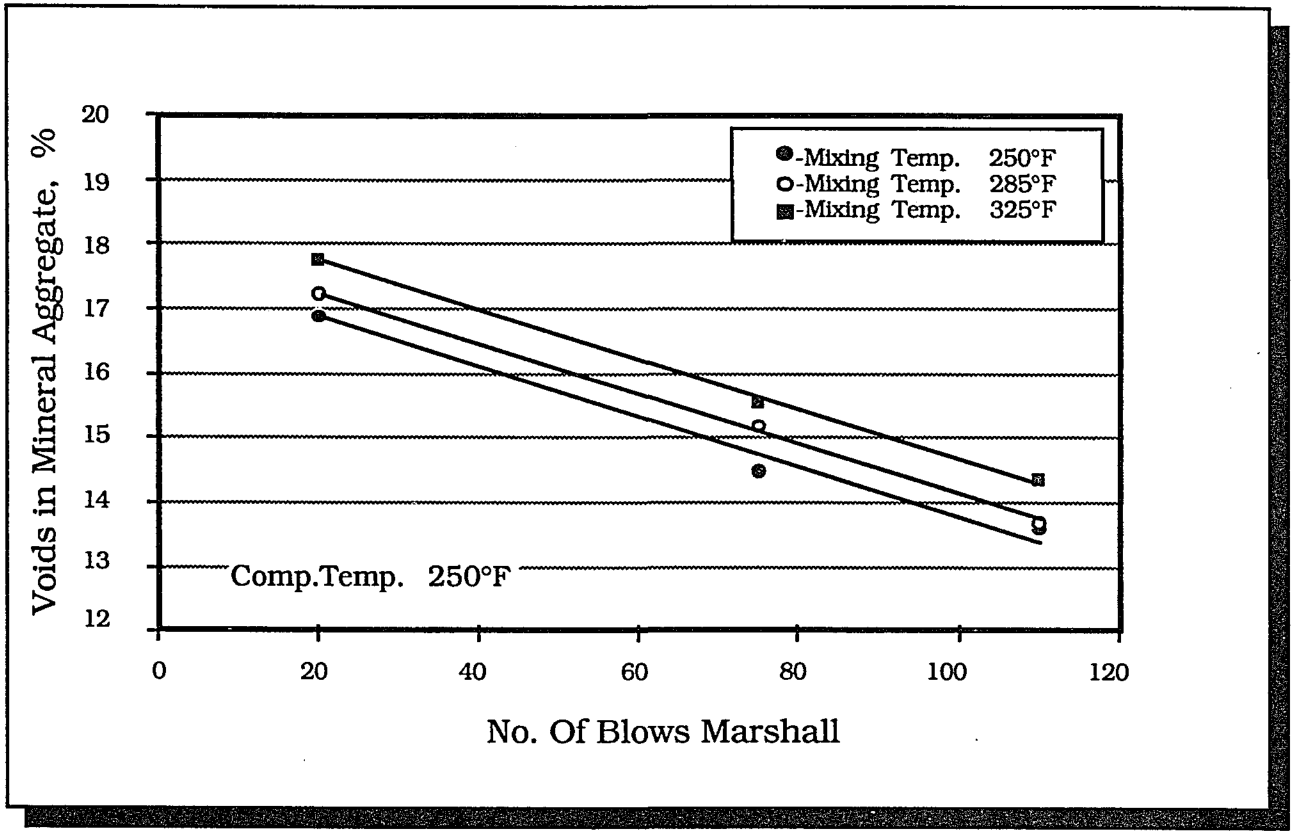

FIGURE 11 Effects of Compactive Effort And Mixing Temperature on VMA

MIX "A", 5% Asphalt

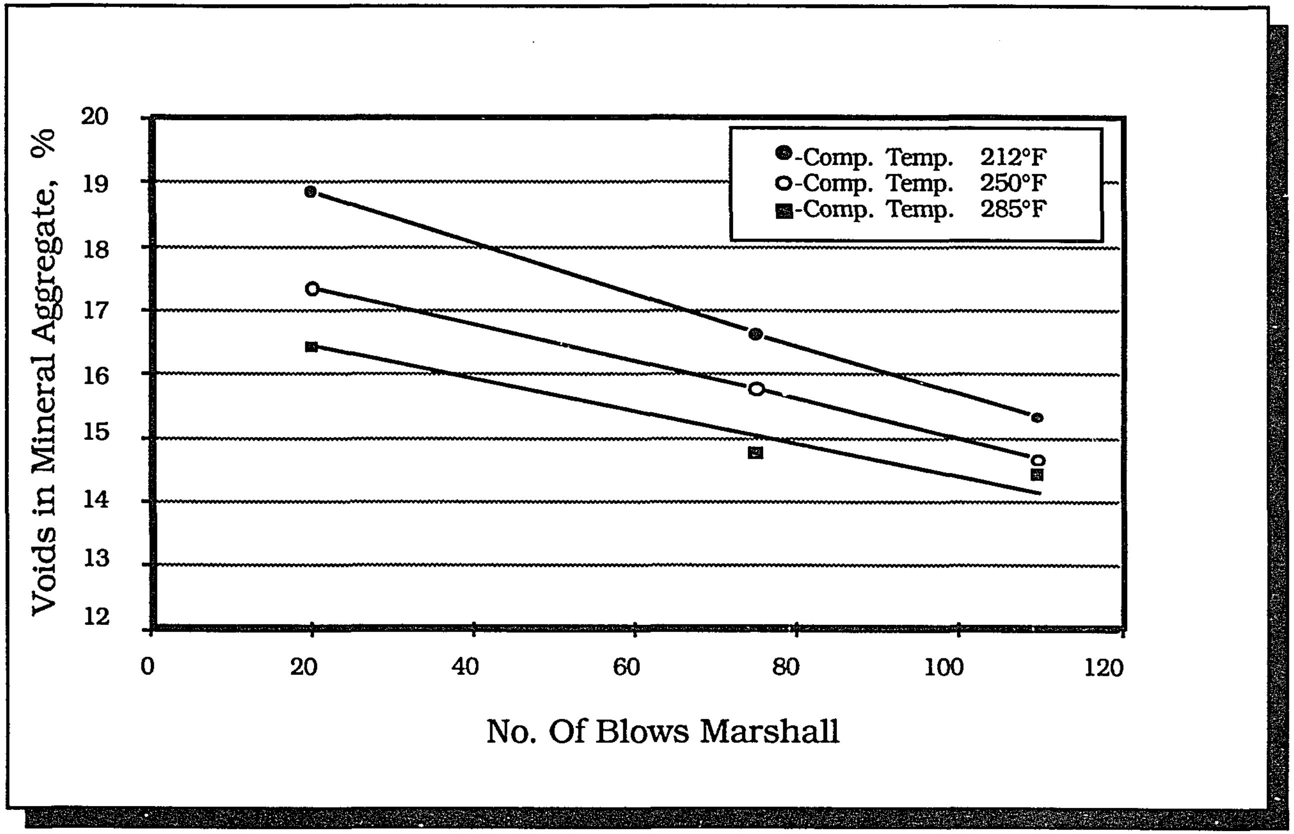

FIGURE 12 Effects of Compactive Effort And Compaction Temperature on VMA

MIX "B", 5.5% Asphalt

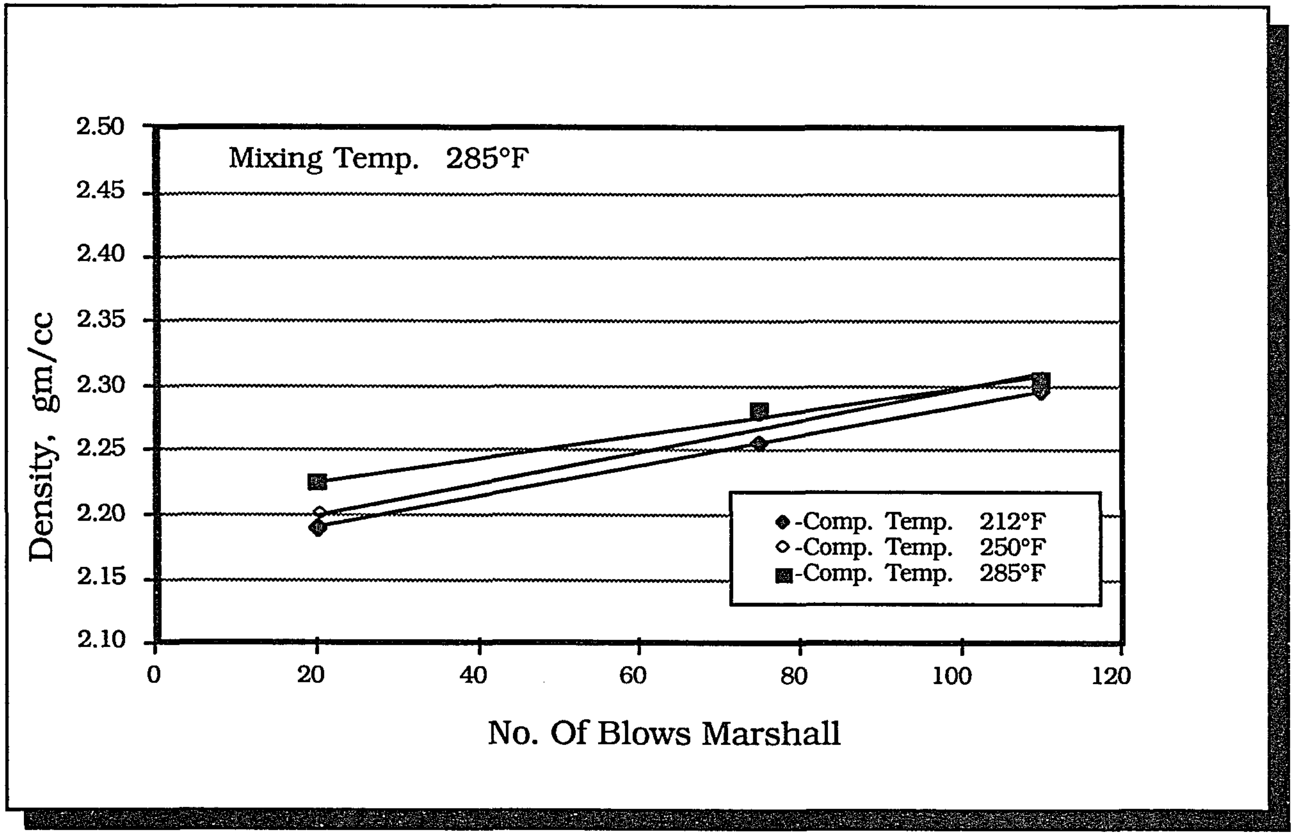

FIGURE 13 Effects of Compactive Effort And Compaction Temperature on Density

MIX "A", 5.5% Asphalt

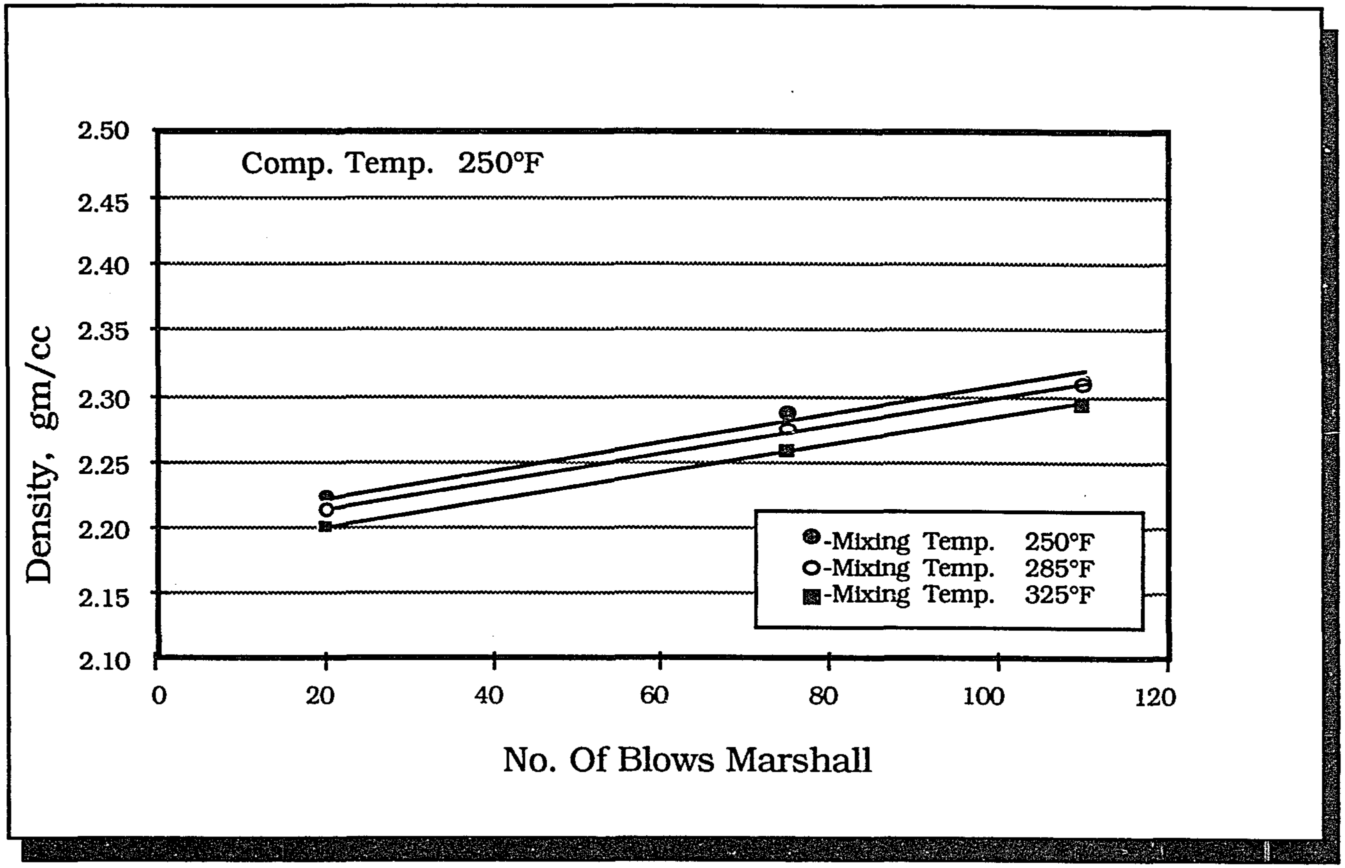

FIGURE 14 Effects of Compactive Effort And Mixing Temperature on Density

MIX "A", 5% Asphalt

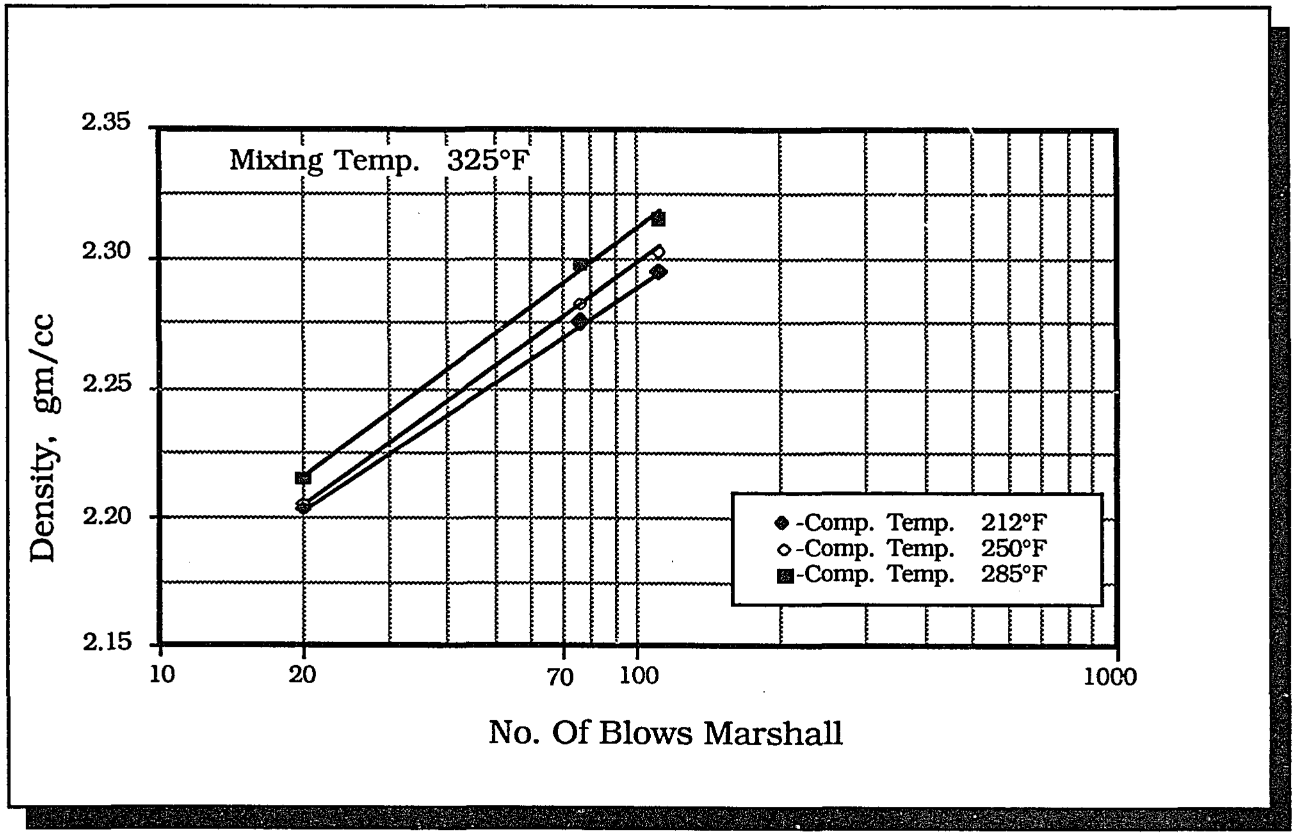

FIGURE 15 Effects of Compactive Effort And Compaction Temperature on Density

MIX "A", 5.5% Asphalt

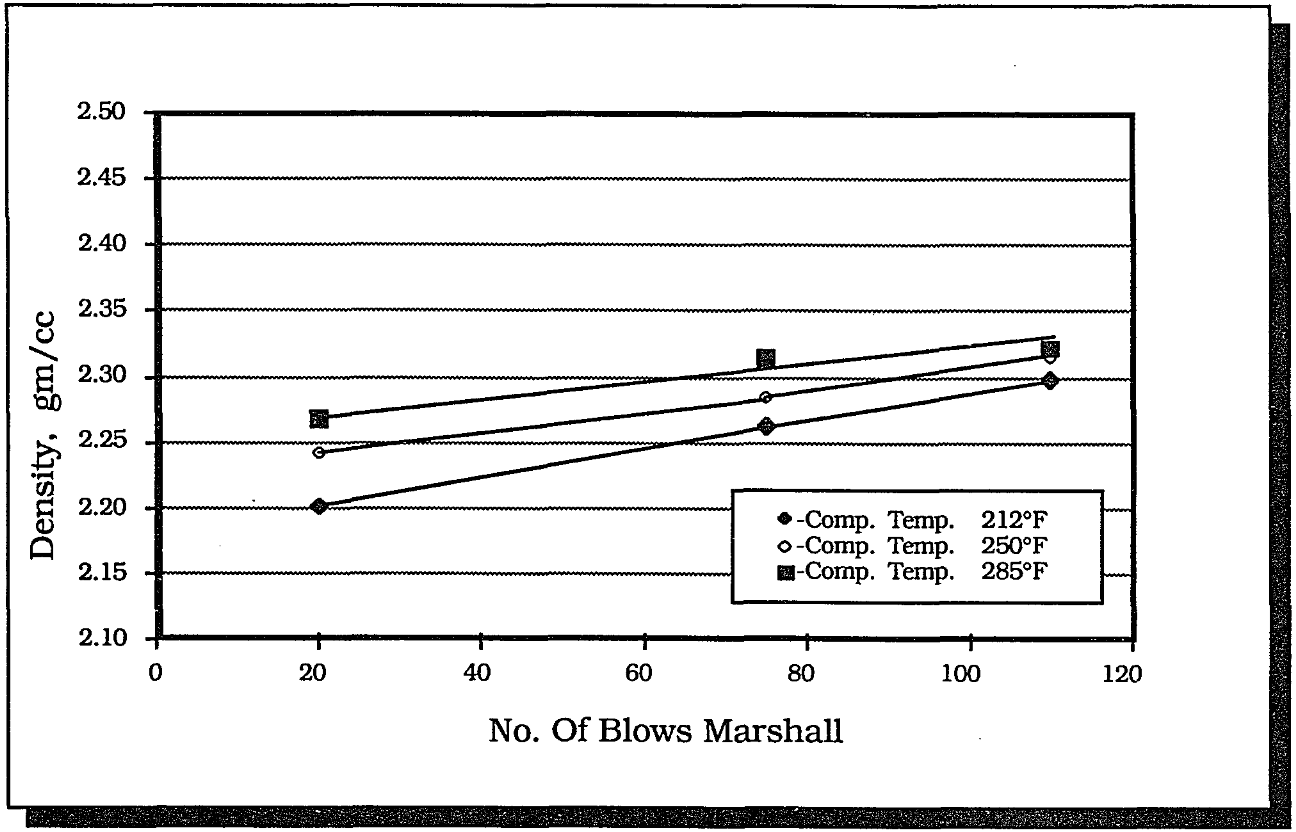

FIGURE 16 Effects of Compactive Effort And Compaction Temperature on Density

MIX "B", 5.5% Asphalt

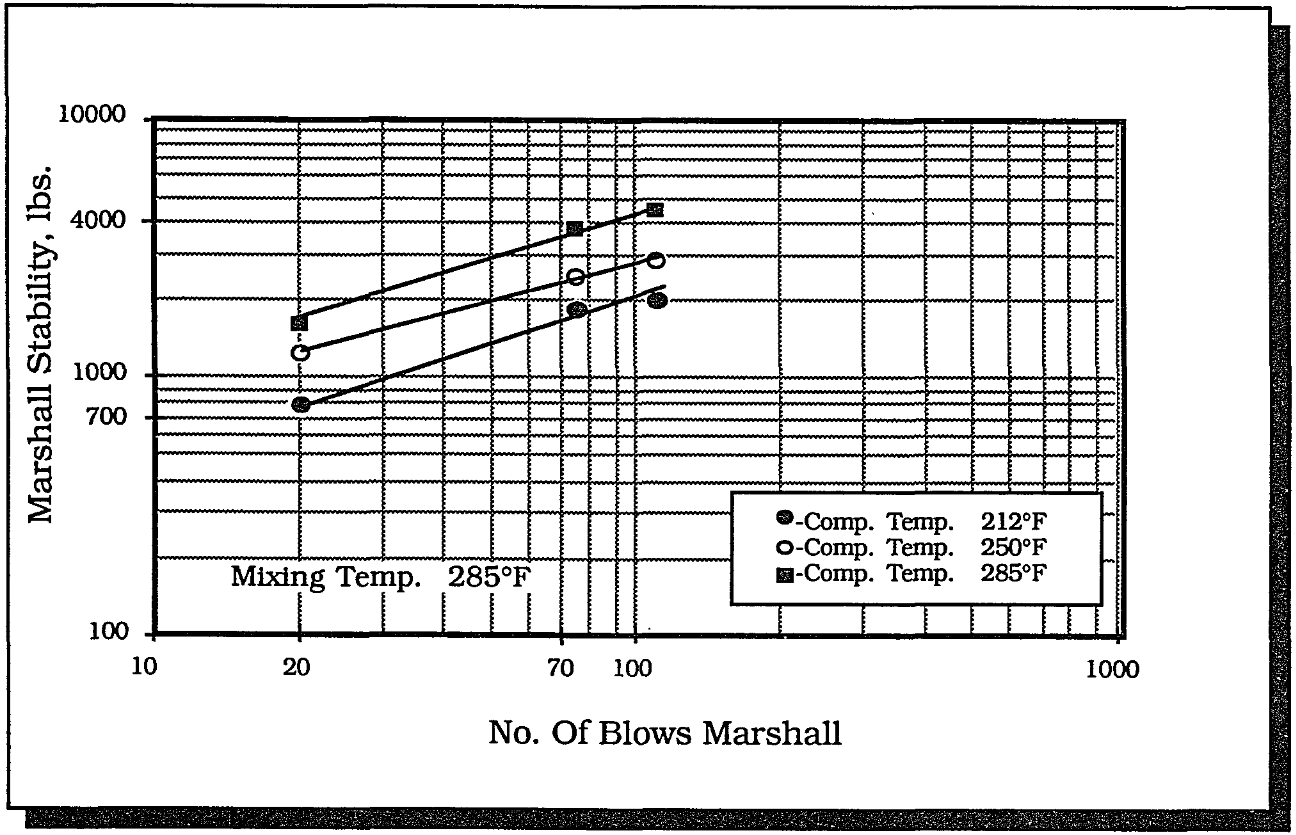

FIGURE 17 Effects of Compactive Effort And Compaction Temperature on Marshall Stability

MIX "A", 5% Asphalt

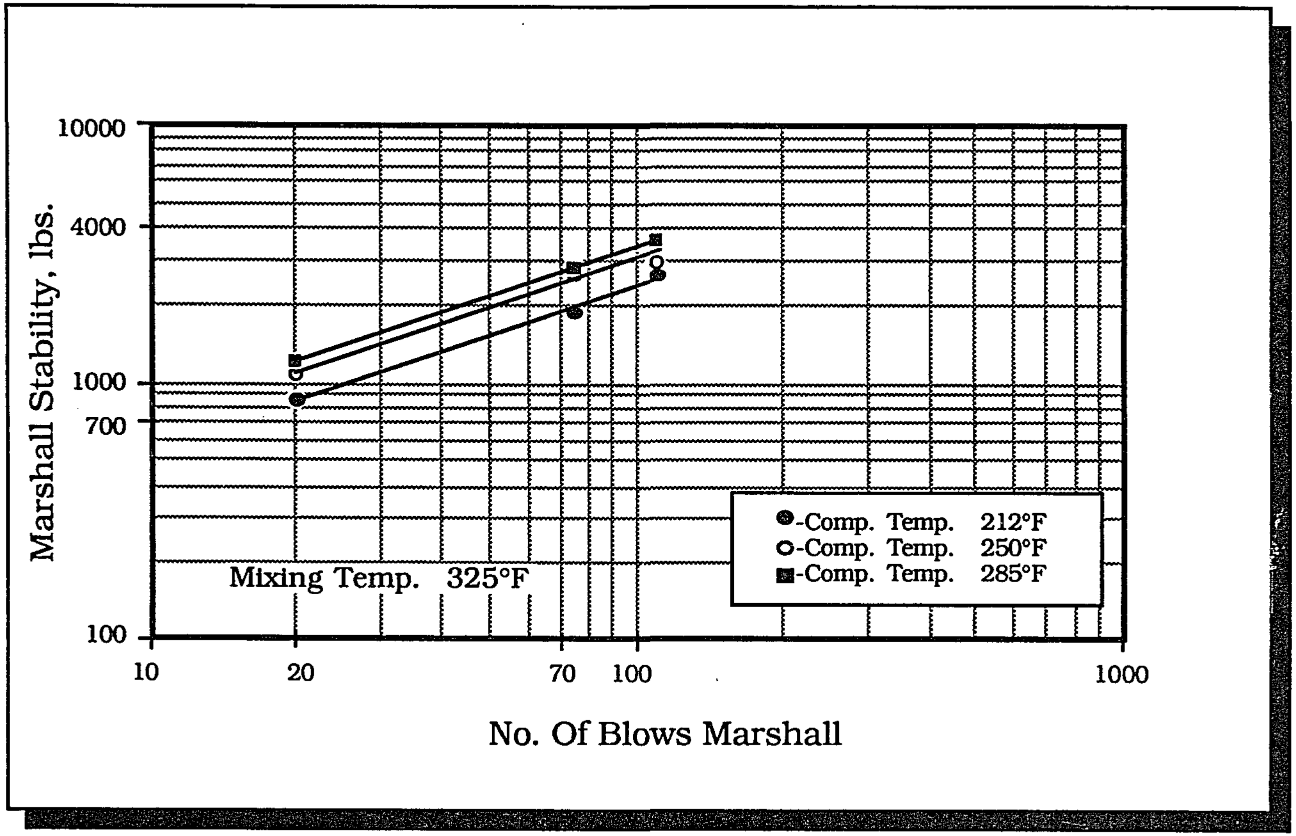

FIGURE 18 Effects of Compactive Effort And Compaction Temperature on Marshall Stability

MIX "A", 5.5% Asphalt

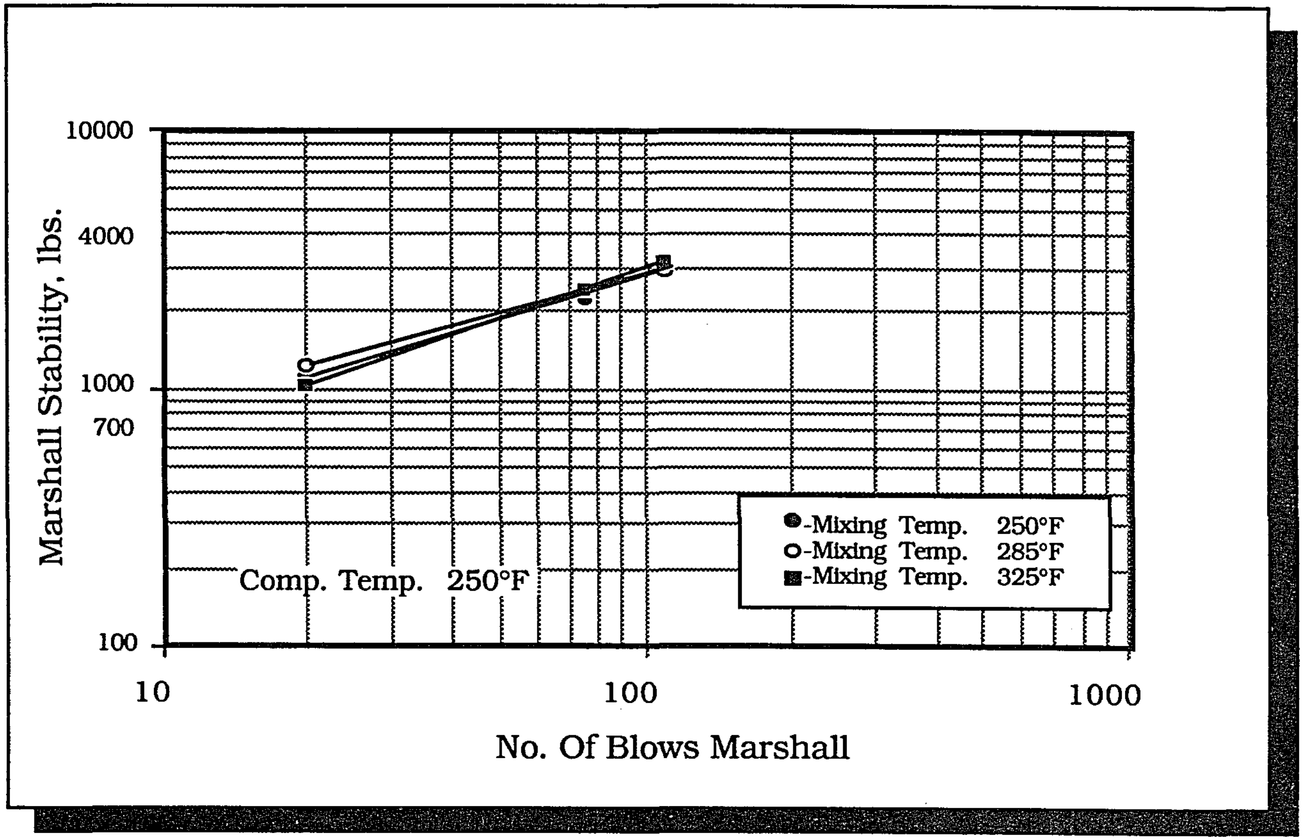

FIGURE 19 Effects of Compactive Effort And Mixing Temperature on Marshall Stability

MIX "A", 5% Asphalt

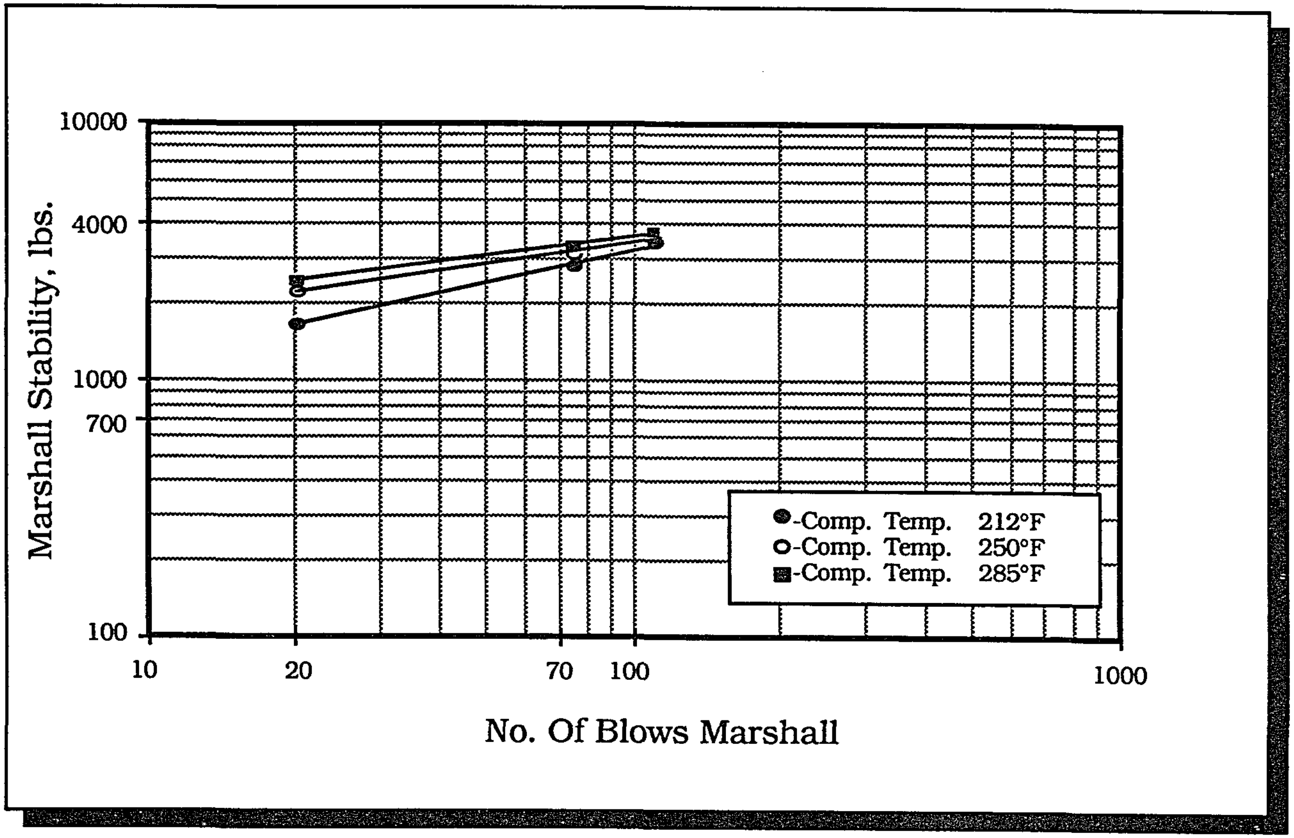

FIGURE 20 Effects of Compactive Effort And Compaction Temperature on Marshall Stability

MIX "B", 5.5% Asphalt

examination of all plots indicates that no plotted point deviates from the straight line drawn by more than 6 percent, and, with the exception of a few points, the deviation does not exceed 2 percent. These values are within the experimental error.

Since the plot of stability versus compactive effort is a straight line on double logarithmic paper, the equation defining this straight line is of the following form:

$$\text{Log } S_N = a \text{ Log } N + \text{Log } B$$

where:

S_N = Marshall stability

N = Number of blows within the range of 20 to 110 blows per face of specimen.

a,B = Material constants

To develop the empirical formulas defining the stability-compactive effort relationship, the constants a and Log B were obtained in the standard manner. Two points on the straight line with well defined coordinates for each point are substituted separately in the general expression which results in two simultaneous equations. The two equations are solved for the unknowns a and Log B.

The general equation defining a straight line on double logarithmic paper is derived below, and the standard compactive effort of 75 blows per face is selected as the specific compactive effort.

$$\text{Log } S_N = a \text{ Log } N + \text{Log } B$$

$$\text{Log } S_{75} = a \text{ Log } 75 + \text{Log } B$$

$$\text{Log } S_N/S_{75} = a \text{ (Log } N/75)$$

$$S_N = 10^{a \text{ (Log } N/75)} S_{75}$$

The average value of a for all compaction temperatures is 0.566. Therefore the empirical formula expressing the relationship between the stability at any compactive effort, within the range of 20 to 110, in terms of the standard stability at 75 blows per face becomes,

$$S_N = 10^{.566\,(\mathrm{Log}\,N/75)} S_{75}$$

$$S_N = 3.68^{(\mathrm{Log}\,N/75)} S_{75}$$

It is noted here that there is much less need to consider the effect of compactive effort on flow value since this quantity is dependent almost entirely on the binder (asphalt + filler) content of the mix (3,4). However, plots of Flow values versus compactive effort are shown in Figures 21 and 22.

Effects of Compaction Temperature on Mix Properties

It is well known that compaction temperature along with compactive effort are the most important variables in asphaltic concrete design. In some instances, it is believed that variance in the allowable time for compaction has led to failure of asphaltic concrete mixtures.

The effect of compaction temperature on the properties of asphaltic concrete mixtures was studied over different compaction temperatures of 212°, 250° and 285°F.

Figures 7,8,9,10 and 12 graphically illustrate the changes that take place in mix properties as the compaction temperature increases. The cooler the mix before compaction, and consequently, the more viscous its asphalt cement, the larger the percent air voids and VMA values.

Compacting a particular mixture at 212°F gave air voids almost 2 times larger than those that obtained when the mixture was compacted at 285°F. For example, for 5 percent asphalt content and a mixing temperature of 285°F the percent

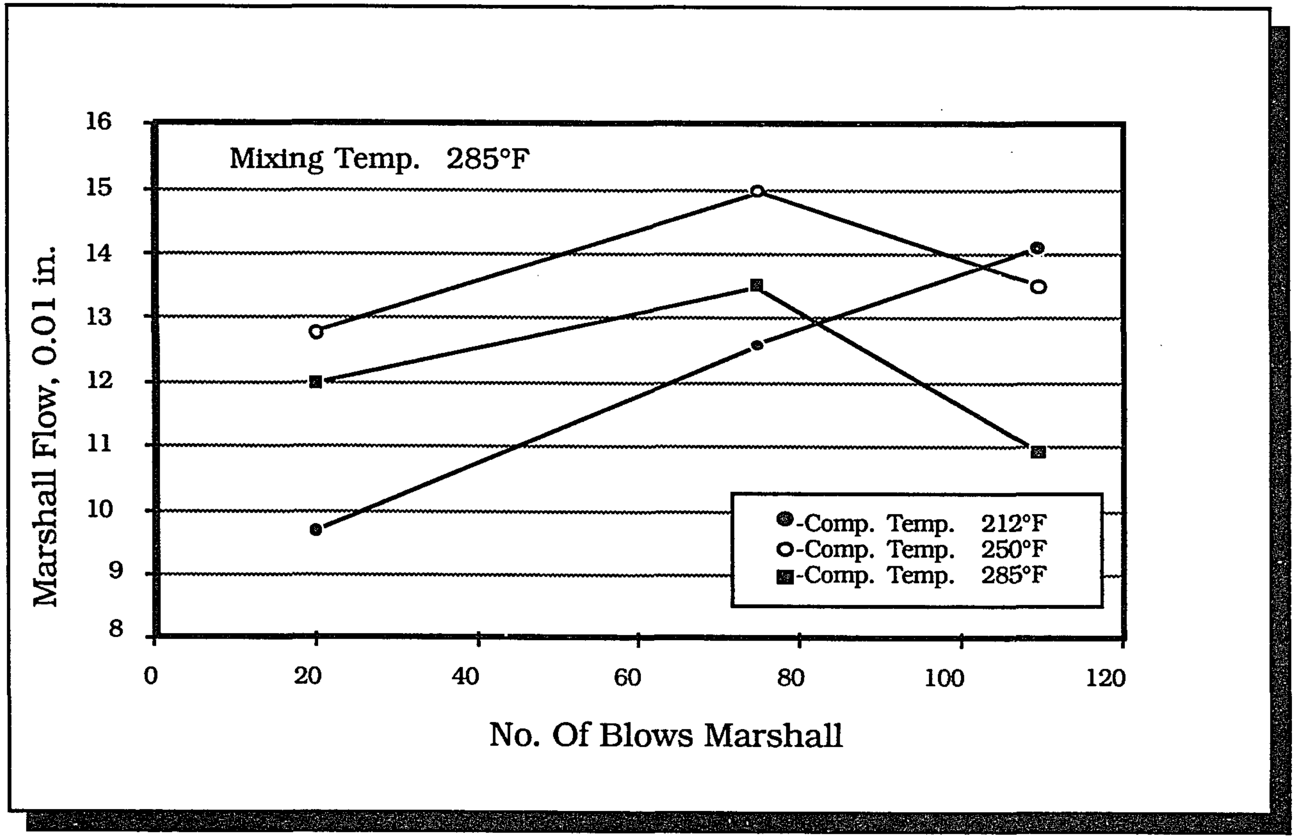

FIGURE 21 Effects of Compactive Effort And Compaction Temperature on Marshall Flow

MIX "A", 5.5% Asphalt

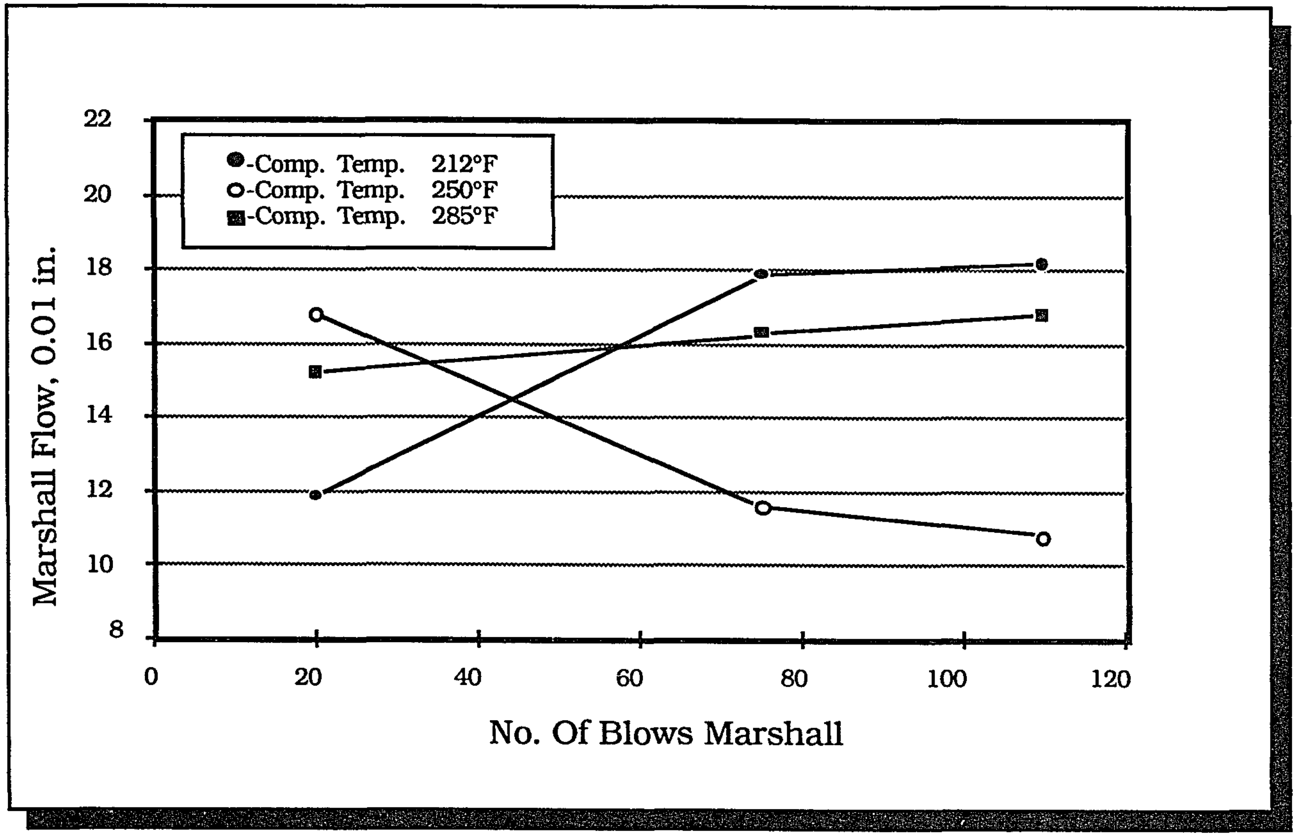

FIGURE 22 Effects of Compactive Effort And Compaction Temperature on Marshall Flow

MIX "B", 5.5% Asphalt

air voids were as follows:

COMPACTIVE EFFORT B/F	COMPACTION TEMPERATURE °F		
	212	250	285
20	**8.30**	**6.35**	**5.05**
75	**4.35**	**3.81**	**2.30**
110	**4.00**	**2.35**	**1.75**

This is also illustrated in Figures 7 and 9 for mixtures A and B for 5.5 percent asphalt. In these figures as well as in the tables of Appendix A, the percent air voids decreased when compaction temperature was increased. It is evident from figures 7 and 9 that similar trends were obtained for mixtures A and B. Similar trends were also obtained for VMA values as illustrated in Figures 10 and 12. In these figures, the VMA values decreased when temperature at compaction was increased.

Considerably higher densities were obtained as the molding temperatures of the Marshall specimens increased. Thus, if the compaction temperature of the mix is increased, the viscosity of the asphalt is reduced and compaction is made easier. This effect is illustrated in Figures 13, 15 and 16. From Figures 13 and 16 it is evident that the densities were very close for the two mixtures A and B. This means that coarse aggregate mixes can be laid at the same temperatures as fine aggregate mixes. Similar trends were obtained for the stability values as demonstrated in Figures 17, 18 and 20. In these figures the stability of the mix increased with increasing compaction temperature. Compacting a mixture at 285°F gave a stability value approximately twice the value when the mixture was compacted at 212°F. For example, for 5.0 percent asphalt content and mixing temperature of 285°F, the stability values were as follows:

COMPACTIVE EFFORT B/F	COMPACTION TEMPERATURE °F		
	212	250	285
20	**777**	**1260**	**1590**
75	**1872**	**2504**	**3727**
110	**2027**	**2908**	**4446**

From Figures 18 and 20 it is clear that higher stabilities were obtained for Mix A than for Mix B, all other conditions being equal. This means that Mix B can be laid at a lower temperature than Mix A.

Compaction temperatures, not mixing temperatures, should determine the compaction attained. On the basis of the temperatures used, it is difficult to recommend an optimum compaction temperature. However, 250°F appears to be an acceptable compaction temperature that would satisfy all the mix properties.

Effects of Mixing Temperature on Mix Properties

The effect of mixing temperature was also investigated as illustrated in Figures 8,11,14 and 19. Laboratory tests were performed on specimens prepared at three different mixing temperatures, 250°, 285°, and 325°F. For mixing times of from 60 to 90 seconds, coating of aggregate was complete at all mixing temperatures. It is possible that the mixing time was greater than that needed for the mix viscosities normally used and that the temperature effect was obscured. Reduction in mixing time might have brought about incomplete mixing at the higher asphalt viscosities.

Figure 8 shows that air voids values increased with increasing the mixing temperature, for a given number of Marshall blows.

Similar trends were also obtained for the VMA values, as can be seen from Figures 11 and 17. In Figure 11, the VMA values increased when the mixing temperature was increased for a given number of Marshall blows.

Density decreased when the mixing temperature was increased as illustrated in Figure 14. In this figure, higher densities were obtained on specimens mixed at lower temperatures than were obtained on higher temperature mixes.

A review of the data shows that the stability values in some cases increased when the mixing temperature was increased and in other cases stability values decreased with increasing the mixing temperature. However, from Figure 19 it is evident that mixing temperatures within the range studied had no major effect on stability. In this figure all data points for all mixing temperatures plotted as one straight line.

It is noted that the effect of mixing temperature on the properties of bituminous mixtures has been studied for many years. However, with the exception of viscosity effects on the hardening of the asphalt during mixing, few clear cut conclusions have been reached.

Effects of Asphalt Content on Mix Properties

Asphalt content generally has a strong effect on mix properties. The typical effect of asphalt content on the five basic mix properties, (air voids, VMA, stability, density and flow) are shown in Figures 23 to 27.

Among all variables of mix composition, adjustment of asphalt content is probably the most readily accessible means of altering stability (12). Specimens were prepared for asphalt contents of 4.5, 5.0, 5.5, and 6.0 percent by weight of total mix.

5.0 percent is the value of the optimum asphalt content that was established through laboratory tests for stability and durability.

Figures 23 to 27 graphically illustrate the changes that take place in mix properties as the asphalt content is changed from the minimum value of 4.5 percent to the maximum value of 6.0 percent. Figure 23 shows that the percent of air voids in the mix decreased when asphalt content was increased for all values of Marshall blows. The larger the asphalt content, the smaller the air void space.

Figure 24 shows that for 75 blows the percentage of voids in the mineral aggregates decreased as the asphalt content increased. VMA values were nearly equal and at the minimum at the two higher bitumen contents. However, for 20 and 110 blows the percent VMA increased when asphalt content was increased. This cannot be explained and could be a result of an error in testing.

In Figure 25, the value of stability rose until it reached a peak in the neighborhood of 5.5 percent asphalt and then decreased . This was true for 20 and 75 blows per face, however, for 110 blows per face the stability value decreased between 5.0 and 5.5 percent asphalt.

In all instances, the results indicated that the asphalt content was highly significant in affecting the increase in bulk density.

Figure 26 shows that for 75 blows the specimens with high asphalt contents densified more than the specimens with the low asphalt content. In this figure, the unit weight increased with no apparent peak as the asphalt content was increased. However, for 20 and 110 blows this is not apparent due to insufficient data.

Flow values steadily increased when asphalt content was increased as illustrated in Figure 27.

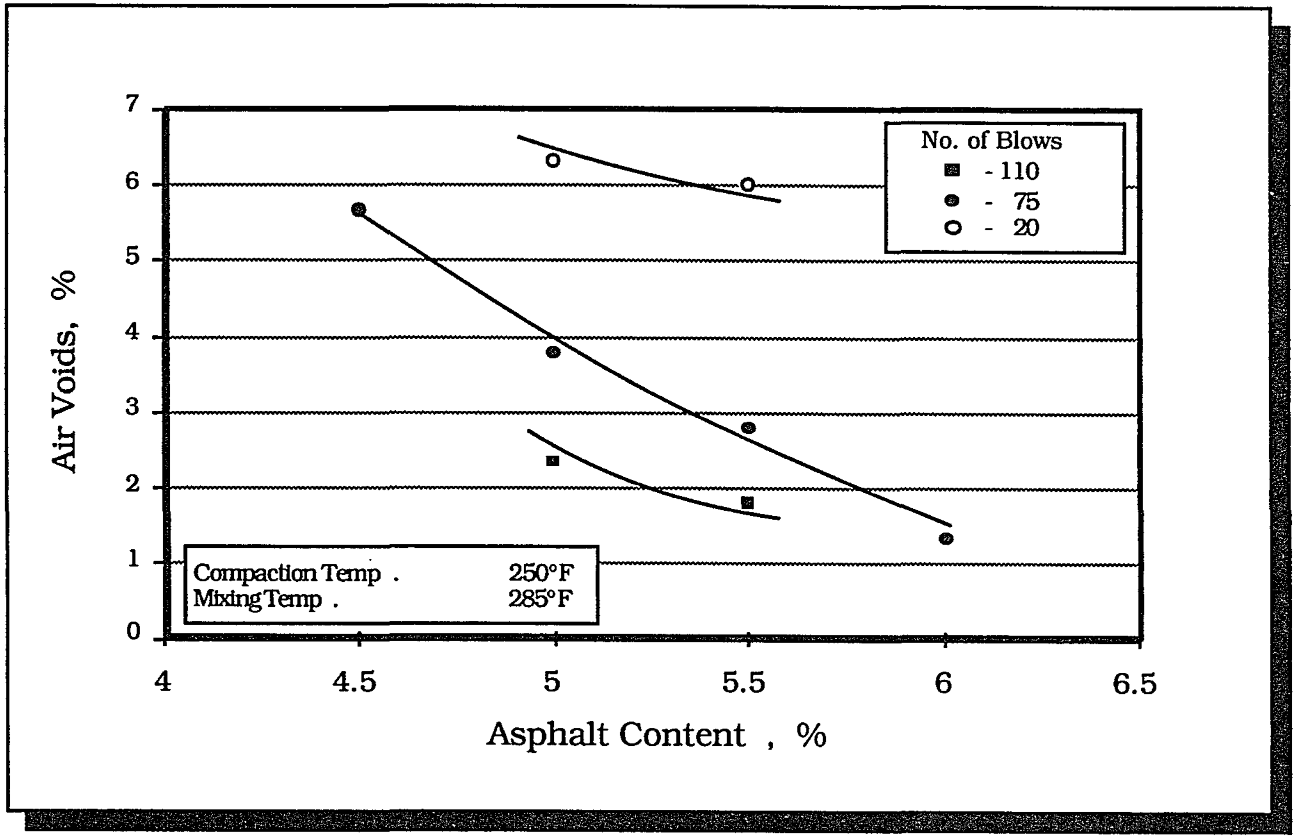

FIGURE 23 Effects of Asphalt Content on Air Voids.

MIX "A"

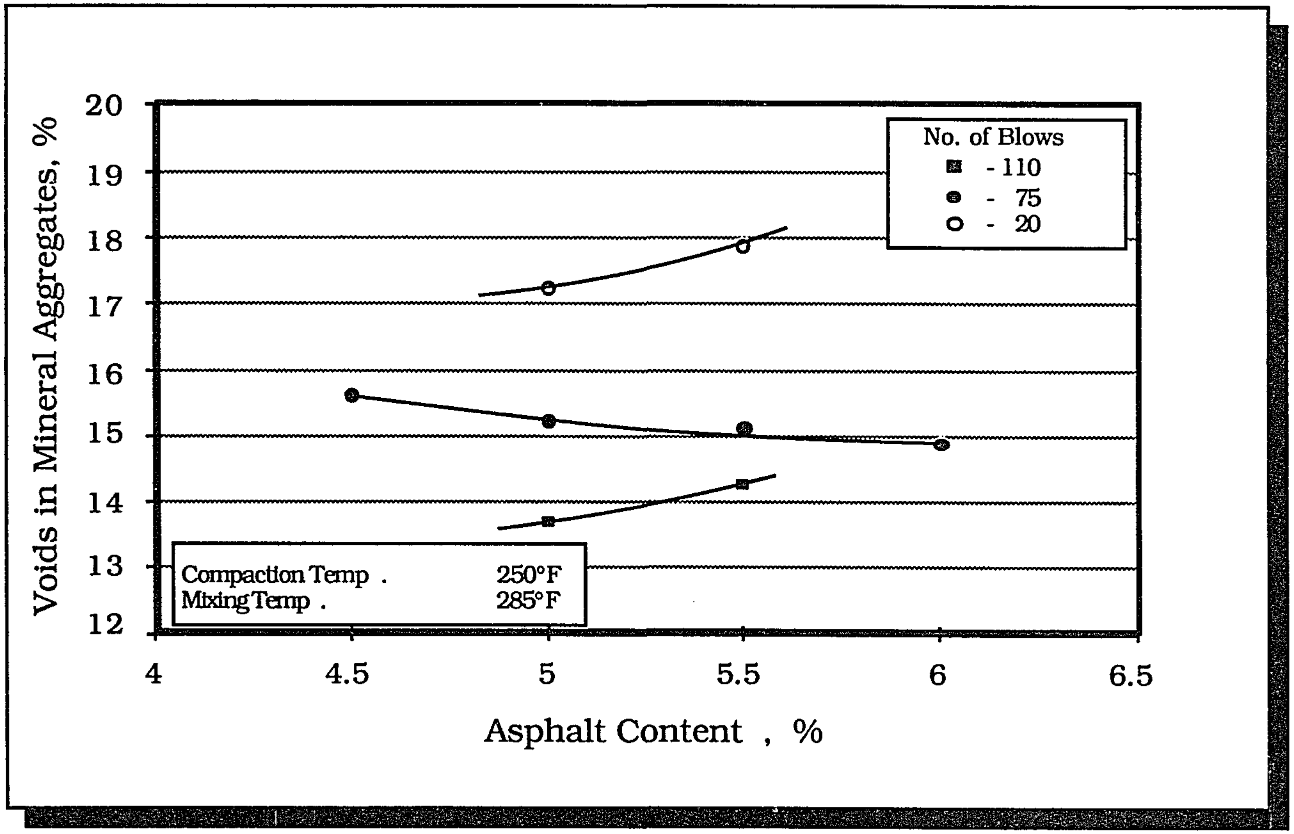

FIGURE 24 Effects of Asphalt Content on VMA.

MIX "A"

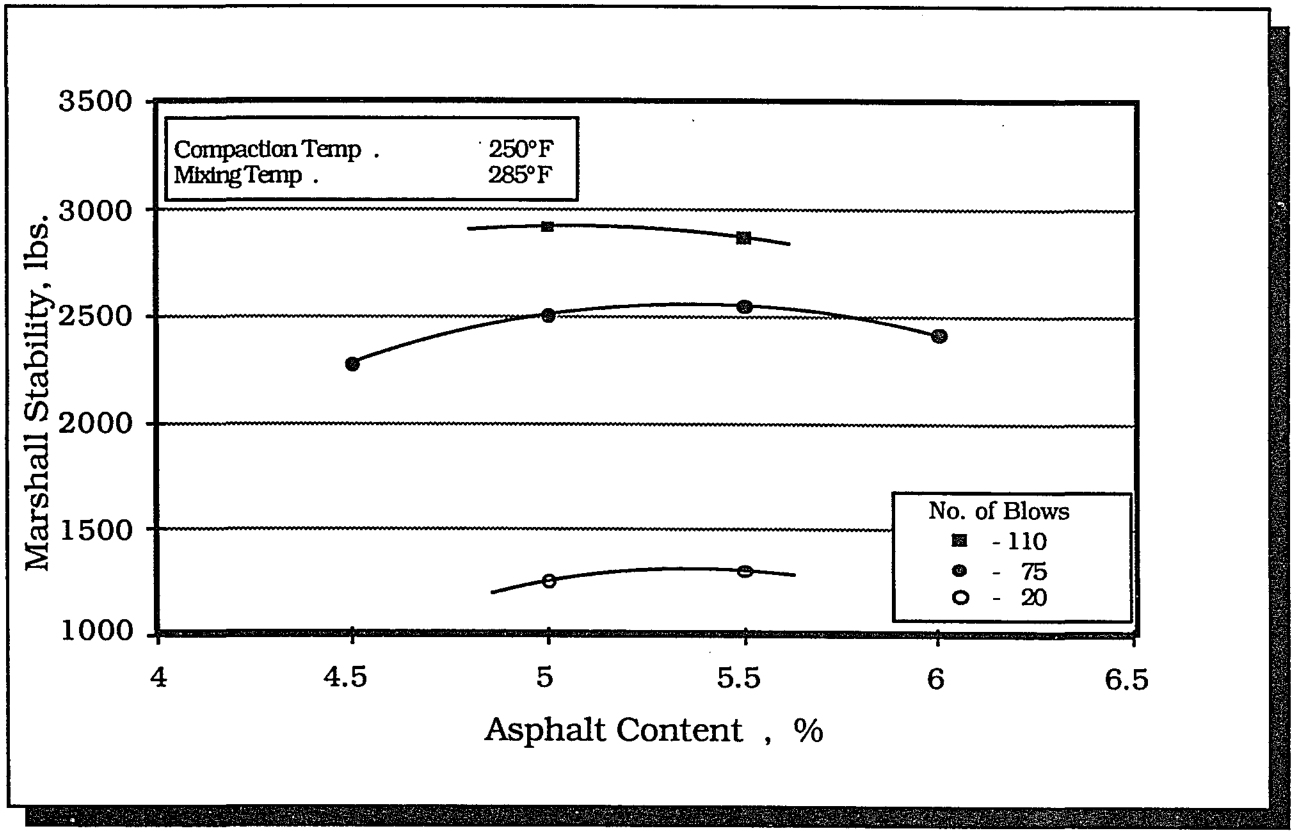

FIGURE 25 Effects of Asphalt Content on Marshall Stability

MIX "A"

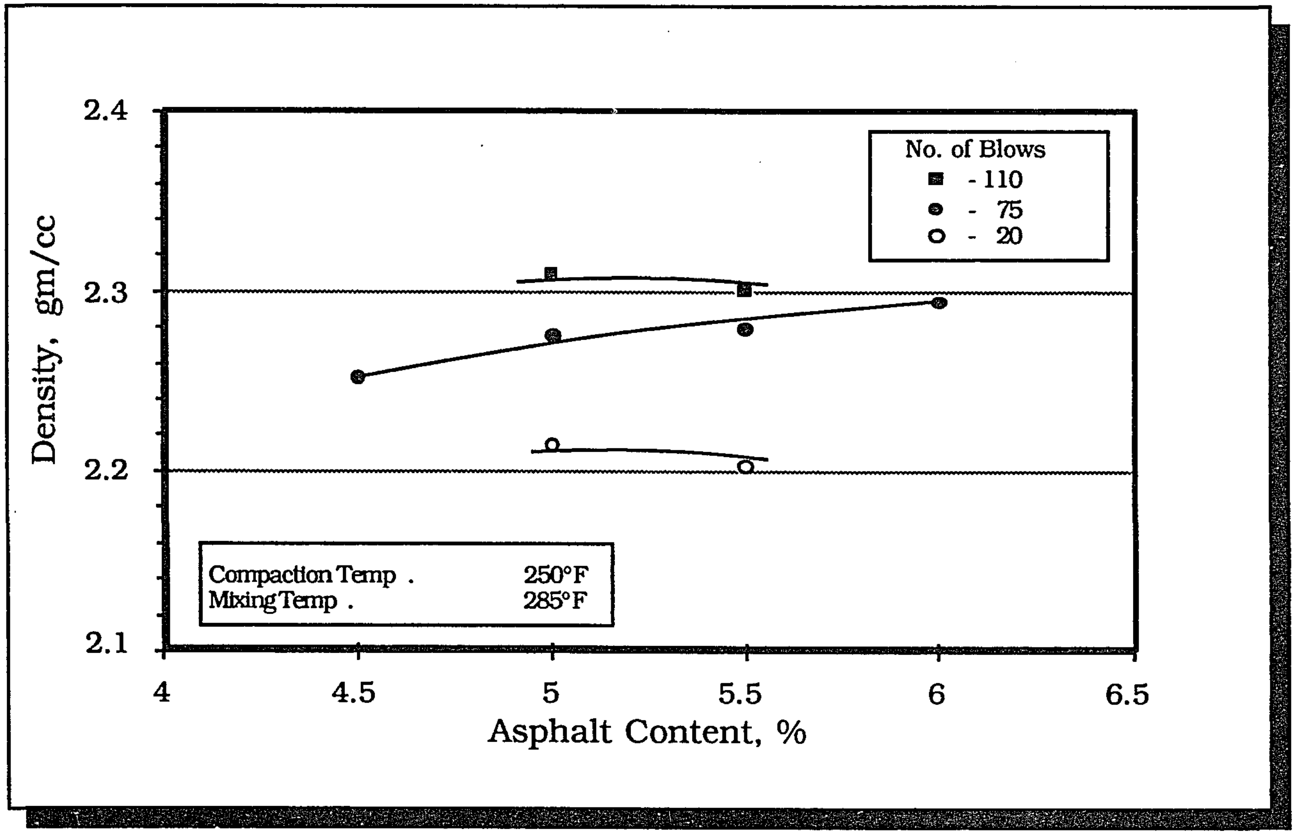

FIGURE 26 Effects of Asphalt Content on Density, **MIX "A".**

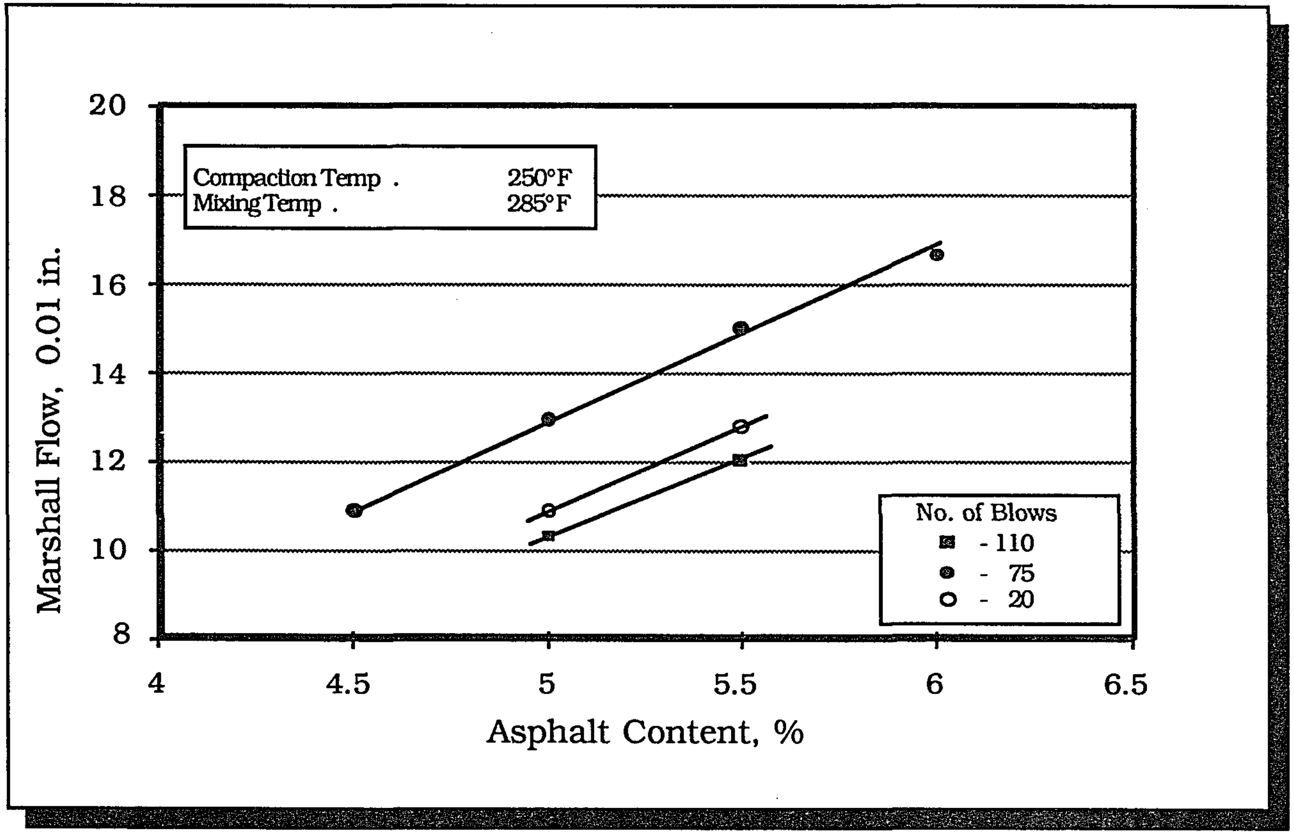

FIGURE 27 Effects of Asphalt Content on Marshall Flow
MIX "A".

CHAPTER 6

CONCLUSIONS

The results of this investigation established the influence of asphalt content, mixing temperature, compactive effort and compaction temperature on void content, VMA, density and stability of asphaltic concrete mixtures. This investigation showed that the mixture variables significantly affected the properties of asphaltic concrete design.

The following conclusions are drawn with basis of the data collected in the investigation. These conclusions are not listed in any order of importance:

(1) For the same asphalt content an increase in the size of the aggregate resulted in a decrease in density and stability of the compacted mix. All other factors (mixing temperature, compactive effort, compaction temperature) being constant.

(2) In most cases, increasing the aggregate size produced a reduction in the percent air voids as well as a reduction in the voids of the mineral aggregates of the compacted mix.

(3) As the compactive effort increased, the void content and the voids-in-the-mineral aggregate decreased when using the same amount of asphalt. The semi-log plot of air voids versus number of blows was a linear one when air voids were plotted on the logarithmic ordinate.

(4) As the compactive effort increased, density and stability increased. Marshall stabilities versus number of blows plotted as a straight line on log-log scales.

(5) The following equation, based on an average slope, can be used to obtain the stability at any compactive effort in terms of the standard stability at 75 blows per face.

$$S_N = 3.68^{(\mathrm{Log}\ N/75)} S_{75}$$

(6) The lower the temperature of the mixture before compaction, the larger the amount of air voids and VMA for a given asphalt content. Considerably higher stabilities were obtained when the compaction temperature was increased. Varying the compaction temperature from 212°F to 285°F had very little effect on the measured density.

(7) Increasing the mixing temperature resulted in:

- (a) An increase in air voids and VMA values.
- (b) No major effect on stability.
- (c) Lower densities.

(8) Increasing the asphalt content resulted in:

- (a) A decrease in air voids.
- (b) A decrease in VMA percentage for 75 blows while for 20 and 110 blows VMA values increased.
- (c) An increase in stability for a compactive effort of 75 blows up to a maximum value in the neighborhood of 5.5 percent asphalt beyond which further increases in asphalt showed a decrease in stability. For 20 and 110

blows there was insufficient data to determine the effect of asphalt content on stability.

(d) An increase in density for 75 blows. For 20 and 110 blows this was not apparent due to insufficient data.

(e) A sharp increase of flow values without reaching a peak value.

(9) The theoretical terminal VMA value of 13.89 percent obtained by the Jimenez method was approached by the value of 13.7 at 110 blows compactive effort. Therefore, it would seem desirable whenever the Marshall method is used to check the mixture properties at 110 blows.

(10) A number of recommendations follow from the conclusions reached for future research:

(1) The use of compaction and test methods other than the Marshall.

(2) Further work using other mixture types such as those with open-graded aggregates.

(3) As a follow-up to the above, a field experiment is proposed to determine the effects of variations in compaction on asphaltic concrete design as related to field conditions.

APPENDIX A

SUMMARY OF TEST DATA

TABLE A.1 EXTRACTION TEST DATA FOR **MIX "B"**

	TOP BASKET	BOTTOM BASKET	TOTAL
	BEFORE ASPHALT EXTRACTION		
WT. OF BASKET, FILTER & SAMPLE, gm	1220.8	1007.4	2228.2
WT. OF BASKET & FILTER, gm	676.6	494.2	1170.8
WT. OF ASPHALTIC CONCRETE, gm	544.2	513.2	1057.4
	AFTER ASPHALT EXTRACTION		
WT. OF BASKET, FILTER & SAMPLE, gm	1190.3	979.7	2170.0
WT. OF BASKET & FILTER, gm	676.6	494.2	1170.8
WT. OF DRY AGGREGATE, gm	513.7	485.5	999.2
WT. OF ASPHALT EXTRACTED, gm	30.5	27.7	58.2
% ASPHALT, BY TOTAL WT. OF MIX	5.6	5.4	5.5
AVERAGE % ASPHALT	5.5		

TABLE A.2 TEST RESULTS FOR **MIX "A"**
4.5 % ASPHALT, MIXING TEMPERATURE 285°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
250	**75**	**2275**	**2.252**	**5.67**	**15.62**	**10.9**

TABLE A.3 TEST RESULTS FOR **MIX "A"**
5.0% ASPHALT, MIXING TEMPERATURE 250°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	738	2.205	6.80	17.60	12.3
	75	1496	2.273	3.90	15.05	12.6
	110	2112	2.302	2.70	14.00	10.9
250	20	1137	2.224	5.95	16.90	11.2
	75	2254	2.288	3.25	14.50	11.1
	110	3101	2.312	2.24	13.60	14.1
285	20	1699	2.245	5.10	16.10	13.5
	75	3072	2.315	2.15	13.50	12.2
	110	3654	2.332	1.40	12.85	15.0

TABLE A.4 TEST RESULTS FOR **MIX** "A"
5.0% ASPHALT, MIXING TEMPERATURE 285°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	777	2.169	8.30	18.95	12.3
	75	1872	2.263	4.35	15.45	10.4
	110	2027	2.270	4.0	15.15	10.7
250	20	1260	2.215	6.35	17.25	10.9
	75	2504	2.275	3.81	15.20	13.0
	110	2908	2.310	2.35	13.70	10.3
285	20	1590	2.246	5.05	16.05	11.4
	75	3727	2.311	2.30	13.65	11.4
	110	4446	2.323	1.75	13.15	10.3

TABLE A.5 TEST RESULTS FOR **MIX** "A"
5.0% ASPHALT, MIXING TEMPERATURE 325°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	806	2.190	7.40	18.20	11.2
	75	1865	2.255	4.60	15.70	9.8
	110	2299	2.277	3.70	14.90	10.6
250	20	1030	2.201	6.90	17.75	10.3
	75	2428	2.259	4.45	15.55	11.2
	110	3191	2.293	3.10	14.35	10.2
285	20	1204	2.231	5.70	16.65	11.5
	75	3304	2.295	3.00	14.25	11.8
	110	3801	2.315	2.15	13.5	10.8

TABLE A.6 TEST RESULTS FOR MIX "A"
5.5 % ASPHALT, MIXING TEMPERATURE 250°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	968	2.208	5.80	17.70	11.9
	75	1800	2.281	2.70	15.00	13.4
	110	2324	2.295	2.10	14.50	10.9
250	20	1143	2.223	5.15	17.15	11.4
	75	2408	2.296	2.10	14.50	13.5
	110	3019	2.309	1.45	13.95	12.8
285	20	1563	2.238	4.50	16.60	9.2
	75	2784	2.301	1.85	14.30	10.4
	110	3390	2.317	1.15	13.65	12.2

TABLE A.7 TEST RESULTS FOR **MIX "A"**
5.5 % ASPHALT, MIXING TEMPERATURE 285°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	804	2.190	6.55	18.40	9.7
	75	1381	2.257	3.65	15.85	12.6
	110	2239	2.297	2.02	14.43	14.1
250	20	1303	2.203	6.01	17.90	12.8
	75	2550	2.279	2.80	15.10	15.0
	110	2855	2.301	1.80	14.26	12.0
285	20	1687	2.227	5.00	17.00	12.0
	75	2613	2.283	2.57	14.90	13.5
	110	3089	2.304	1.76	14.20	10.9

TABLE A.8 TEST RESULTS FOR **MIX** "A"
5.5 % ASPHALT, MIXING TEMPERATURE 325°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	873	2.204	6.00	17.90	12.1
	75	1914	2.276	2.90	15.20	13.2
	110	2656	2.296	2.05	14.45	14.3
250	20	1096	2.204	5.95	17.85	12.4
	75	2694	2.283	2.60	14.95	11.7
	110	2980	2.303	1.70	14.15	11.5
285	20	1204	2.216	5.50	17.45	11.9
	75	2811	2.298	2.00	14.40	13.8
	110	3597	2.316	1.20	13.70	10.8

TABLE A.9 TEST RESULTS FOR **MIX "A"**
6.0% ASPHALT, MIXING TEMPERATURE 285°F.

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
250	**75**	**2413**	**2.295**	**1.35**	**14.88**	**16.7**

TABLE A.10 TEST RESULTS FOR **MIX "B"**
5.5 % ASPHALT

COMPACTION TEMPERATURE °F	COMPACTIVE EFFORT B/F	STABILITY pounds	DENSITY gm/cc	AIR VOIDS %	VMA %	FLOW 1/100"
212	20	1658	2.203	6.85	18.84	11.9
	75	2777	2.263	4.31	16.62	17.9
	110	3473	2.299	2.82	15.32	18.2
250	20	2224	2.244	5.14	17.35	16.8
	75	3101	2.286	3.34	15.78	11.6
	110	3612	2.317	2.05	14.66	10.8
285	20	2420	2.269	4.06	16.41	15.2
	75	3294	2.314	2.16	14.75	16.3
	110	3749	2.323	1.78	14.42	16.8

APPENDIX B

PHOTOGRAPHIC ILLUSTRATIONS

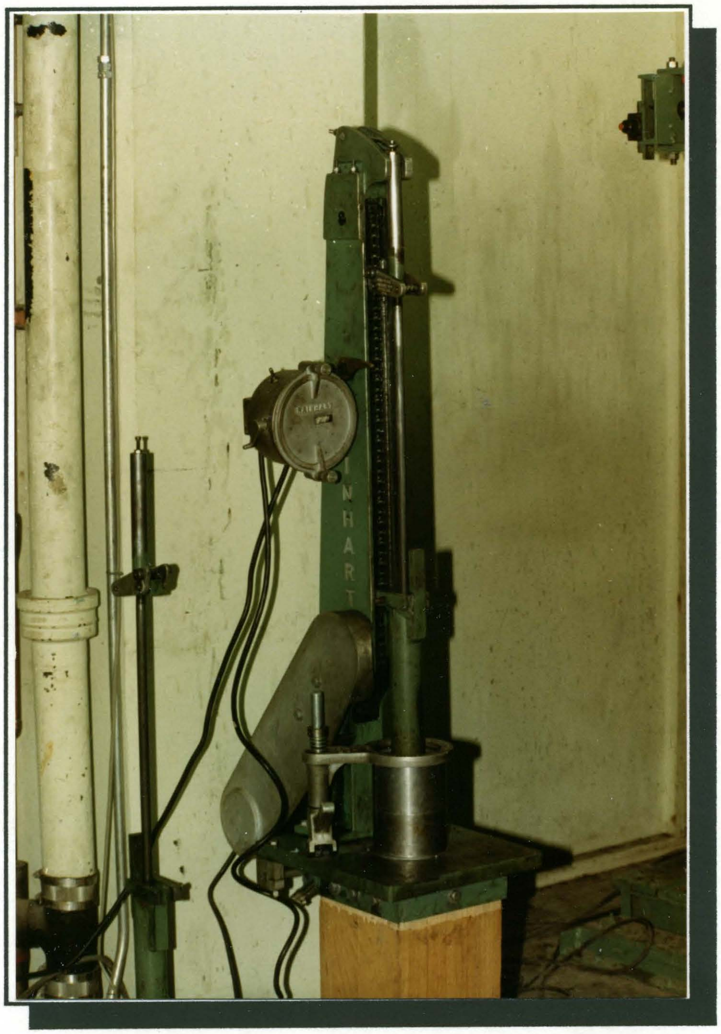

Table B.1 Marshall Hammer

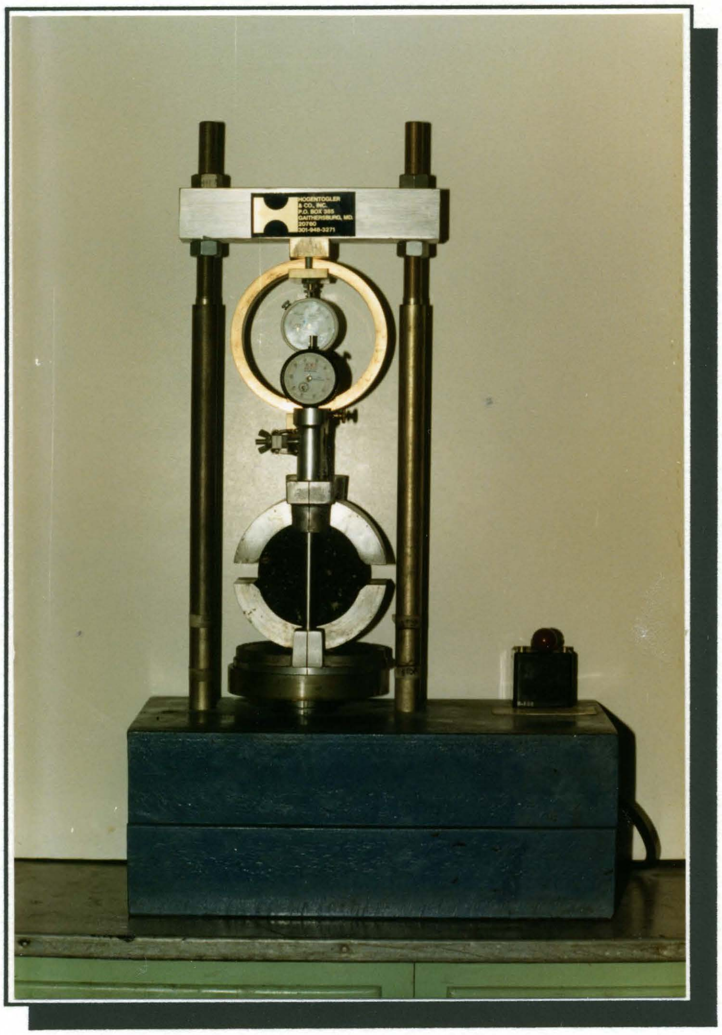

Table B.2 Marshall Stability and Flow Test

Table B.3 Mechanical Mixer

Table B.4 Specimen Preparation Apparatus

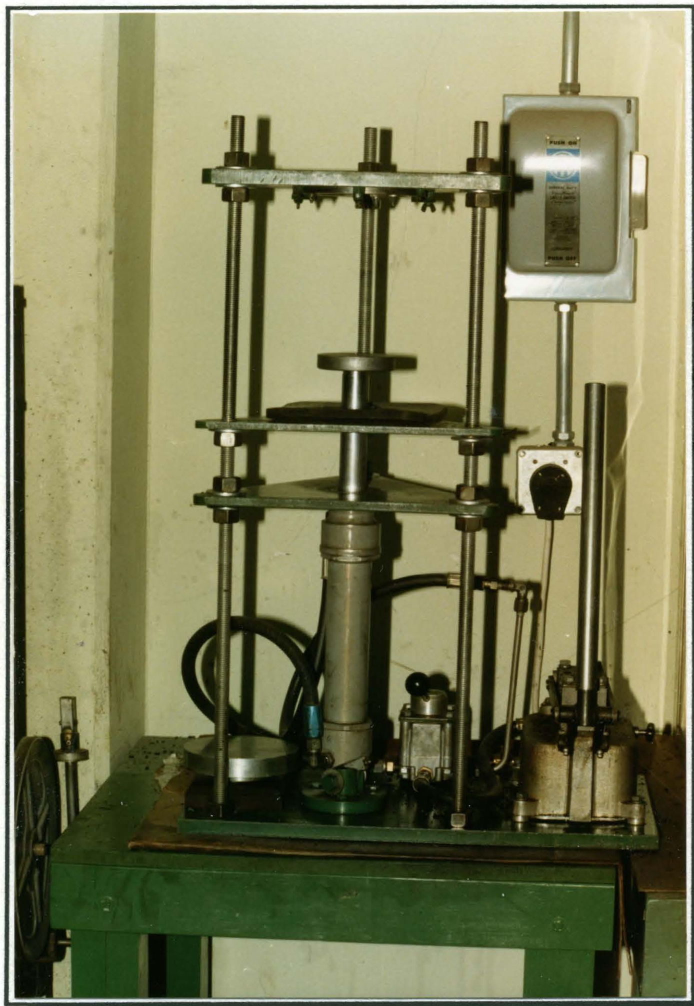

Table B.5 Extrusion Jack

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