Gap-graded gravel for asphaltic paving mixtures

Ernest Harrington Martin

GAP-GRADED GRAVEL FOR ASPHALTIC PAVING MIXTURES

BY

ERNEST HARRINGTON MARTIN - 1933

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Approved by

Thomas S. Fry (advisor) W. J. Murphy

Glenn M. Vaughn (?) N. B. Aughenbaugh

ABSTRACT

The objective of this investigation was to determine if naturally occurring gap-graded gravel can produce asphaltic mixtures meeting minimum requirements for satisfactory pavement behavior.

Ten gap-graded mixes were blended by eliminating certain intermediate sized fractions or combination of fractions from the gradation of a control mix. The weight of the fractions eliminated was distributed to either the coarser or finer aggregate fractions.

All specimens were prepared and tested in strict accordance with procedures set forth in ASTM Designation D1559, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus."

The physical properties compared and analyzed were (1) unit weight, (2) stability, (3) flow, (4) percent air, (5) percent voids filled with bitumen, and (6) voids in the mineral aggregate. Test results reveal that some of the mixtures can meet minimum criteria for a satisfactory mix with the principle problem being one of deficient air-voids relationships.

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I. INTRODUCTION

A. General.

It has been almost 100 years since the first bituminous pavement was constructed in the United States.[1] Since that time, highway engineers and, in particular, the asphalt industry have been confronted with solving the problem of producing bituminous pavements which can meet the ever-increasing demands of modern day traffic. Today, as a result of their success, some 90 percent of all roads and streets in the United States are surfaced with some form of bituminous material.[2]

The strength characteristics of bituminous pavements have been a matter of primary concern for many years. The years of experience and research indicated that pavements containing sharply angular and densely graded aggregate produce stronger pavements than those containing rounded and/or poorly graded gravels. As a result, most specifications have required the use of crushed or angular dense graded aggregate in paving mixtures for many years.[3]

B. Constituents of a Bituminous Pavement.

A bituminous paving mixture is composed of three basic components: (1) mineral aggregate, (2) bituminous binder, and (3) air. The function of the aggregate is to: (1) transmit the traffic load from the surface of the pavement to the underlying base through mechanical interlock and point-to-point contact between aggregate particles; (2) resist abrasive action of traffic; and (3) provide a non-skid surface. The bituminous binder provides a watertight surface and holds the aggregate together thus preventing displacement or dislodgement of aggregate particles.

Air must be present in a bituminous pavement to allow for both further densification of the pavement while in service and expansion of asphalt in hot weather. Overfilling the voids can develop pore pressures which can force aggregate particles apart, thereby reducing the strength of a pavement, and/or force asphalt to the surface resulting in what is known as "bleeding."[4]

1. Mineral Aggregate. The mineral aggregate comprises approximately 95 percent of a bituminous mixture and is the primary strength producing ingredient. A mix is normally classified according to aggregate gradation which is determined by the amount of aggregate which will pass or be retained on a particular set of sieves.

If a mixture has the proportions of all sizes of aggregate which produces the maximum density and minimum voids it is called a dense graded mix. If the aggregate gradation is such that there is little or no mineral filler, resulting in a rather porous mixture, it is referred to as an open graded mix. A uniform mix is one in which all of the aggregate is approximately the same size. Gap graded mixtures are mixtures which have one or more of the intermediate sized aggregate fractions missing.

The gradation is normally divided into three fractions known as coarse aggregate, fine aggregate, and mineral filler. Coarse aggregate is generally defined as that material which is retained on the No. 8 sieve; the fine aggregate is that material which will pass the No. 8 sieve and be retained on a No. 200 sieve; and mineral filler is that material which will pass a No. 200 mesh sieve. The coarse and fine aggregate can be made up entirely of crushed rock, sand and gravel, or slag, or any combination thereof. Mineral filler usually consists of limestone or silica dust, Portland cement, or flyash.[4]

2. Bituminous Binder. The bituminous binder or asphalt cement, often referred to as asphalt or bitumen, is the cementing agent which binds the aggregate together and forms the watertight surface. Although sometimes naturally occurring the most common source is the by-product produced by fractional distillation of petroleum. It is the heavy residue remaining after the volatiles to produce gasoline, kerosene, diesel oil, and lubricating oil have been removed. Consistency of the residue is a function of the temperature, pressure, and time associated with the distillation process. This residue, called asphalt cement, is classified in terms of consistency which is measured and identified by the distance (in units of 1/100 of a centimeter) that a needle with a 100 gram load will penetrate into an asphalt sample in 5 seconds at 77° Fahrenheit. There are nine grades of asphalt cements ranging in penetration values from 40 to 300. Those asphalts having penetration values of 50 to 150 are normally used in bituminous paving mixtures.[1][5]

Over an extended period of time asphalt will tend to lose plasticity and become brittle due to exposure to the elements and internal chemical reactions. To reduce the effects of time and exposure, thereby insuring a long lasting flexible pavement, it is common practice to use as high a percentage of asphalt and as soft a grade of asphalt as possible without sacrificing other properties of the mixture. In colder climates, for example, generally the softer or higher penetration asphalt is used.[4]

C. Purpose of Investigation.

Many early highways were constructed using local source aggregates which were rounded in shape and, often, poorly graded. Pavement failures using these materials were quite common and, as a result, specifications required the use of well graded sharply angular aggregates. This somewhat arbitrary exclusion of naturally occurring aggregate overlooked the fact that there were many roads constructed of these materials which performed satisfactorily for many years while some pavements using densely graded angular aggregate did fail. Some engineers objected to condemning aggregate purely on the grounds of gradation and shape, however, this issue was not pressed because, in most areas, a better quality material was available in rather abundant supply. It was also generally accepted that well graded angular aggregate did produce better roads.[(6)]

For several reasons engineers are re-evaluating the potential use of these local materials. The first is the result of the tremendous road construction program during the past 10 to 20 years which has seriously depleted the available supply of quality aggregate. Secondly, techniques and procedures for design, testing, placement and field control have been vastly improved resulting in higher quality pavements. The third is the economic advantage created by using local materials without costly processing. Because of these reasons, a knowledge of the behavior of bituminous mixtures as influenced by different aggregate shape and gradation is required.[(6)]

The purpose of this research is to evaluate the behavior of asphaltic mixtures using materials and gradation previously considered unsatisfactory and to determine whether significant departures from current specifications pertaining to aggregate shape and gradation can produce mixtures meeting minimum requirements for satisfactory pavement behavior.

II. REVIEW OF LITERATURE

A. General.

There has been very little research concerning the use of gap-graded materials or naturally occurring rounded gravels as aggregate for bituminous mixes. The U. S. Army Corps of Engineers Waterways Experiment Station, in 1948, conducted extensive research into the design and control of asphaltic paving mixtures which included a limited amount of research into the use of gap-graded aggregate. The conclusion was that some gap-graded mixtures can produce satisfactory mixtures.[7] This led Maurice L. Northcutt, in 1964, to determine if even larger gaps can produce mixtures that can satisfy minimum requirements. He concluded that deviations from gradations normally specified can be quite large and still satisfy minimum laboratory test requirements.[8]

Proudley and Waller, in 1947, published a paper which discusses the affect that dense graded gravels have on properties of bituminous mixtures as opposed to an identical gradation using crushed aggregate.[9] Herrin and Goetz, in 1954, report the influence that various percentages of crushed aggregate have on the stability of dense and open graded mixtures.[6]

B. Properties of a Bituminous Mixture.

The quality of a bituminous pavement is predicted by evaluating the basic properties measured in compacted laboratory specimens. These properties are: (1) unit weight, (2) stability, (3) flow, and (4) the air-voids relationships.

Unit weight represents the weight per unit volume of the compacted mix. This quantity, by itself, may not have any great significance. It is basically an intermediate value used to determine the more important air-voids relationships.[4] Unit weight is directly related to gradation, aggregate shape, asphalt content, specific gravity of the constituents, and compactive effort. It is also used to give the designer an optimum value to help establish the optimum asphalt content.

Stability can be best described as the resistance to deformation and is attained through interlock and friction developed between aggregate particles and cohesion of the binder. Stability is the property which gives the pavement the strength necessary to resist rutting and shoving and is considered by many as the most important property of a pavement. Experience has shown that a mixture is rarely found to be unsuitable from purely the stability standpoint. Limiting criteria for adequate stability ranges from 500 to 1200 pounds, depending on the anticipated load and traffic conditions.[4]

Flow represents the diametric distortion required to produce fracture of the specimen.[10] It is a measure of the brittleness of a pavement. The primary factor affecting flow is the degree to which the aggregate voids are filled with asphalt. A pavement with little or no flow indicates that the pavement is brittle and will be susceptible to cracking and eventual disintegration. Experience has shown that flow values should range from 8 to 20.[4]

There are three quantities involving voids in the mineral aggregate used to evaluate the behavior of a bituminous mixture. They are: (1) percent air in the total mix; (2) total voids in the mineral aggregate, known as VMA; and (3) percent voids filled with bitumen. These values are obtained by comparing the volume of the compacted specimen with the volume of the constituents in a theoritical voidless mixture. Percent air is a property which is used to measure the ability of a pavement to allow for expansion of the asphalt in hot weather and further densification under the abuse of traffic. White brings out, for example, that the density of a pavement continues to increase for a period of 11 years or more after placed into service.(11) Experience has shown that in a densely graded mix the percentage of air should range from 3 to 5. If above 5 percent the pavement will tend to be porous which will lead to premature hardening of the bituminous binder due to exposure to the elements.

Norman McLeod recommends a minimum value of 15 percent be applied to the VMA in order to provide room for air voids and room for the volume of binder necessary for a durable pavement.(12) This recommendation, however, is considered to apply only to densely graded angular aggregates. The Marshall Consulting Laboratory, for example, states that no limit can be placed on VMA because of the versatile application of bituminous materials to the many types and gradations of aggregates.(10) The Asphalt Institute recommends limiting values for VMA, however, the value recommended is a function of the maximum size of the aggregate and applies only to mixtures containing densely graded and angular aggregate.(1)

Some agencies, such as the Corps of Engineers, use a "percent voids filled with bitumen" concept instead of VMA and recommend values between 75 and 85 percent. As the "percent voids filled with bitumen" approach 100 the pavement will become susceptible to bleeding and may become unstable because of pore pressure developing a "quick" condition.

Durability is defined by Sonderegger as the ability of a pavement to withstand the detrimental effects of traffic, water, ice, air, and temperature.[4] Although not a measurable value in the laboratory, durability can be implied by correlation with the other properties and is important enough to warrant consideration. Durability can only be measured in terms of time in service.

C. Factors Affecting Properties of a Bituminous Mixture.

There are many factors which determine the basic properties of a bituminous mixture prepared in the laboratory. These factors include: composition, hardness, durability, size, shape, texture, absorption, and gradation of the aggregate; composition, consistency, source, ductility, amount of bitumen; and, most important, laboratory testing techniques. In order to be able to discuss and/or investigate the affect of any one or a number of variables, it is imperative that all variables, except the ones under investigation, be held constant. This is accomplished by, first, obtaining each constituent from the same source thus insuring uniformity and, second, developing a laboratory technique in which each sample is blended, prepared, and tested in exactly the same manner. The variables under investigation in this research, as opposed to the average high quality bituminous mixture, are gradation and aggregate shape.

Gradation has been generally accepted by the entire asphalt industry for many years as the most essential factor in the design of a quality pavement. Only in recent years have engineers started to question the validity of the restrictive gradation bands that have been so strictly enforced for so long.[6] Norman McLeod was, perhaps, one of the first to recommend a relaxation in the tight gradation requirements in favor of more emphasis on other properties, particularly in the voids-air relationships. He states, first, that the densest mix does not necessarily produce the best pavements, second, that tight gradation bands are not justified on the basis of what has been learned in recent years and, third, that it is common knowledge that many mixtures which lie well outside existing gradation limits have provided excellent service for many years. He also points out that a dense graded pavement will often lack the desired voids and by changing gradation (increasing the percent fine aggregate) voids can be increased resulting in a much better pavement.(12) The limited amount of research into gap-gradation by the Waterways Experiment Station reveals that such gradations can produce asphaltic concrete with test properties comparable to dense-graded mixtures.(7) Maurice L. Northcutt, in 1964, went one step further by investigating just how large the gaps can be and still produce a satisfactory mix. Many of his mixes met minimum criteria.(8) Csanyi conducted research into what effect varying percentages of mineral filler had on a dense mixture (although not gap-gradation, the results may be related). He explained that excessive filler in a pavement tends to increase stability, brittleness, and prolivity to cracking. He states that the excess filler becomes suspended in the bitumen, thus creating a mastic, which substantially lowers the original consistency of the bitumen.(13)

It has also been generally accepted for many years that angular aggregate substantially increases the stability of mixtures through mechanical interlock of angular aggregate particles. Goetz and Herrin, in order to determine just what part angularity played in stability, conducted triaxial stability tests on open and dense graded mixtures containing varying percentages of crushed aggregate. They concluded that higher percentages of angular aggregate substantially increased the stability of open-graded mixtures while having a negligible effect on dense graded mixes and that angular fine aggregate increase stability of a mixture more than angular coarse aggregate.(6) Proudley and Waller state that a high quality heavy duty pavement can be constructed with rounded gravel provided the fine aggregate is angular. Their discussion also brought out that dense-graded gravel mixtures, as opposed to crushed aggregate with identical gradation, produce: (1) a lower optimum asphalt content, (2) a stability value and void content approximately 5 percent lower, and (3) a lower asphalt content for any given property.(9)

There are many factors which affect flow; however, for any given mix, the primary factor influencing flow is the degree to which the aggregate voids are filled with asphalt. Flow always increases with increase in asphalt content.(10)

The air-voids relationships for any given mixture depend primarily on the asphalt content. The value of the air-voids relationships (percent of air voids, VMA, and "percent voids filled") for a compacted mixture depend on two major factors: (1) the value selected for the specific gravity of the aggregate and (2) whether or not bitumen absorbed into the aggregate is taken into account.

By A.S.T.M. definition there are three different specific gravities: (1) bulk specific gravity, (2) apparent specific gravity, and (3) effective specific gravity. The bulk specific gravity is the volume occupied by the aggregate minus the pore spaces between the aggregate particles.

The apparent specific gravity is the volume of the aggregate minus both the pore space between aggregate and the volume of the water permeable pore space within the aggregate particles. Effective specific gravity is the volume occupied by the aggregate minus both the volume of void space between particles and the voids in the aggregate particles occupied by asphalt.

When bulk specific gravity is used for the aggregate the VMA becomes the sum of the volume of only the void space between aggregate particles. If apparent specific gravity is used, the calculated VMA will have added to it the volume of water permeable voids within the individual aggregate particles. If effective specific gravity is used, the calculated VMA will have added to it the volume of the asphalt permeable voids. The use of either of the latter two specific gravities will indicate that the volume of the solid skeleton of a paving mixture is smaller than it really is, thus implying that a mixture contains more voids than can be occupied by asphalt. For this reason the bulk specific gravity with an appropriate adjustment to determine the effective asphalt content (actual asphalt content less that which is absorbed into the aggregate) should be used for analysis.[12]

D. The Marshall Method of Testing Bituminous Mixtures.

Around 1941, the Corps of Engineers was looking for a method of testing bituminous mixtures that would be rapid, highly portable, and easy to use. This search led to a newly developed and still experimental procedure called the Marshall method which was conceived and developed by Mr. Bruce G. Marshall, formerly of the Mississippi Highway Department. After extensive research, correlation studies, and modifications, the Marshall method was adopted by the Corps of Engineers. The

Marshall procedure is now standardized under ASTM Designation D1559 and has been adopted by many state highway departments and private consulting firms.[4][7]

The Marshall method determines five properties of a bituminous mixture: stability, flow, unit weight, percent air, and percent voids filled with bitumen. Some agencies, to include the Asphalt Institute, have modified the air-voids relationships by adopting the property of "voids in the mineral aggregate" (VMA) in lieu of "percent voids filled with bitumen."[4][1]

The air-voids relationships are determined by comparing the volume of a compacted specimen to the volume of the constituents in a theoritical voidless mix. Stability and flow are determined by failing a compacted 4 inch diameter by 2 1/2 inch thick specimen, at 140°F., between two segiments of a 4 inch (inside) diameter ring. The load is applied by the Marshall machine at the rate of 2 inches per minute until the specimen fails. The stability value is the maximum load, in pounds, required to produce failure. The flow value is the deformation or strain (in units of 1/100 inch) that the specimen undergoes during failure.[4][7]

III. PROCEDURE AND RESULTS

A. General.

The primary objective of this investigation was to determine if asphaltic mixtures containing gap-graded gravel aggregate can meet minimum criteria established for a bituminous pavement. The gap-gradations were produced by varying the quantity of certain intermediate sized aggregate from a densely graded control mix.

All specimens were prepared and tested in accordance with the Marshall procedure. Numerous practice specimens were prepared and tested prior to the investigation in order to standardize on laboratory technique and insure that the procedures to be used were understood and strictly followed.

B. Materials.

Both coarse and fine aggregate were obtained from a submerged natural deposit of glacial sand and gravel located adjacent to the west bank of the Mississippi River. The Glacial Sand and Gravel Company, located one mile north of Old Monroe, Missouri, operates the gravel pit. The aggregate was acquired by means of a hydraulic dredge which performs a dual function of washing the aggregate as well as dredging. The aggregate used for the investigation was taken from stockpiles which were sized according to coarse gravel, "pea-gravel," coarse sand, and fine sand.

Mineral filler was a commercial silica dust produced by the Pioneer Silica Products Company, St. Louis, Missouri, under the trade name "Super Sil."

The bituminous binder was a 85/100 penetration grade asphalt produced by the Chevron Asphalt Company, Cincinnati, Ohio.

C. Preparation of Materials.

The aggregate was separated according to sieve size. The coarse aggregate consisted of gravel retained on the 1/2 inch, No. 4. and No. 8 sieves. The fine aggregate consisted of material retained on the Nos. 40, 80, and 200 sieves. The silica dust made up the fraction passing the No. 200 sieve.

The coarse aggregate ranged from rounded to subrounded in shape and had an ASTM bulk specific gravity of 2.56. An indication of the mineralogical composition of the coarse fraction was determined by performing a "pebble count" on the 1/2 inch sieve fraction. This analysis revealed a rather even distribution of igneous and metamorphic rock with the dominant mineral being quartz (Table I).

The fine aggregate was examined using a 15-power Spencer microscope. This examination revealed that the fine fraction was predominately individual glassy to opaque quartz particles subangular to subrounded in shape with a scattering of unidentified dark brown and black particles. There was no reaction to the acid test indicating an absence of carbonate rock. The ASTM bulk specific gravity of this fine aggregate was 2.63.

The ASTM apparent specific gravity of the mineral filler was 2.65 which is the generally accepted value for silica dust. A method for determining the bulk specific gravity of mineral filler has not been developed. However, the error is usually negigible if apparent specific gravity is used instead.[1]

TABLE I

PEBBLE COUNT OF AGGREGATE RETAINED ON THE 1/2 INCH SIEVE

MINERALOGICAL CLASSIFICATION	NUMBER COUNTED	PERCENT OF TOTAL
IGNEOUS		
Granite, Monzonite, etc.	43	19.0
Rhyolite	12	5.2
Basaltic (Aphanitic, Basic)	36	15.9
Unidentified	3	1.3
METAMORPHIC		
Granite Gneiss	2	0.9
Quartzite (Meta & Ortho)*	75	33.0
Quartzite (Weathered)	23	10.1
SEDIMENTARY		
Sandstone	21	9.3
Siltstone	2	0.9
MINERALS		
Quartz	10	4.4
TOTALS	227	100%

NOTE: *It is difficult to differentiate between metaquartzite and orthoquartzite in a pebble count.

The specific gravity of the asphalt was 1.01. Penetration tests were performed on the asphalt at regular intervals throughout the investigation and averaged 88. The amount of asphalt absorbed by the aggregate was determined by the Rice Method[1] and was found to be only 0.06 pounds per 100 pounds of total mix (Table II). Because such a small amount of absorbed asphalt would produce a negligible effect on specific gravity of the aggregate, it was decided to use bulk specific gravity as a basis for determination of the void-density relationships.

D. Establishing Aggregate Gradation.

A control mix, designated as Mix A, was blended by use of the gradation chart for maximum density developed by Goode and Lufsey.[14] Mix A was used as a basis for comparison with the gap-graded mixtures and to establish a standard gradation from which the gap-gradations could be determined. The gap-gradations were established by eliminating certain intermediate fractions from the gradation of Mix A and adding the weight eliminated, in proportionate amounts, to the weight of aggregate retained on either larger or smaller sieves. Coarse textured mixtures, designated as the C Mixes, were produced when the distributed weight was allocated to the larger sized sieves. Fine textured mixtures, designated as the F Mixes, resulted by proportioning the weight to the smaller sized sieves. Five different gradations were produced within each of the two broad categories of C and F Mixes. These were designated as Mixes C1 through C5 and F1 through F5.

Adjustments made to establish the gradation for each mix are shown in both graphical and tabulated form. The grain size distribution of all the mixtures used are summarized in Figure I. Tables III and IV summarize the adjustments that were made to produce the desired gradation for the C and F Mixes. Table V is a summary tabulation of the grain size distribution for each of the mixes used.

E. Preparation of Specimens.

Each test specimen was blended and prepared individually in order to insure uniformity. Approximately 1200 grams (enough for the preparation of one specimen) of aggregate were combined in the proportions established by the desired gradation (Figure 1 and Table V). The aggregate was poured into a container and placed overnight in an oven which was maintained at a temperature of 300°F. (± 5° F.). On the following day asphalt heated to 275°F. (± 5° F.), was weighed directly into the hot aggregate and the constituents thoroughly mixed over a hot plate for a period of four minutes. Care was exercised to avoid either prolonged or over heating of the asphalt prior to weighing into the mix in order to avoid a change in consistency caused by loss of volatiles. The mixture was then placed in a preheated compaction mold, allowed to cool to 250°F. (± 5° F.), then compacted by applying 50 blows of the 10 pound Marshall drop-hammer to each face. The compaction head of the hammer, like the compaction mold, was preheated to minimize heat loss. The mold and specimen were then air cooled under a fan until the consistency of the compacted specimen was such that it could be removed from the mold without rupture or deformation. The specimen was removed from the mold by means of the Marshall machine, marked, and allowed to cool over night.

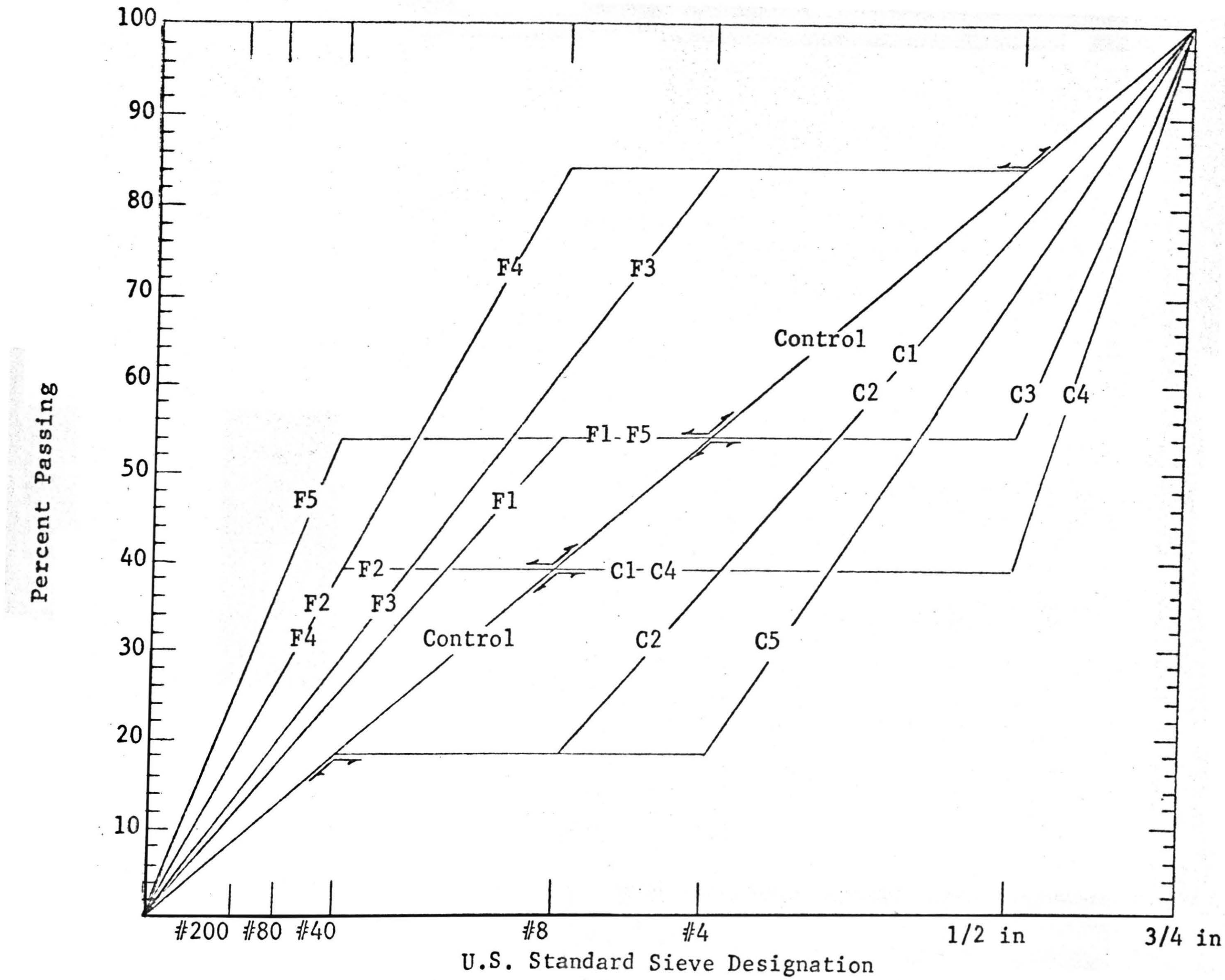

FIGURE 1. AGGREGATE GRADATION CURVES

F. Testing of Specimens.

The first step in determining the properties of a compacted specimen was to weigh the specimen in air and then in water in order to determine the voids-density relationships. The specimen was then placed in a 140° F. (± 1.8° F.) hot water bath. After 35 minutes (± 5 minutes) had elapsed the specimen was removed and immediately placed in the Marshall testing machine and loaded to failure. The specimen was failed within 30 seconds after removal from the hot water bath in order to avoid hardening of the asphalt in the specimen caused by cooling.

The stability of the specimen was established by converting, into pounds, the highest reading of the load measuring dial attached to the proving ring of the Marshall machine. The final stability value was determined using a correlation ratio which converts the stability of the specimen tested to that of a 2 1/2 inch specimen. The flow value was determined concurrently with the stability test. A flow meter was placed on the guide post of the breaking head and held in place during the test. It was removed as soon as the maximum stability reading was indicated on the load measuring dial.

Six briquettes were prepared at each asphalt content so that the high and low values could be eliminated. The properties of the four remaining briquettes were then averaged. Properties determined for the A mix, along with sample calculations, are shown in Table VI. Table VII and Table VIII lists properties of the C Mixes and F Mixes respectively. Figures 1 through 13 relate in graphical form the individual property curves of the C and F Mixes. Figures 14 and 15 combine the property curves of the C and F Mixes respectively.

Optimum asphalt contents were determined by averaging the asphalt contents that produce maximum unit weight, maximum stability and 4 percent air voids (Table IX). The other properties of each mix were then taken from the curves using the optimum asphalt content. Table IX lists the properties of all the mixes at their respective optimum asphalt content.

G. Results.

Test results are presented similar to the method recommended by the Asphalt Institute. This method plots the basic properties as a function of the asphalt content (Figures 1-15). Ten rather significant trends were observed from the results of the tests performed.

1. Unit weight for all mixes increased with increasing asphalt content up to a maximum value, then decreased.

2. Stability curves followed the same pattern as the unit weight curves except that maximum stability normally occurred at a lower asphalt content.

3. Percent air voids decreased with increasing asphalt content while percent voids filled with asphalt increased. Both approached an ultimate value then started to level off.

4. Percent voids in the mineral aggregate (VMA) generally decreased with an increase in percent asphalt, to a minimum value, then increased.

5. Flow increased with increasing asphalt content.

6. Mix A produced a higher maximum unit weight than any of the C or F Mixes.

7. The F Mixes reached a higher stability and lower flow value than either Mix A or the C Mixes.

8. The C Mixes produced a lower maximum stability and higher flow value than either the A Mix or F Mixes.

9. The F Mixes had a higher optimum asphalt content than Mix A while the C Mixes generally produced a lower optimum asphalt content.

10. The F Mixes produced a higher percent air at a given asphalt content than Mix A.

The properties for all the mixtures followed trends which were rather consistent with what could be anticipated. Most surprising was the fact that all the mixtures, in spite of large gaps in gradation, yielded high density. The mix properties resulting from this investigation are discussed in detail in the discussion section of this thesis, which follows.

TABLE II

DETERMINATION OF ASPHALT ABSORBED BY AGGREGATE
(RICE METHOD)

DEFINITION OF TERMS

*G_v:	Virtual Specific Gravity of Aggregate
G_{ag}:	Bulk Specific Gravity of Aggregate
G_{ac}:	Apparent Specific Gravity of Asphalt
W_{ag}:	Weight of Aggregate
W_{tac}:	Total Weight of Asphalt
V_{mm}:	Volume of Voidless Mix
A_{ac}:	Asphalt Absorbed By Aggregate

GIVEN

Percent Asphalt in Mix: 4.5

Weight of Mixture in Air: 1998 gm

Weight of Flask Filled With Water: 5010 gm

Weight of Flask, Water, and Mixture: 6185 gm

G_{ac}: 1.01 G_{ag}: 2.59

VIRTUAL SPECIFIC GRAVITY

$$G_v = \frac{W_{ag}}{V_{mm} - \frac{W_{tac}}{G_{ac}}} = \frac{(1998)\ (95.5)}{(1998 + 5010 - 6185) - 4.5 \times 1198/1.01} = 2.60$$

ASPHALT LOST BY ABSORPTION

$$A_{ac} = \frac{G_v - G_{ag}}{G_v \times G_{ag}}\ 100 = \frac{2.60 - 2.59}{2.60 \times 2.59}\ 100 = 0.06 \text{ lbs/100 lbs of mix}$$

Note: *Virtual specific gravity assumes that the total asphalt content exists in the form of a coating on the outside of the aggregate particles (i.e. no absorption).

TABLE III

GRADATION DETERMINATION - F MIXES

MIX	SIEVE SIZE	PERCENT PASSING, MIX A	PERCENT RETAINED, MIX A	GRADATION ADJUSTMENT, PERCENT	PERCENT RETAINED, ADJUSTED	PERCENT PASSING, ADJUSTED
F1	3/4"	100	0		0	100
	1/2"	84	16		16	84
	#4	54	30		30	54
	#8	39	15	-15	0	54
	#40	18	21	+ 8	29	25
	#80	12	6	+ 2	8	17
	#200	8	4	+ 2	6	11
	PAN	0	8	+ 3	11	0
F2	3/4"	100	0		0	100
	1/2"	84	16		16	84
	#4	54	30		30	54
	#8	39	15		15	39
	#40	18	21	-21	0	39
	#80	12	6	+ 7	13	26
	#200	8	4	+ 5	9	17
	PAN	0	8	+ 9	17	0
F3	3/4"	100	0		0	100
	1/2"	84	16		16	84
	#4	54	30	-30	0	84
	#8	39	15	+ 8	23	61
	#40	18	21	+12	33	28
	#80	12	6	+ 3	9	19
	#200	8	4	+ 2	6	13
	PAN	0	8	+ 5	13	0
F4	3/4"	100	0		0	100
	1/2"	84	16		16	84
	#4	54	30	-30	0	84
	#8	39	15	-15	0	84
	#40	18	21	+25	46	38
	#80	12	6	+ 7	13	25
	#200	8	4	+ 4	8	17
	PAN	0	8	+ 9	17	0
F5	3/4"	100	0		0	100
	1/2"	84	16		16	84
	#4	54	30		30	54
	#8	39	15	-15	0	54
	#40	18	21	-21	0	54
	#80	12	6	+12	18	36
	#200	8	4	+ 8	12	24
	PAN	0	8	+16	24	0

TABLE IV

GRADATION DETERMINATION - C MIXES

MIX	SIEVE SIZE	PERCENT PASSING, MIX A	PERCENT RETAINED, MIX A	GRADATION ADJUSTMENT, PERCENT	PERCENT RETAINED, ADJUSTED	PERCENT PASSING, ADJUSTED
C1	3/4"	100	0		0	100
	1/2"	84	16	+ 5	21	79
	#4	54	30	+10	40	39
	#8	39	15	-15	0	39
	#40	18	21		21	18
	#80	12	6		6	12
	#200	8	4		4	8
	PAN	0	8		8	0
C2	3/4"	100	0		0	100
	1/2"	84	16	+ 6	22	78
	#4	54	30	+10	40	38
	#8	39	15	+ 5	20	18
	#40	18	21	-21	0	18
	#80	12	6		6	12
	#200	8	4		4	8
	PAN	0	8		8	0
C3	3/4"	100	0		0	100
	1/2"	84	16	+30	46	54
	#4	54	30	-30	0	54
	#8	39	15		15	39
	#40	18	21		21	18
	#80	12	6		6	12
	#200	8	4		4	8
	PAN	0	8		8	0
C4	3/4"	100	0		0	100
	1/2"	84	16	+45	61	39
	#4	54	30	-30	0	39
	#8	39	15	-15	0	39
	#40	18	21		21	18
	#80	12	6		6	12
	#200	8	4		4	8
	PAN	0	8		8	0
C5	3/4"	100	0		0	100
	1/2"	84	16	+13	29	71
	#4	54	30	+23	53	18
	#8	39	15	-15	0	18
	#40	18	21	-21	0	18
	#80	12	6		6	12
	#200	8	4		4	8
	PAN	0	8		8	0

TABLE V

AGGREGATE GRADATION DATA

U. S. STANDARD SIEVE DESIGNATION	GRADATION PERCENT FINER BY WEIGHT — COARSE MIXES C1	C2	C3	C4	C5	CONTROL MIX "A"	FINE MIXES F1	F2	F3	F4	F5	
3/4"	100	100	100	100	100	100	100	100	100	100	100	COARSE
1/2"	79	78	54	39	71	84	84	84	84	84	84	COARSE
#4	39	38	54*	39*	18	54	54	54	84*	84*	54	COARSE
#8	39*	18	39	39*	18*	39	54*	39	61	84*	54*	COARSE
#40	18	18*	18	18	18*	18	25	39*	28	38	54*	FINE
#80	12	12	12	12	12	12	17	26	19	28	36	FINE
#200	8	8	8	8	8	8	11	17	13	17	24	FILLER

Note: *Fractions eliminated.

TABLE VI

TEST PROPERTIES OF BITUMINOUS MIXES - MIX A

ASPHALT (%)	DENSITY (pcf)	STABILITY (pounds)	VMA (%)	AIR (%)	VOIDS FILLED (%)	FLOW (1/100 inch)
2.5	145.8	1195	11.7	5.8	50.3	6.0
3.0	146.7	1585	11.5	4.8	60.9	6.0
3.5	149.3	1630	10.5	2.3	78.8	6.3
4.0*	150.8	1457	10.4	0.8	92.2	8.3
4.5	150.4	1413	11.2	0.5	95.3	10.0
5.0	149.2	1121	12.3	0.5	95.4	15.2
5.5	148.0	906	----	0.0	100.0	22.0

*Sample Calculations - Mix A (4.0 Percent Asphalt)

Bulk specific gravities

Coarse aggregate:	2.56
Fine aggregate:	2.62
Mineral filler:	2.65

Percentages of aggregate

Coarse aggregate:	61
Fine aggregate:	31
Mineral filler:	8

Average bulk specific gravity of aggregate in mix:

$$\frac{61.0 + 31.0 + 8.0}{\frac{61.0}{2.56} + \frac{31.0}{2.63} + \frac{8.0}{2.65}} = 2.59$$

Apparent specific gravity of asphalt = 1.01

Weight relationships (grams):

Average weight of briquettes:		118.1
Weight of asphalt in briquettes:	1188.1 x 0.04 =	47.5
Weight of aggregate in briquettes:	1188.1 x 0.96 =	1140.6

TABLE VI

TEST PROPERTIES OF BITUMINOUS MIXES - MIX A

(CONTINUED)

Volume relationships (cm^3)

Average volume of briquett:		491.5
Volume of asphalt in briquett:	47.5 x 1.01	= 47.3
Volume of aggregate in briquett:	1140.6 x 2.59	= 440.2
Volume of asphalt and aggregate:	47.3 + 440.2	= 487.5
Volume of air:	491.5 - 487.5	= 4.0
Volume of voids in aggregate:	4.0 + 47.3	= 51.3

Void relationships

Percent voids in mineral aggregate (VMA):	491.5/51.3	= 10.4
Percent air, total mix:	4.0/491.5	= 0.8
Percent voids filled with asphalt:	47.3/51.3	= 92.2

TABLE VII

TEST PROPERTIES OF BITUMINOUS MIXES - C MIXES

MIX	ASPHALT (%)	DENSITY (pcf)	STABILITY (pounds)	VMA (%)	AIR (%)	VOIDS FILLED (%)	FLOW (1/100 inch)
C1	3.0	148.6	1214	10.0	2.8	71.8	7.5
	3.5	151.1	1648	9.0	0.6	93.6	8.5
	4.0	150.6	1481	10.1	0.4	96.3	11.0
	4.5	149.9	1325	10.9	0.1	99.2	14.5
C2	3.0	143.0	850	13.1	6.2	52.3	7.0
	3.5	146.0	973	11.8	3.7	69.0	8.0
	4.0	145.9	948	12.3	3.0	76.0	9.0
	4.5	145.3	852	13.1	2.7	79.5	13.0
C3	2.5	147.0	1216	10.7	4.8	54.9	6.0
	3.0	149.0	1228	10.2	3.1	69.8	6.0
	3.5	149.8	1097	10.1	1.8	82.8	8.0
	4.0	150.0	1079	10.4	0.8	92.2	13.0
C4	3.0	147.5	1089	11.5	4.4	61.5	7.5
	3.5	148.6	1100	11.3	3.1	72.9	9.0
	4.0	148.1	1053	12.0	2.6	78.5	14.7
	4.5	147.2	816	13.0	2.4	81.2	19.3
C5	3.0	141.7	807	14.5	7.8	46.6	10.3
	3.5	144.0	813	13.6	5.5	59.3	11.5
	4.0	143.3	780	14.5	5.3	63.1	12.3
	4.5	142.4	768	15.3	5.1	66.5	13.3

TABLE VIII

TEST PROPERTIES OF BITUMINOUS MIXES - F MIXES

MIX	ASPHALT (%)	DENSITY (pcf)	STABILITY (pounds)	VMA (%)	AIR (%)	VOIDS FILLED (%)	FLOW (1/100 inch)
F1	2.5	144.7	1400		7.4	43.5	4.3
	3.0	146.6	1994	12.4	5.4	56.6	4.4
	3.5	147.8	1924	12.1	3.9	68.0	5.0
	4.0	149.2	1808	11.7	2.2	81.2	6.2
	4.5	150.7	1567	11.3	0.6	94.4	11.3
	5.0	149.4	1268	13.1	0.6	94.9	14.2
F2	4.0	146.2	2013	13.2	3.9	70.5	5.4
	4.5	147.5	2087	13.0	2.4	81.5	6.1
	5.0	147.5	1704	13.4	1.6	88.4	9.5
	5.5	146.8	1640	14.1	1.2	91.4	16.6
F3	3.5	145.0	2049	14.0	5.9	57.9	4.7
	4.0	147.2	2149	12.8	3.4	73.4	4.7
	4.5	148.9	2149	12.5	1.8	85.4	5.7
	5.0	149.5	1618	12.7	0.9	93.2	9.8
	5.5	149.1	1304	13.3	0.4	97.2	19.0
F4	4.0	143.0	1693	16.1	7.0	56.6	5.7
	4.5	143.9	1860	16.0	5.7	64.5	6.0
	5.0	145.7	1968	15.4	3.8	75.4	6.0
	5.5	146.3	1946	15.3	2.6	83.0	6.2
	6.0	145.4	1183	14.4	0.7	92.7	15.2
F5	4.5	143.4	2177	15.7	5.6	64.6	5.4
	5.0	144.3	2654	15.7	4.3	72.6	5.6
	5.5	145.6	2324	15.4	2.7	82.2	6.6
	6.0	145.6	2178	15.8	2.0	87.4	8.1

TABLE IX

DETERMINATION OF OPTIMUM ASPHALT CONTENTS

MIX	MAXIMUM STABILITY (lbs)	% AC AT MAXIMUM STABILITY	MAXIMUM DENSITY (pcf)	% AC AT MAXIMUM DENSITY	% AC AT 4% AIR CONTENT	OPTIMUM AC CONTENT (%)
A	1640	3.4	150.9	4.2	3.2	3.6
C1	1650	3.5	151.1	3.6	2.8	3.3
C2	980	3.7	146.0	3.7	3.4	3.6
C3	1230	2.9	150.0	3.6	2.8	3.1
C4	1110	3.4	148.7	3.6	3.7	3.4
C5	813	3.4	144.0	3.6	6.5	4.3
F1	2100	3.3	150.7	4.5	3.4	3.7
F2	2100	4.4	147.6	4.8	4.0	4.4
F3	2200	4.3	149.5	5.2	3.9	4.5
F4	1990	5.4	146.4	5.4	5.0	5.3
F5	2680	5.1	145.8	5.8	5.1	5.3

TABLE X

PROPERTIES OF BITUMINOUS MIXES AT OPTIMUM ASPHALT CONTENT

MIX	OPTIMUM AC CONTENT (%)	STABILITY (lbs)	DENSITY (pcf)	AIR (%)	VOIDS FILLED (%)	VMA (%)	FLOW (1/100 inch)
A	3.6	1640	149.7	2.3	82	11.9	6
C1	3.3	1560	150.4	1.3	89	10.0	8
C2	3.6	980	146.0	3.5	70	12.9	8
C3	3.1	1220	149.3	3.0	71	10.1	7
C4	3.4	1110	148.5	3.2	72	11.3	9
C5	4.3	770	142.9	5.1	66	15.1	14
F1	3.7	1930	148.3	3.2	74	12.1	5
F2	4.4	2080	147.4	2.7	80	13.1	6
F3	4.5	2160	148.9	1.8	85	12.5	6
F4	5.3	1980	146.4	3.0	81	13.1	7
F5	5.3	2540	147.2	3.4	78	15.4	6

IV. DISCUSSION

A. General.

The gradation for the control mix was established by the use of the dense gradation chart developed by Goode and Lufsey.[14] The chart differs from the one presently used by the Asphalt Institute in that the scale of the sieve openings on the abscissa is a power function of the Talbot formula for maximum theoretical density rather than a logarithmic function. Gradation was determined by extending a straight line from the point where zero percent aggregate passes a zero size theoretical sieve to the point where one hundred percent of the aggregate passes the 3/4 inch sieve. The line falls within the gradation band recommended by the Asphalt Institute and closely parallels the lower limit of this recommended gradation.

Test property curves were smooth and followed reasonably consistent patterns. On no occasion was it necessary to rerun any test because of questionable or erratic results. The properties of the mixes closely coincided with what could be anticipated on the basis of literature study and judgment. Results were quite gratifying in that they were more consummate than related investigations previously conducted.

The serviceability of some of the mixtures for pavements is open to debate. Some agencies, for example, would reject some of the mixtures on the grounds of low VMA and/or flow while other agencies, using "percent voids filled with bitumen" instead of VMA and do not set a lower limit of flow, would find the same mixtures entirely satisfactory. This conflict can be resolved only by further investigation and actual performance observations.

B. Properties of the C Mixes.

The C Mixes were blended by eliminating various intermediate sized fractions and proportionating the weight eliminated to larger sieves (Tables III and IV and Figure 1). Test results disclosed that unit weights (Figure 2) and stabilities (Figure 4) of the C Mixes were lower than Mix A while flow values (Figure 6), at a given percent asphalt, were higher than the control mix.

Unit weights were lower for two reasons. First, the gradation deviated from that which is necessary to produce maximum density and, second, larger sized aggregate with a specific gravity of 2.56 was substituted for smaller aggregate which had a higher specific gravity of 2.62. Maximum unit weight was reached at approximately half a percent lower asphalt content. This was due to a reduction of aggregate surface area caused by replacing intermediate sized particles by larger aggregate.

The lower stabilities were caused by the reduction of grain-to-grain contact between particles created by the absence of intermediate size aggregate.

The higher flow values, at any given percent of asphalt, were due to the lubricating effect caused by a thicker film of asphalt surrounding each particle. The thicker film of asphalt is caused by the reduction of the surface of the aggregate.

None of the mixtures met all criteria set forth for a satisfactory pavement. The principal deviation was due to low air-voids relationships (Table 10). Only three C Mixes met minimum criteria for percent air, one for VMA and none fell within limits established for "percent voids filled with bitumen."

1. Mix C1. Final gradation for Mix C1 was produced by eliminating the No. 8 fraction. This was only a 15 percent gradation adjustment, the smallest of all C Mixes. The comparatively small change in gradation produced only slight variations from properties observed in Mix A. Texture of the mix closely resembled that of Mix A except that it was slightly more sandy.

It is doubtful if this mix would have a prolonged service life. At optimum asphalt content the mix is excessively low in the air-voids relationships (Table X) which gives doubt to its ability to allow for temperature and volume change. In addition, at optimum asphalt content (Table X), the stability curve (Figure 4) is decreasing with decrease in asphalt content. This implies that such a pavement will lose stability with asphalt hardening.

2. Mix C2. The elimination of the No. 40 fraction in Mix C2 increased the amount of coarse aggregate from 61 to 82 percent with a corresponding decrease in the amount of fine aggregate from 31 to 10 percent (Table IV). The predominance of coarse aggregate, coupled with the absence of the No. 40 fraction, created more voids than the fine aggregate could fill. As a result, stability (Figure 4) and unit weight (Figure 2) were substantially reduced while percent air (Figure 8) was increased. The ratio of coarse aggregate to fine aggregate was

the largest of all C Mixes with the exception of Mix C5, which was the same (Table IV). This explains why the property curves of Mix C2 lie closer to those of Mix C5 than any other mix (Figure 14).

The only criteria for a satisfactory mix that was not met was VMA and "percent voids filled with bitumen," both of which were slightly low.

3. Mix C3. Mix C3 was blended with the No. 4 sieve fraction eliminated resulting in almost half of the mix being composed of material retained on the 1/2 inch sieve. The absence of the No. 4 fraction reduced intergranular contact (thereby reducing resistance to compaction) to the extent that unit weight (Figure 2) and percent air (Figure 8) curves were quite similar to those of Mix A. However, this reduced intergranular contact also resulted in a substantial loss in stability (Figure 4).

Only stability and percent air met minimum criteria for a satisfactory pavement. VMA, percent voids filled with bitumen, and flow were slightly low.

4. Mix C4. Gradation for Mix C4 was produced by eliminating both the No. 4 and No. 8 sieve fractions. This resulted in the coarse fraction being comprised entirely of material retained on the 1/2 inch sieve which was 61 percent of the total mix. The large gap in gradation coupled with only one sized coarse fraction created more voids than the fine aggregate could fill. As a result, unit weight (Figure 2) and stability (Figure 4) were reduced while percent air (Figure 8) was raised. Although the adjustment in gradation was the highest of all C Mixes, 45 percent, there was no reduction in the amount of fine

aggregate in the mix. This would explain why the curves were not lower than those for either Mix C2 or C5.

The mix meets all criteria for a satisfactory mix except for VMA and "percent voids filled with bitumen."

5. Mix C5. The gradation for Mix C5 was missing both the No. 40 and No. 8 sieve fractions. The ratio of coarse aggregate to fine aggregate, like Mix C2, was altered in favor of the coarse aggregate. Unlike Mix C2, however, the coarse fraction consisted of only two fractions while Mix C2 had three. This resulted in Mix C5 having not only a predominance of coarse aggregate, but a predominance of coarse aggregate of rather uniform size. This gradation created a mix with an unusually high percent of air (Figure 8), low stability (Figure 4), and low unit weight (Figure 2).

Mix C5 met all criteria for a satisfactory mix (Table X) except for percent voids filled with asphalt. This raises doubt as to the validity of VMA when applied to mixes containing rounded and/or gap-graded aggregate. The VMA in this mix was 15.1, which is supposed to be good; however, it was a very coarse, unworkable, and porous mixture which would be completely unsatisfactory for a pavement surface.

C. Properties of the F Mixes.

The F Mixes were blended in the same manner as the C Mixes except that the fractions eliminated were distributed to smaller sieves rather than the larger ones. This resulted in mixtures made up predominately of fine material (Table III).

The test results revealed that, at any given asphalt content, all F Mixes produced higher stabilities (Figure 5) and air contents (Figure

9) than Mix A while flow values (Figure 7) were lower. Stabilities were higher and flow values lower because of a lowering of the consistency of the bituminous binder caused by the suspension of excess filler in the bitumen which created a stiff mastic. Test results also indicate that consistency of the asphaltic mastic has a direct relationship to the amount of filler present in the mix. The unit weight was lower and air content was higher because of the lack of gradation for maximum density and a higher resistance to compaction due to the stiff asphaltic mastic.

The optimum asphalt content was observed to increase with a corresponding increase in the concentration of finer material. This was due to an increase in surface area of the aggregate caused by the substitution of smaller sized particles. It was also observed that the F Mixes had a broader operating range around the optimum asphalt content than the C Mixes. In other words, slight variation in asphalt content in the F Mixes produced less pronounced changes in the properties of the mixes.

Only two of the mixes met minimum criteria for percent air. Four of the mixes were within criteria established for "percent voids filled with bitumen" while only one met minimum criteria for VMA. The flow values were low for all five (Table X).

1. Mix F1. The elimination of the No. 8 fraction for blending Mix F1 was only a 15 percent adjustment in gradation. Accordingly, the properties found in Mix F1 were quite close to those of the control mix. It was a workable mixture closely approaching the appearance of Mix A except that it was slightly more sandy in texture.

This mix is one of those which may or may not meet minimum criteria for a satisfactory pavement, depending on which criteria is followed. If VMA criteria and minimum flow criteria are used the mix would be deemed unacceptable. If "percent voids filled with bitumen" is used as criteria the mix may be acceptable (it is only 1 percent below minimum criteria).

2. Mix F2. The No. 40 sieve fraction was eliminated in the gradation for Mix F2. Although the gradation adjustment was only 6 percent more than Mix F1 (15 versus 21 percent), proportioning of the weight was concentrated on three rather than four sieves (Table III) with a substantial increase in the amount of mineral filler. As a result, unit weight (Figure 3) was substantially lowered and percent air (Figure 9) was raised. What the mixture lacked in grain-to-grain contact between aggregate particles necessary to produce a high stability it made up for by decreasing the consistency of the bituminous binder. This is indicated by a definite increase in the asphalt content for maximum stability (Figure 5).

This mixture could be construed as another borderline mixture. Under one criteria it may be considered satisfactory because percent voids filled with bitumen are within limits and percent air is only 0.3 percent lower than the minimum. On the other hand, the mixture would be considered unacceptable if the minimum VMA and flow criteria is specified.

3. Mix F3. The gradation for Mix F3 was established by eliminating the No. 4 sieve fraction. Although this was a 30 percent adjustment, distribution of weight was proportioned to five sieves resulting in a broader distribution of weight (Table III). The amount of mineral

filler in the mix was only 13 percent as compared with 17 percent for Mix F2. Because of this, the property curves for Mix F3 generally fell between the curves for Mixes F1 and F2.

This mix would probably be rejected for use as a pavement because of marginal or low air-voids relationships and a low flow value.

4. Mix F4. Gradation for Mix F4 was blended by eliminating both the No. 4 and No. 8 sieves. The fine fractions comprised 84 percent of the total mix which resulted in the coarse aggregate being suspended in the mix and contributing little to the mixtures overall properties. Unit weight (Figure 3) was substantially reduced and percent air (Figure 9) increased because of the extreme variance from a dense gradation and the presence of such a large percentage of void producing fine aggregate. Maximum stability (Figure 5) was approximately the same as Mixes F1 and F2 except that the peak occurred at a substantially higher percent asphalt. Like Mix F2, what the mix lost in stability due to poor gradation, the mineral filler made up by reducing the consistency of the bituminous binder.

Similar to some of the mixtures just discussed, the acceptability of this mixture for use as a pavement would depend on what criteria is followed. The governing factor, however, most likely would be the uneconomical aspect of having to use such a high percentage of mineral filler.

5. Mix F5. Mix F5 was blended by eliminating the No. 8 and No. 40 fractions. As a result, the concentration of fine aggregate and mineral filler was the highest of all F Mixes (Table III).

Although the concentration was high, there was 46 percent coarse fraction remaining in the mix which allowed point-to-point contact between the larger particles which added to the stability (Figure 5). This intergranular contact between coarse aggregate coupled with a high concentration of fine material brought about the highest stability of all the mixes tested.

This mixture met all criteria for a satisfactory pavement except for a low flow value. However, use of such a mix may be uneconomical because of the high percentage of mineral filler (24 percent).

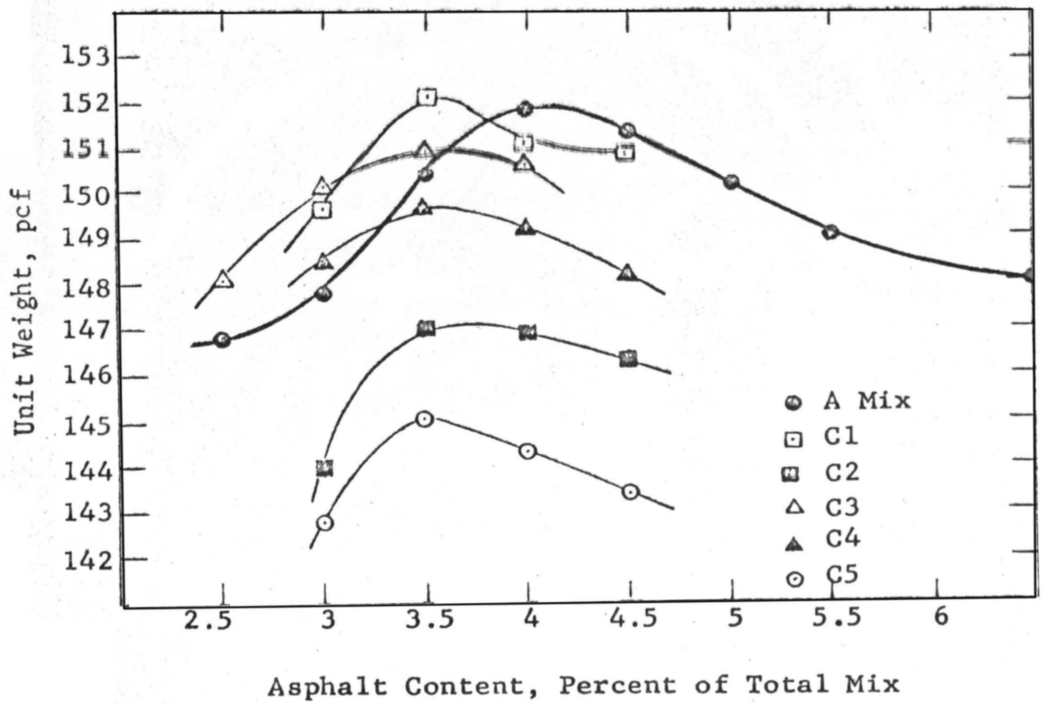

FIGURE 2. UNIT WEIGHT RELATIONSHIPS - C MIXES

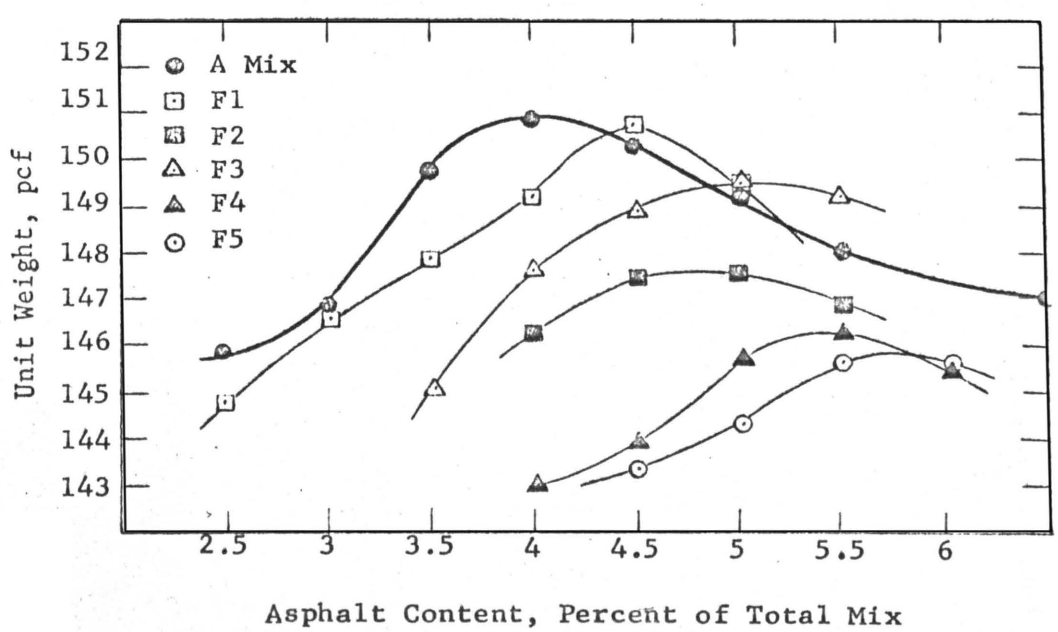

FIGURE 3. UNIT WEIGHT RELATIONSHIPS - F MIXES

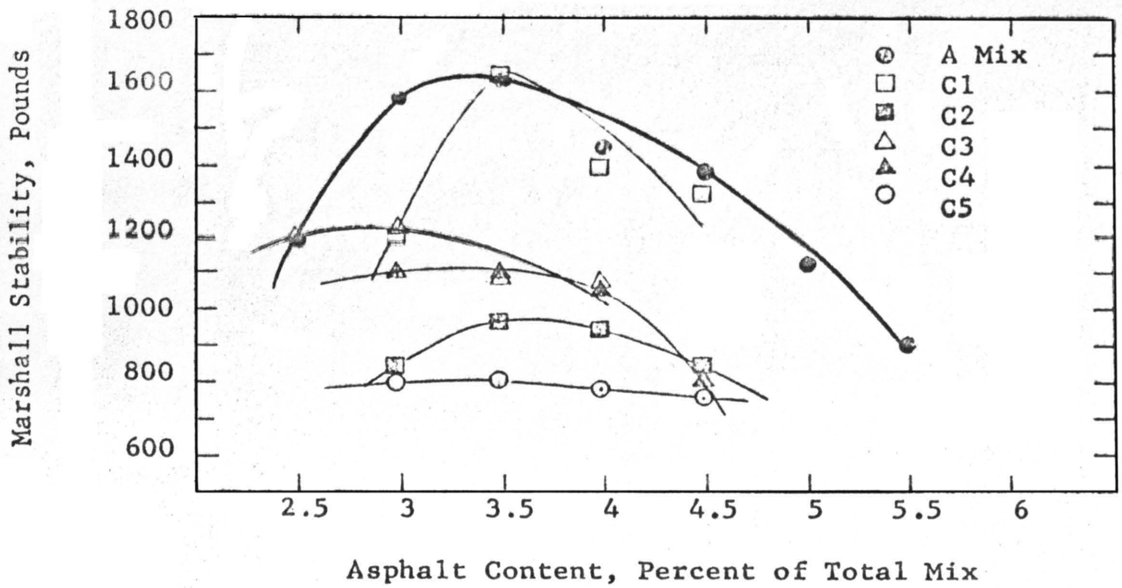

FIGURE 4. MARSHALL STABILITY RELATIONSHIPS - C MIXES

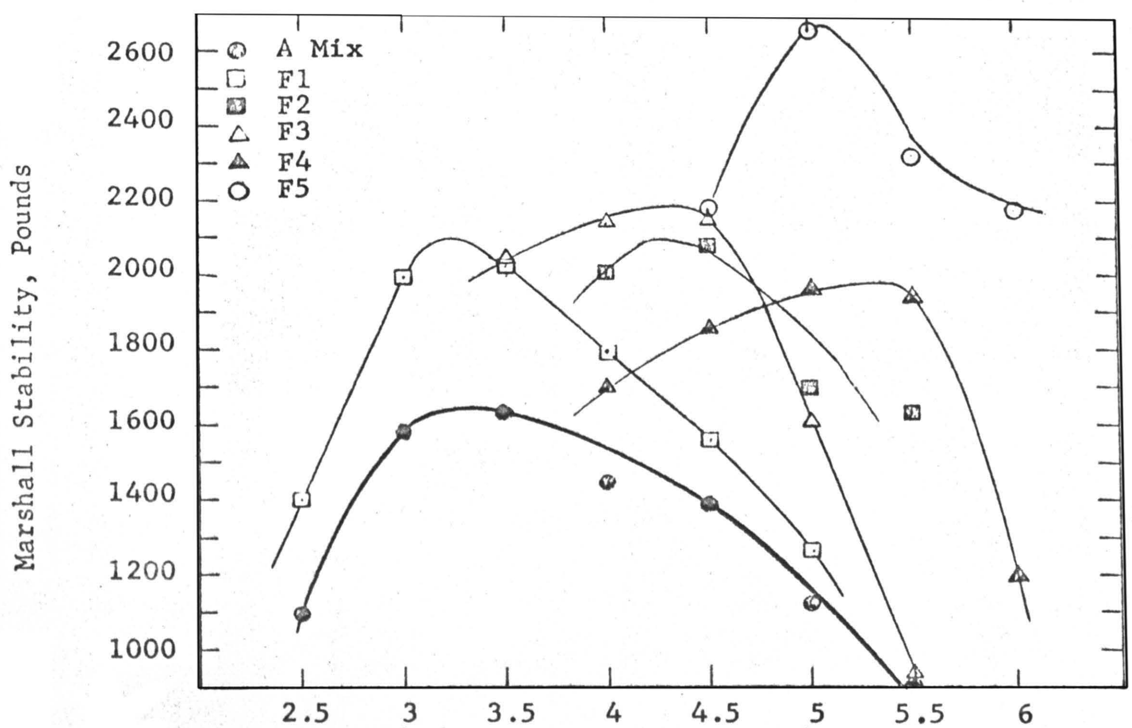

FIGURE 5. MARSHALL STABILITY RELATIONSHIP - F MIXES

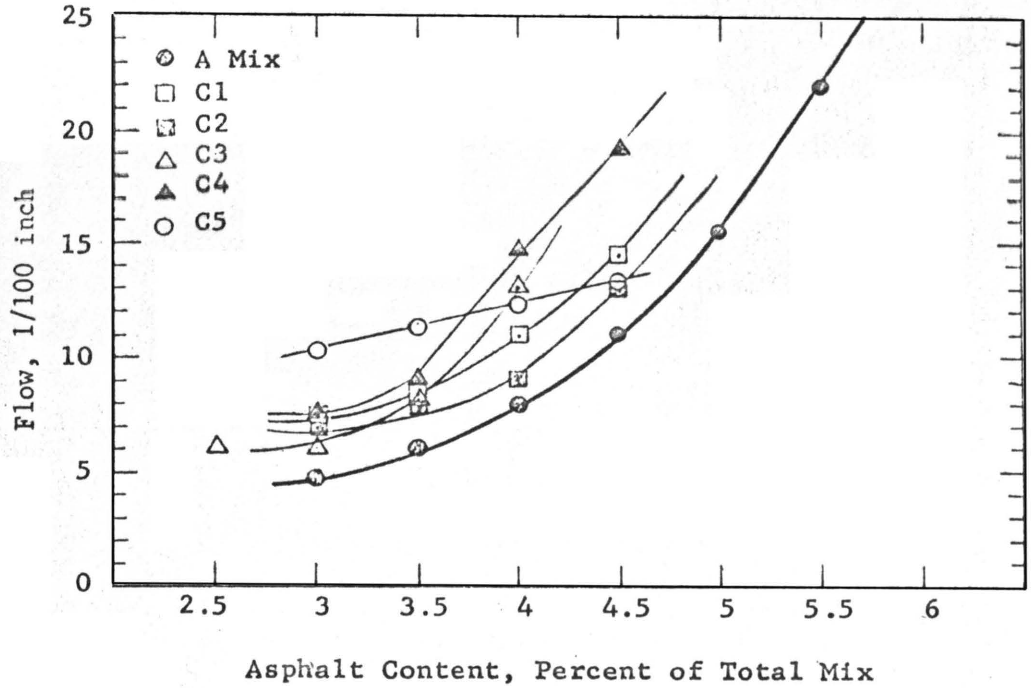

FIGURE 6. FLOW RELATIONSHIPS - C MIXES

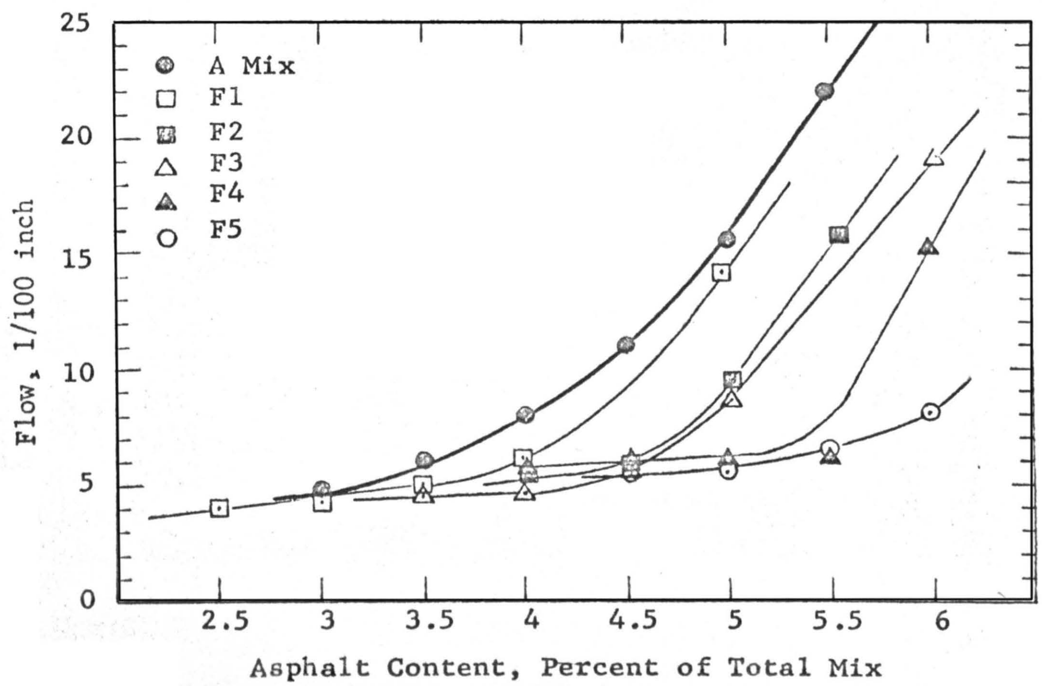

FIGURE 7. FLOW RELATIONSHIPS - F MIXES

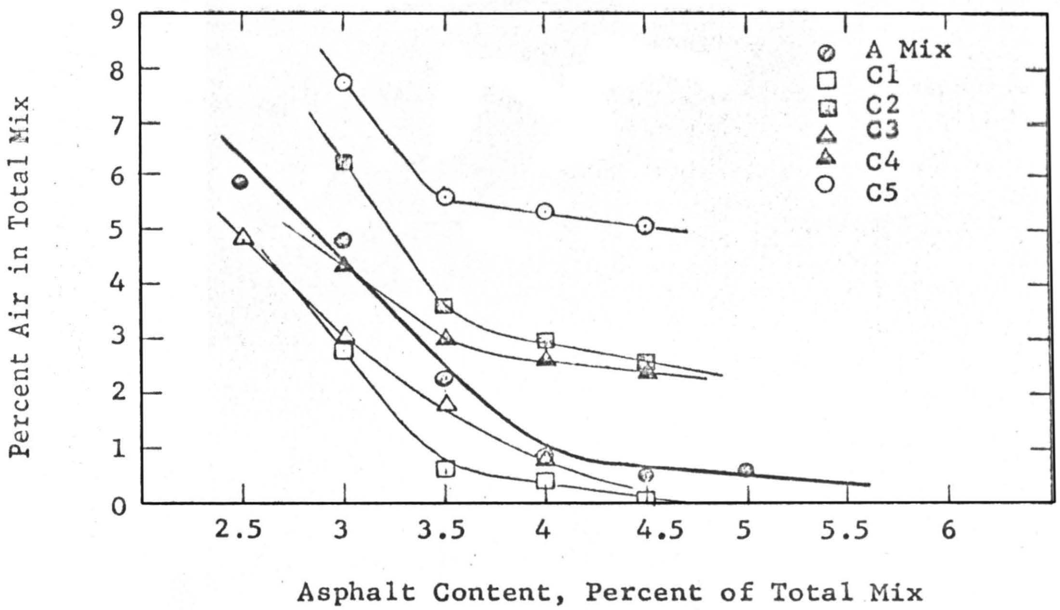

FIGURE 8. AIR IN TOTAL MIX RELATIONSHIPS - C MIXES

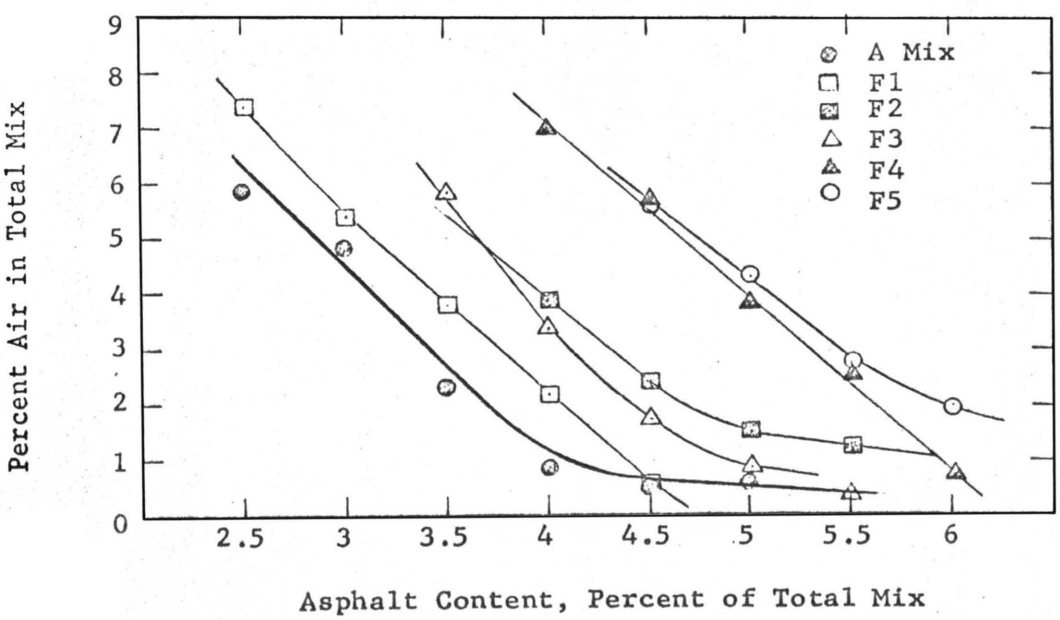

FIGURE 9. AIR IN TOTAL MIX RELATIONSHIPS - F MIXES

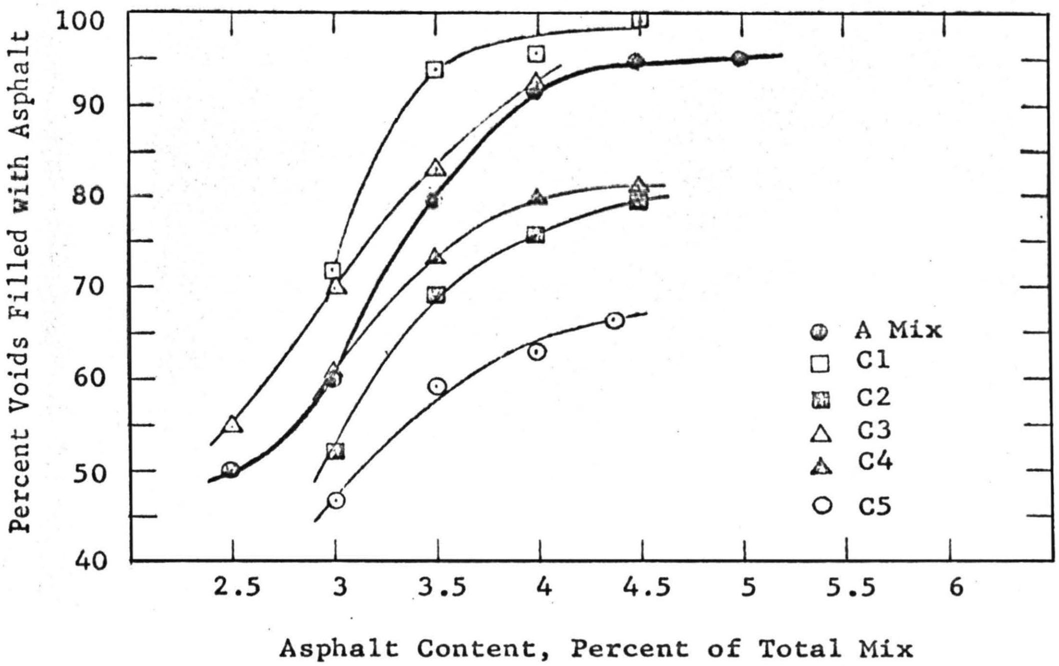

FIGURE 10. PERCENT VOIDS FILLED WITH ASPHALT RELATIONSHIPS - C MIXES

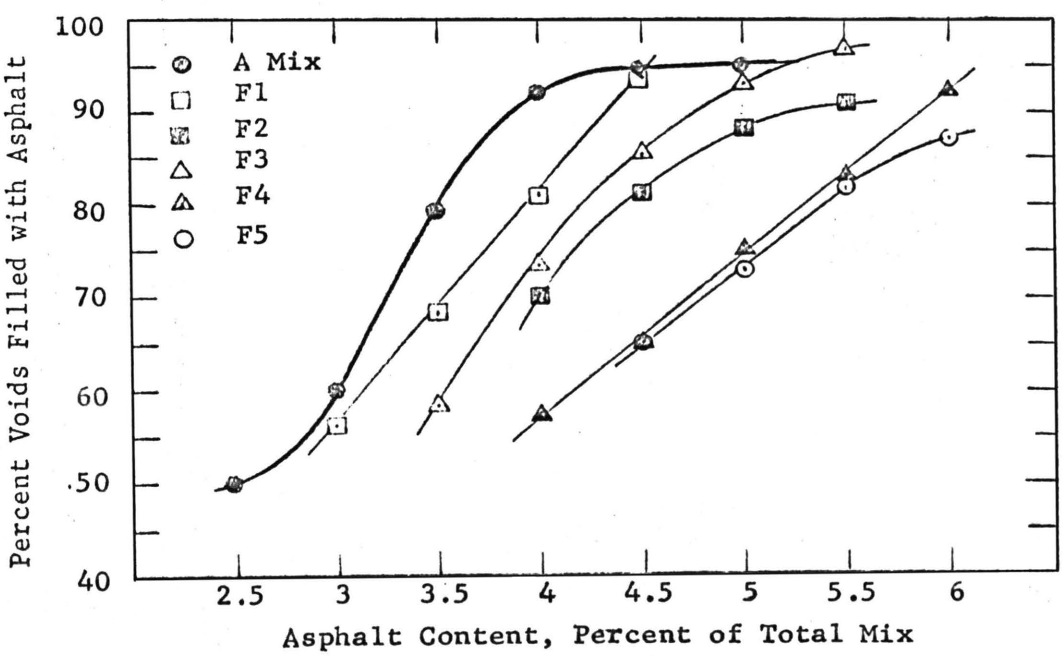

FIGURE 11. PERCENT VOIDS FILLED WITH ASPHALT RELATIONSHIPS - F MIXES

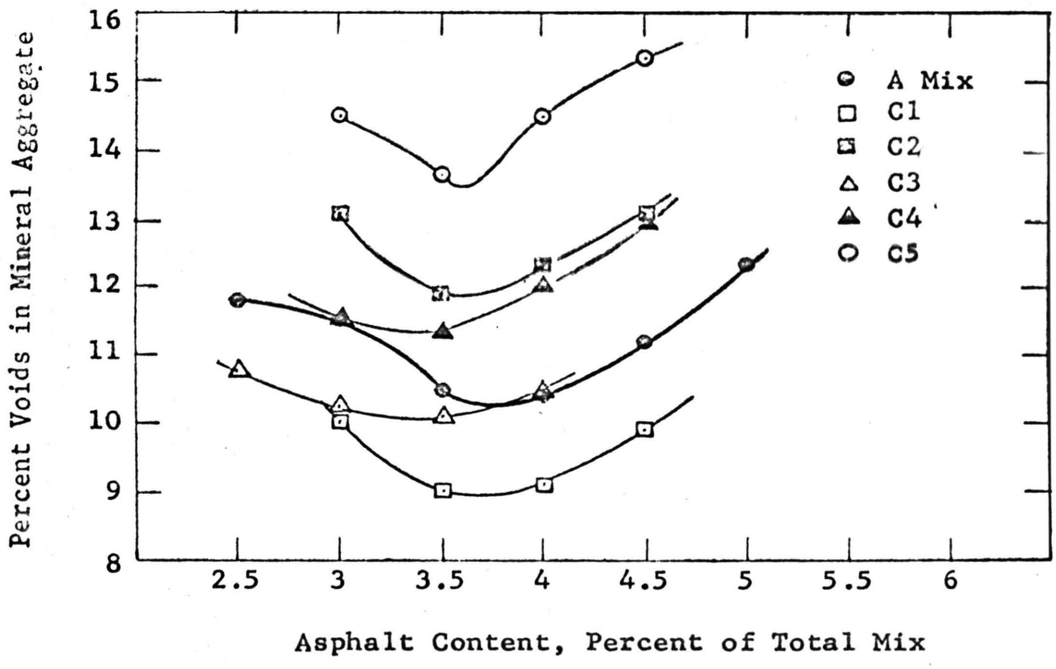

FIGURE 12. VOIDS IN MINERAL AGGREGATE - C MIXES

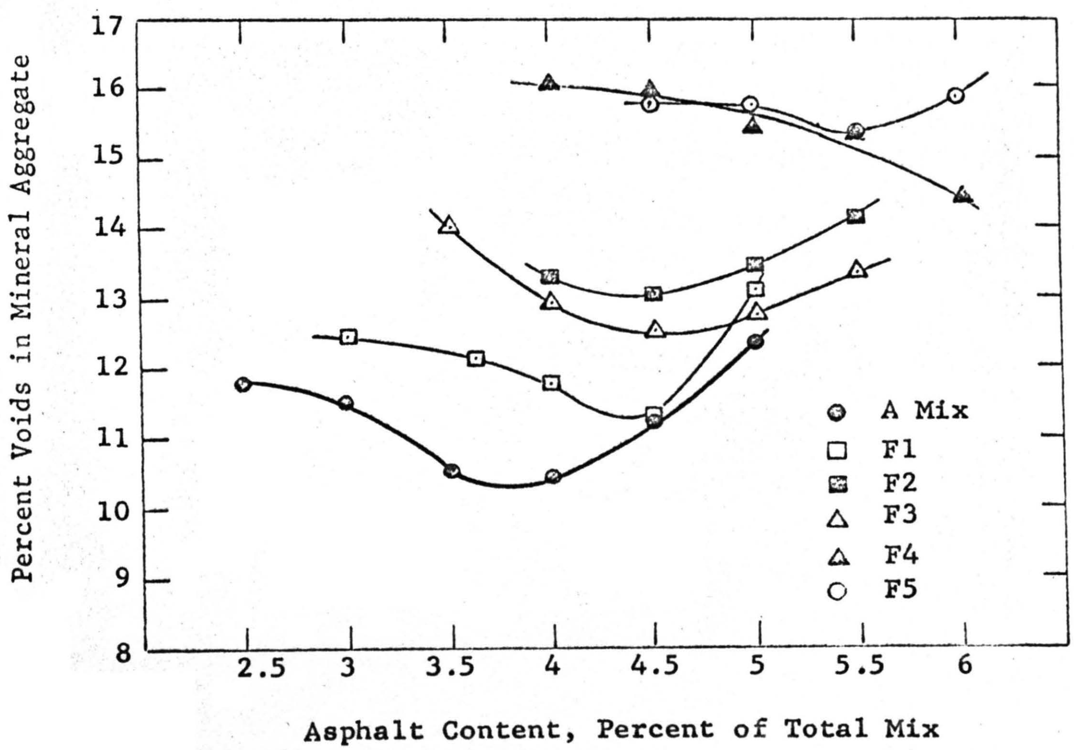

FIGURE 13. VOIDS IN MINERAL AGGREGATE - F MIXES

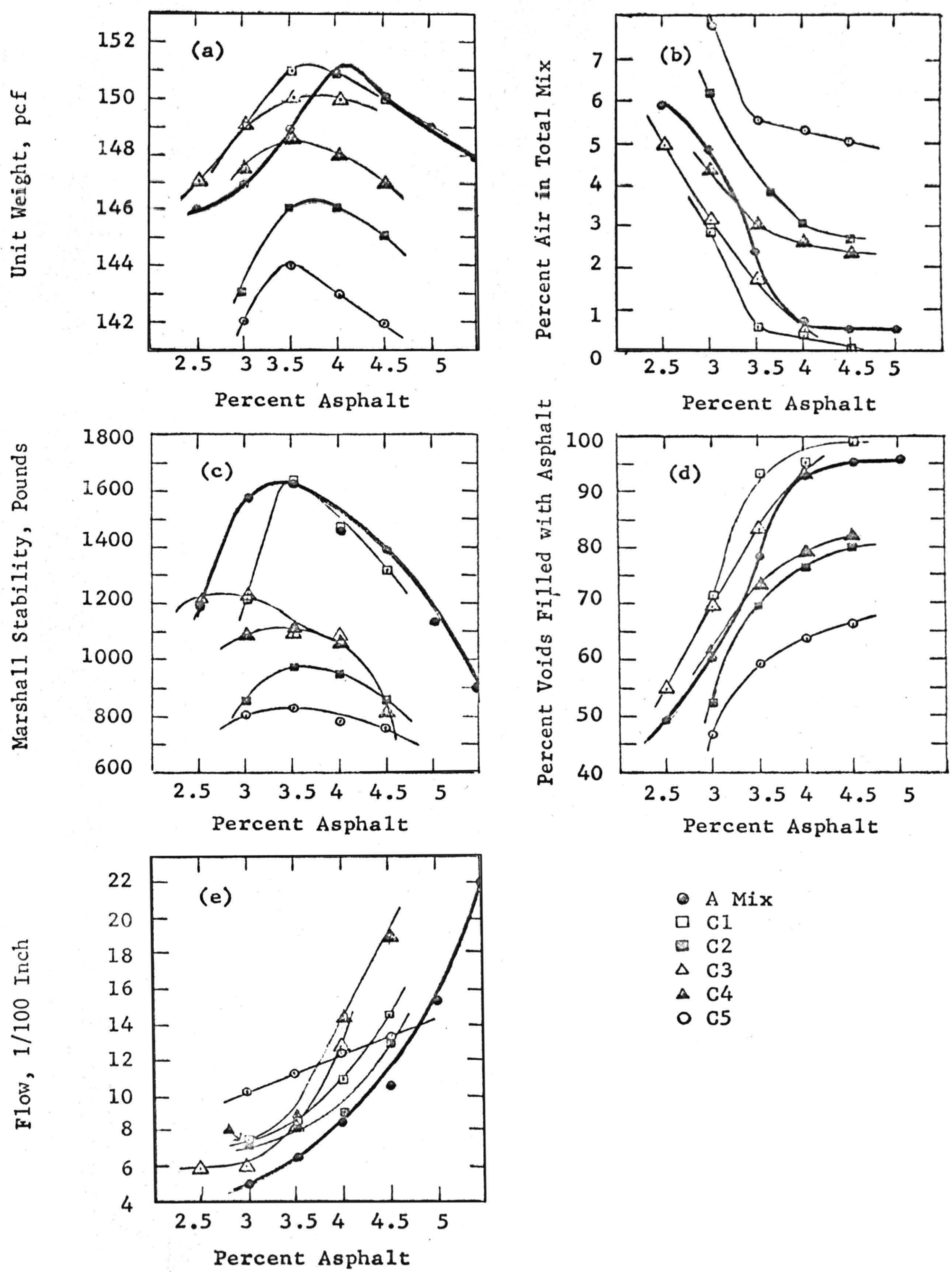

FIGURE 14. COMBINED PROPERTIES - C MIXES

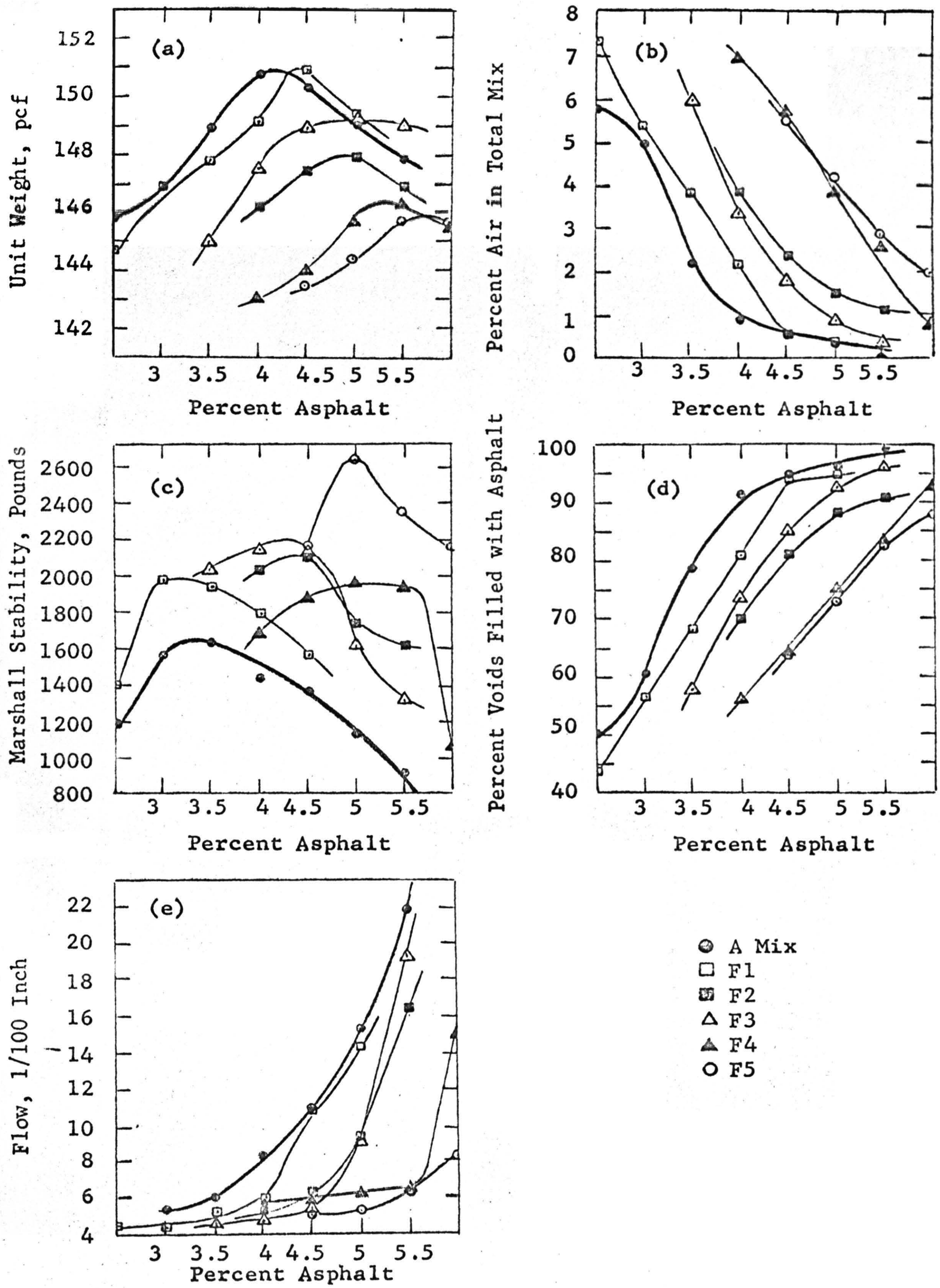

FIGURE 15. COMBINED PROPERTIES - F MIXES

V. CONCLUSIONS

Several conclusions can be made from the accumulation of data resulting from this investigation.

Properties of a bituminous mixture containing rounded aggregate can be materially improved by adjusting the gradation of the aggregate. Densely graded rounded aggregate produces mixtures which are very dense and therefore deficient in the air-voids relationship values. Gap in gradation can raise these values to acceptable standards. Those mixtures with a predominance of fine aggregate (F Mixes) generally produce more air-voids than do mixtures consisting of predominately coarse aggregate (C Mixes).

The surface area of the aggregate in a bituminous mixture has a direct relationship to the optimum asphalt content. The coarse textured mixtures require less asphalt to reach optimum values than do fine textured mixtures. The surface area is also related to the sensitivity of the values of various properties around the optimum asphalt content. The coarse textured mixtures are generally more sensitive to small variations in asphalt content than fine textured mixtures.

When compared to a densely graded mixture, coarse textured mixtures produce lower stability and higher flow values while fine textured mixtures produce higher stability and lower flow values.

A high concentration of mineral filler in a bituminous mixture reduce the consistency of a bituminous binder thereby increasing stability and reducing flow values.

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VITA

Ernest Harrington Martin was born on February 13, 1933 at Starkville, Mississippi. He is the son of an Army officer and, as a result, attended numerous primary schools until his father's retirement in 1947. The family settled in Irving, Texas where Ernest commenced his secondary education at Irving High School and completed it in June 1952. He received a Bachelor of Science in Civil Engineering from Texas A&M College in 1956 and then entered active military service as a Lieutenant in the Corps of Engineers.

Duty assignments have included Fort Belvoir, Virginia, Camp Wolters, Texas, Fort Richardson, Alaska, VietNam, and the University of Missouri at Rolla where he served as Assistant Professor of Military Science, 1962-1965. While assigned at the University he commenced his studies leading to a Master of Science Degree in Civil Engineering and was chosen to continue his degree requirements as a full time student starting the 1965 summer semester. However, military requirements in VietNam took precedence and his schooling was suspended for a year. He was returned to the University in time for the 1966 summer semester to complete his work.

Major Martin is married to the former Beverly Jane Jay of Howe, Texas. They have three sons, Ernest Harrington, Jr., Walter Jay, and Edward Graham.