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FINE AGGREGATE SHAPE AND SURFACE TEXTURE

Final Report

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16. Abstract

Aggregate shape and surface texture of fine aggregate for three different aggregate sources and four levels of degree of crushing was studied by seven different test procedures. Asphalt concrete mixtures using these aggregates were tested for deformation under load by five different tests. Efforts were made to correlate the fine aggregate test measurements to the asphalt concrete deformation properties.

The results from three of the fine aggregate tests were correlated with Hveem stability for the best relationships that were developed.

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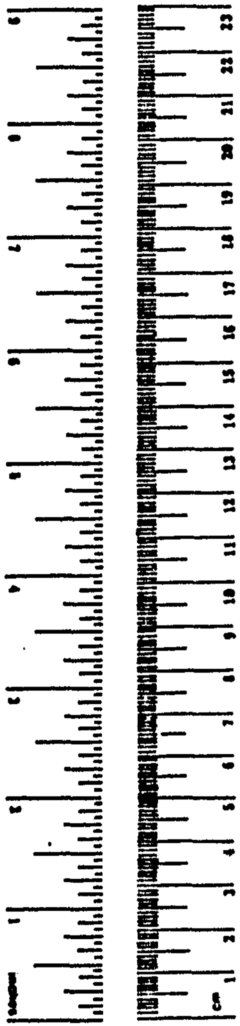
METRIC CONVERSION FACTORS

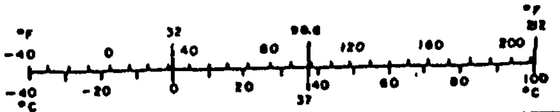
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

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INTRODUCTION

The properties of asphalt concrete depend upon a large number of factors, many of which relate to the aggregate used. It is recognized that the aggregate shape and/or surface texture have a significant effect on these properties. Whereas aggregate gradation and durability have fairly definitive tests, aggregate shape and surface texture generally do not. Visual examination of coarse aggregate particles larger than the No. 4 or No. 8 sieve to identify particles with fractured faces is the most common method of judging aggregate shape and surface texture. This method has a number of drawbacks, one of which is that it tells nothing about the fine aggregate.

This project was designed to evaluate various test methods that provide information about the shape and surface texture of fine aggregate for asphalt concrete. It was also intended to relate these fine aggregate properties to asphalt concrete properties. The following objectives were set for this project:

- To study and evaluate several tests of fine aggregate shape and surface texture
- To study asphalt concrete mix design properties for various aggregate shapes and surface textures
- To relate fine aggregate shape and surface texture to permanent deformation properties of asphalt concrete
- To develop procedures relating fine aggregate shape and surface texture laboratory evaluations to asphalt concrete properties for preparation of specifications and mix designs

REVIEW OF LITERATURE

Prior to initiating the work for determining the influence fine aggregate shape and texture has on the properties of asphalt concrete mixtures, a literature survey of the field was made. The primary areas of literature review were directed to tests that determine the geometric properties of fine mineral aggregate and deformation of asphalt concrete mixtures by simple creep tests.

Engineers and other investigators have determined that the properties of the asphalt alone are not sufficient to predict nor control the deformation of asphalt concrete mixtures. As early as 1954, Herrin and Goetz[1] reported on the effect of aggregate shape on stability of bituminous mixtures. In 1956 Rex and Peck[2] developed a simple direct test to measure the relative angularity and surface roughness of sand. Huang[3] developed a particle index test (rhombohedron mold) to reflect the discernible geometric characteristics of an aggregate. Tons and Goetz[4] measured specific rugosity and packing volume of aggregates. In 1977, Ishai and Tons [5] developed a pouring test for the direct measurement of the packing specific gravity of one-sized aggregate particles. McLeod and Davidson[6] presented test data showing that 2 and 3-inch diameter molds could be used to determine the particle index values for a fine aggregate. Other organizations such as the National Crushed Stone Association[7] (now National Stone Association) have proposed other test methods for determining characteristics of fine aggregate.

The geometric irregularity of aggregate particles has a major effect on the physical properties and mechanical behavior of bituminous paving mixtures. Griffith and Kallas[8] determined that the type of fine aggregate greatly influenced the stability of asphalt mixtures. Boutilier[9] determined that there was a relationship between the particle index of an aggregate and the physical properties of a bituminous aggregate mixture. Further, work by Ishai and Tons[10], Kalcheff and Tunnicliff[11] and Ishai and Gelber[12] have produced in-depth evidence that the surface texture of the aggregate is a significant factor in the deformation characteristics of bituminous mixtures.

In recent years, permanent deformations (rutting) and flushing have become major problems. There have been numerous efforts to develop deformation or rutting models for various rational design procedures. Of particular interest is the Shell proposed rutting model[13] which is based on simple creep tests. Although there has been concern expressed regarding test reproducibility, Finn, Monismith and Markevich[14] reported that, "Valid results can be obtained by measuring the deformations occurring in the central portion of taller specimens or by applying heavier preconditioning loads." Mamlouk[15] used creep tests to evaluate recycled pavement materials to determine both early and accelerated long-term aging characteristics. The North Dakota State Highway Department performed creep testing/rut predicting for 35 paving projects constructed throughout the state. The work performed did show that the creep test results do relate to characteristics of an asphalt mix[16, 17, 18].

MATERIALS

Aggregates

Three aggregate sources were selected for use in the test program. Crushed basalt was obtained from Flagstaff, Arizona and crushed river gravel was obtained from the Salt River at Tanner's 19th Avenue plant in Phoenix, Arizona and the Santa Cruz River near Tucson, Arizona. Uncrushed fine aggregate was obtained from the Santa Cruz River near Tucson, Arizona. Physical properties for coarse and fine aggregates are shown in Table 1.

Asphalt

AC-20 asphalt cement from the Edgington Refinery (Wilmington crude) source was supplied by Sahuaro Petroleum and Asphalt Company. See Table 2 for physical properties. A large number of samples were taken in metal containers. Individual samples were heated to mixing temperature as required for batching mixtures with any unused balance discarded. This allowed all work to be performed using the same quality asphalt cement in a once-heated condition.

Aggregate Preparation

The ledge material (basalt) obtained from Flagstaff contained all newly fractured faces. The Salt River and Tucson materials required laboratory crushing to obtain fractured faces on all particles. The materials were dried and separated into -3/4 to +1/2, -1/2 to +3/8, -3/8 to +1/4 and -1/4 to +No.4 sizes by mechanical sieving. The Salt River and Tucson material passing the No. 4 sieve was discarded and the +No.4 material was put through a jaw crusher three to five times to produce material approximately 1/4 in. maximum size. The jaw of the crusher had a surcharge of material over the jaw openings to reduce the production of elongated particles.

The crushed and uncrushed materials were separated into sizes (-No.4 to +No.8, -No.8 to +No.16, -No.16 to +No.30, -No.30 to +No.50 and -No.50 to +No.200) by means of a mechanical shaker. The Flagstaff aggregate was prepared in the same manner except that the -No.4 material was separated in the same manner as the crushed fines. No recrushing of the Flagstaff aggregate was performed at any time.

TABLE 1. PHYSICAL PROPERTIES OF AGGREGATES

CRUSHED COARSE AGGREGATE

	Salt River	Tucson	Flagstaff
L.A. Abrasion	20.5	15.7	14.4
Bulk Sp. Gr.	2.650	2.530	2.840
S.S.D. Sp. Gr.	2.673	2.571	2.865
App. Sp. Gr.	2.712	2.638	2.913
Absorption (%)	0.86	1.63	0.88

CRUSHED FINE AGGREGATE

	Salt River	Tucson	Flagstaff	Tucson*
L.A. Abrasion				
Bulk Sp. Gr.	2.632	2.510	2.920	2.456
S.S.D. Sp. Gr.	2.664	2.561	2.946	2.519
App. Sp. Gr.	2.719	2.647	2.999	2.620
Absorption (%)	1.21	2.06	0.91	2.50
Sand Equivalent	82	73	41	81

*Note: Uncrushed Fine Aggregate

TABLE 2. PHYSICAL PROPERTIES OF AC-20 ASPHALT CEMENT

Property	Unit	Test Value
Absolute Viscosity @ 140F	Poises	2235
Kinematic Viscosity @ 275F	cSt	263.1
Penetration @ 77F	1/10 mm	44
Flash Point, Cleveland Open Cup	F	529
Solubility in Trichloroethylene	Percent	99.98
Absolute Viscosity @ 140F*	Poises	4262
Ductility*	cm	50+

*Tests conducted on residue from thin film oven test

TESTS AND TEST PROCEDURES

Tests and test procedures are described in a general form in the following paragraphs. Detailed descriptions are given in referenced standards or in Appendix A.

Tests of Aggregate Shape and Texture

National Crushed Stone Association (now National Stone Association)

This test is used to determine the voids in individual size fractions of sand. A cylinder of known volume is filled by letting sand flow into the cylinder until it is overflowing. The cylinder is then carefully struck off and weighed. The sand is recombined and two additional weight determinations made. Three different sized aggregate fractions are used and an average test result of the three results is calculated.

Index of Aggregate Particle Shape and Texture

This test method provides an index value of the relative particle shape and texture characteristics of aggregates. A single size of material is compacted into a mold using two different compactive efforts (50 drops and 10 drops). The weighted average index of the material is a numerical indicator of the particle shape and surface texture.

The ASTM D3398-81 method quoted was modified to use a 3 in. x 3.5 in. mold and a tamping rod 5/16 in. in diameter with a mass of between 115 and 117.5 gm. The volume of the mold was calibrated at 411.4 cc. Tests were run on each combination of aggregates and on each of the following sizes -No.4 to +No.8, -No.8 to +No.16, -No.16 to +No.30, -No.30 to +No.50, -No.50 to +No.100 and -No.100 to +No.200. The results are based on weighted averages of the size in the final products.

Rex and Peck Time Index

This test is based upon the principle that smooth textured, rounded sand particles offer less resistance to free flow than do rough textured, angular particles. In performing this test, a 50 gm sample of washed aggregate (-No.20 to +No.30) is placed in a jar. The jar is then inverted, a stopper removed and timer started. The rate of flow for the sample is then compared to the rate of flow for standard Ottawa sand of the same size.

Void Ratio by Western Technologies

The void ratio test is based on comparing a calculated absolute volume of aggregate with a measured volume of aggregate. The test is performed by placing a known weight of a specific size aggregate in a graduated cylinder and finding the loose volume of this aggregate. This is done for three different aggregate fractions with an average void ratio being computed.

Florida Bearing Value

This test method (Indiana State Highway Commission Test Method Ind. 201-72) is used to determine the bearing value (psi) of a fine aggregate. A sample of material passing the No. 4 sieve is mixed with a known percent of water and placed in a bearing cup. A known amount of load is applied to the material. More material is added to the bearing cup and the same compressive load is applied. The bearing cup, filled in this manner, is placed in a compression testing machine and the material compressed at a rate of 2.4 in. per minute up to a total load of 1500 lb. A 1 sq in. area is centered on the compressed sample and placed in a Bearing Value machine. Weight is applied to the 1 sq in. area by use of shot. When a deformation of 0.01 in. in 5 seconds is achieved, the weight of the shot is recorded and the bearing value is calculated.

Direct Shear Test

This test method is used to determine the friction angle of an aggregate under different normal stresses. A prepared sample of aggregate is placed in a shear mold and consolidated. The sample is then placed in a direct shear device and a predetermined normal stress applied. A horizontal force is applied to the sample, and the sample is sheared. This procedure is repeated using a new sample and a higher normal stress.

Specific Rugosity by Packing Volume

The pouring test is used for direct measurement of the packing specific gravity of one-size aggregate particles. Each size particle is placed in a cone-shaped bin and then poured into a calibrated constant-volume container. The surface of the aggregates was leveled, the container and aggregate was weighed and the packing volume was calculated. Each pouring test was repeated three times for the same sample.

Asphalt Concrete Mix Design

Marshall Method

Triplicate samples were produced at asphalt contents ranging from 4 to 6 percent. The aggregate was proportioned according to Table 3. The coarse aggregate used for each mix design was the same as the crushed fine aggregate. The uncrushed fine aggregate used was from one source, Santa Cruz River in Tucson, for all mix designs. The Marshall samples were prepared using a once heated AC-20 asphalt cement. Samples were compacted at a temperature of 280F and 75 blows were applied to each specimen face using a mechanized compactor.

TABLE 3. MARSHALL MIX DESIGN

Aggregate Pit	Percent Crushed Fine Aggregate	Aggregate Proportions (%)*		
		CA	FA, Crushed	FA, Uncrushed
Salt River	100	38.0	62.0	0
	67	38.5	41.6	19.9
	33	38.8	20.9	40.3
	0	39.8	0	60.2
Tucson	100	38.0	62.0	0
	67	38.1	41.3	20.6
	33	38.3	20.4	41.3
	0	38.7	0	61.3
Flagstaff	100	37.4	62.6	0
	67	38.4	43.1	18.5
	33	39.5	22.1	38.4
	0	41.4	0	58.6

CA: Coarse Aggregate
FA: Fine Aggregate

* Aggregate Gradation

Sieve Size	Percent Passing
3/4 - in.	100
1/2 - in.	92
3/8 - in.	82
1/4 - in.	70
No. 4	62
No. 8	47
No. 16	33
No. 30	23
No. 50	15
No. 200	5

After the specimens were cooled, they were weight in air and in water. Samples were then placed in a water bath at 140F for 30 to 40 minutes and then tested in a Marshall testing machine for stability and flow. Voids, voids in mineral aggregate, voids filled with asphalt and asphalt absorption were calculated from bulk specific gravities of specimens and maximum specific gravity of the mixture.

Asphalt Concrete Strength and Deformation Tests

A number of strength and deformation tests of compacted asphalt concrete specimens were performed to develop data on the effect crushed fine aggregate has on these properties. Testing was performed at 77F and 140F using the three aggregate sources. Tests were performed using mixtures with asphalt contents at approximately 4 percent air voids and at these asphalt contents plus 0.5 percent.

Pavement deformation (rutting) is influenced by the amount of air voids in a compacted asphalt concrete. This is particularly evident if air voids are low. The strength and deformation of mixtures studied here were proportioned and compacted to maintain constant air voids in the specimens. Pavements in service typically reach air void levels from 2 to 4 percent while under traffic. Four percent air voids would constitute a well designed asphalt concrete with moderately low air voids such that other mix design property effects on deformation could be observed. Testing at that asphalt content plus 0.5 percent was performed to measure the mixture's sensitivity to a small increase in asphalt content.

Static Creep, 77F

Specimens were compacted by the 75-blow Marshall procedure at the two asphalt contents. Following a short loading period at 14.5 psi each specimen was loaded in axial compression with 1.6 psi while an initial reading was taken on the top of the specimen with a dial gage. Specimens were then loaded at 14.5 psi for 22 hr. The load was removed and the 1.6 psi load returned to the specimen. The permanent deformation was measured by the dial gage when the recovery of deflection had stabilized. The creep modulus for each specimen was computed using the unit strain and unit stress from the test.

Static Creep, 140F

Specimen preparation and the test procedure for the 140F creep testing was the same as used for the 77F creep testing except that the 14.5 psi loading prior to taking the initial reading with the dial gage was not used. Instead, the specimens were loaded with the 1.6 psi load and the initial reading taken when the dial gage movement had stabilized, which occurred within 5 minutes after placement of the load. Specimens were then loaded for 22 hr with 14.5 psi. The permanent deformation was measured with the 1.6 psi load in place and the creep modulus was calculated.

Hveem Stability

Specimens representing each of the aggregate pits and each of the crushed fine aggregate percentages were compacted at the two asphalt contents by ASTM Test Method D-1561. Specimens were then tested for Hveem stability by ASTM Test Method D-1560. Specimens were carefully removed following testing and cooled to laboratory temperature for further testing by diametral loading with a resilient modulus device.

Resilient Modulus, 77F

Following testing for Hveem stability and return to laboratory temperature, specimens were tested in a Mark IV resilient modulus device using a diametral impulse load of 70 lb. The lateral deflection was measured. The resilient modulus was calculated from these data.

Diametral Creep, 140F

Following resilient modulus testing, specimens were placed in a 140F environmental room for 2 hr and then diametrally loaded for 1000 sec with a 7 lb load. The load was removed and the permanent deformation measured after the resulting deflection had stabilized. The creep modulus was calculated from these data.

TEST RESULTS

Aggregate Shape and Surface Texture

Aggregate shape and surface texture tests were performed and analyzed using crushed fine aggregate from three sources and for three percentages of crushed and uncrushed fine aggregate. Tests were also performed using 100 percent uncrushed aggregate; however, the uncrushed aggregate data were not used in the analysis of variance as these tests were the same for all three aggregate sources.

National Crushed Stone Association

The proposed method of test by the National Crushed Stone Association was performed on three different sources of crushed fine aggregate and three percentages of crushed fine aggregate. Three sieve groups were used (No.8 to No.16, No.16 to No.30, No.30 to No.50) and three trials were performed for each group. Figure 1 is a plot of the percentage voids measured for the aggregate sources and percentage of crushed fine aggregate. All uncrushed fine aggregate was from Santa Cruz River near Tucson, Arizona.

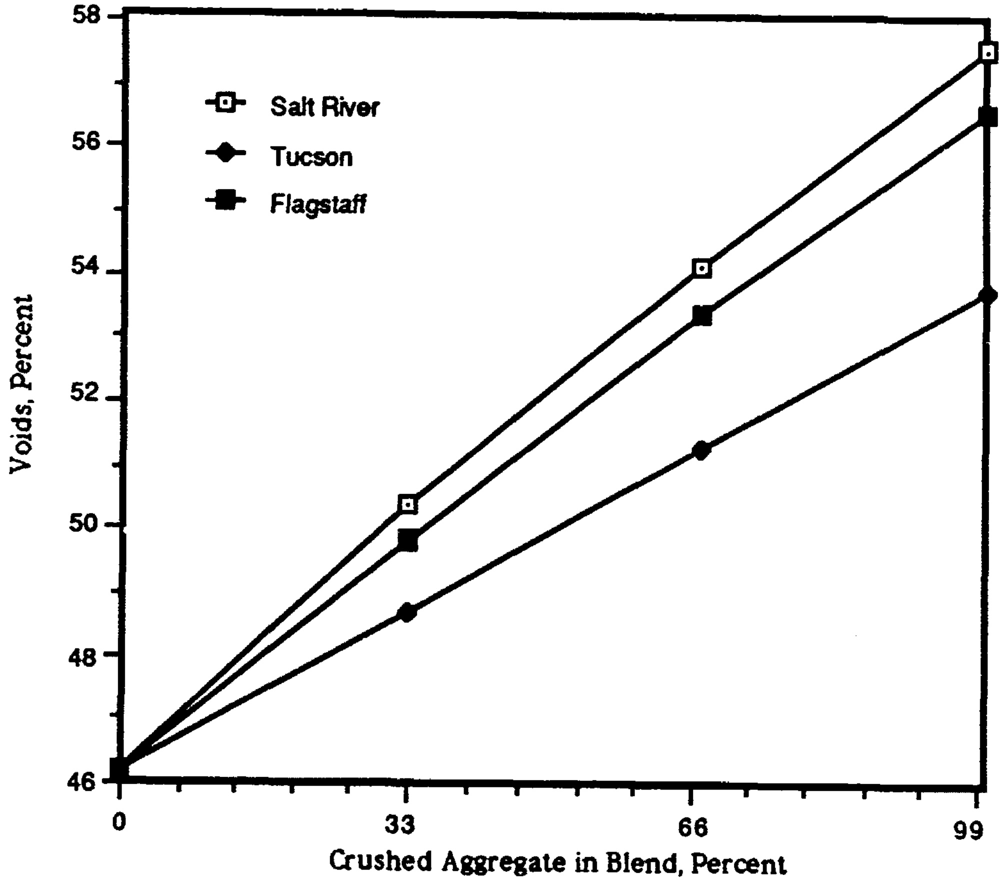

Figure 1 National Crushed Stone Association

Table 4 gives the percent voids for each combination of aggregates used. Table B-1 in Appendix B gives the analysis of variance. This analysis had three different aggregate sources and three percentages of crushing. There were three trials of the test performed for each combination of variables. By use of the analysis of variance and the F-test, it was concluded that the test results for the source of crushed fine aggregate used and the percent crushed fine aggregate each produced highly significant effects. An explanation of the F-test appears in Appendix D.

Index of Particle Shape and Texture

This test was performed on three different sources of crushed fine aggregate and three percentages of crushed fine aggregate. Six sieve groups were used (No.4 to No.8, No.8 to No.16, No.16 to No.30, No.30 to No.50, No.50 to No.100 and No.100 to No.200) and a weighted average was determined.

The results of the Particle Index tests are tabulated in Table 5 and are shown graphically in Figure 2. These data indicate a definite relationship between the particle index and percent of crushed fine aggregate for the three sources studied. The Tucson source had significantly lower particle indexes than the Salt River and Flagstaff sources which were not significantly different from each other.

This test method is very time consuming and is primarily used in research work. Therefore, sufficient data were not generated to perform an analysis of variance. Because of the nature of this test, it is not recommended for general laboratory use as a fine aggregate texture test.

TABLE 4. NATIONAL CRUSHED STONE ASSOCIATION TEST

Test Results - Percent Voids

Aggregate Pit	Percent Crushed	Trial	#8-#16	#16-#30	#30-#50	Average	Average
Salt River	100	1	56.1	58.6	57.9	57.5	57.6
		2	56.3	58.2	58.1	57.5	
		3	56.3	58.4	58.0	57.6	
	67	1	52.7	55.1	54.8	54.2	54.2
		2	53.0	54.6	55.2	54.3	
		3	52.7	54.9	54.9	54.2	
	33	1	48.7	51.1	51.4	50.4	50.4
		2	48.9	50.6	51.7	50.4	
		3	48.7	50.8	51.5	50.3	
Tucson	100	1	51.5	54.3	55.8	53.9	53.8
		2	51.4	54.0	55.8	53.7	
		3	51.4	54.1	55.6	53.7	
	67	1	49.2	51.7	53.3	51.4	51.3
		2	49.0	51.2	53.3	51.2	
		3	49.2	51.4	53.3	51.3	
	33	1	46.9	48.9	50.4	48.7	48.7
		2	47.0	48.5	50.6	48.7	
		3	46.8	48.9	50.4	48.7	
Flagstaff	100	1	55.5	57.0	57.4	56.6	56.6
		2	55.6	56.7	57.4	56.6	
		3	55.6	56.6	57.4	56.5	
	67	1	52.3	53.5	54.3	53.4	53.4
		2	52.3	53.4	54.4	53.4	
		3	52.3	53.4	54.3	53.3	
	33	1	48.6	49.9	51.1	49.9	49.8
		2	48.6	49.6	51.2	49.8	
		3	48.6	49.8	51.1	49.8	
Tucson	0	1	44.7	46.5	47.8	46.3	46.2
		2	44.6	45.8	48.0	46.1	
		3	44.5	46.2	47.8	46.2	

TABLE 5. ASTM D3398-81 INDEX OF AGGREGATE PARTICLE SHAPE AND TEXTURE

Test Results - Particle Index

Aggregate Pit	Sieve Fraction	Percent Crushed			
		100	67	33	0
Salt River	# 4-# 8	19.05	15.33	12.15	8.65
	# 8-# 16	19.93	16.53	13.18	9.25
	# 16-# 30	21.28	17.48	14.05	10.47
	# 30-# 50	20.70	17.63	14.83	12.45
	# 50-#100	20.68	18.23	16.32	15.30
	#100-#200	21.35	19.68	18.48	17.82
	Weighted Avg	20.22	16.97	14.03	11.03
Tucson	# 4-# 8	12.88	11.88	9.65	Same as Salt River
	# 8-# 16	15.40	13.48	11.38	
	# 16-# 30	17.10	14.98	12.43	
	# 30-# 50	18.00	16.58	13.98	
	# 50-#100	19.02	17.55	20.03	
	#100-#200	19.60	18.73	18.97	
	Weighted Avg	16.09	14.63	12.89	
Flagstaff	# 4-# 8	19.40	16.38	12.00	Same as Salt River
	# 8-# 16	19.55	16.28	12.50	
	# 16-# 30	21.60	16.75	13.08	
	# 30-# 50	19.75	17.30	13.98	
	# 50-#100	19.40	17.65	15.95	
	#100-#200	18.37	17.78	16.95	
	Weighted Avg	19.78	16.79	13.37	

Rex and Peck Time Index

This test was performed on three different sources of crushed fine aggregate and three percentages of crushed fine aggregate. Three trials were performed on each aggregate combinations.

Test results indicate the time index to have significant variation between aggregate sources. The time index also indicates a definite relationship with the percent of crushed fine aggregate for all three aggregate sources. Test results are graphically shown in Figure 3.

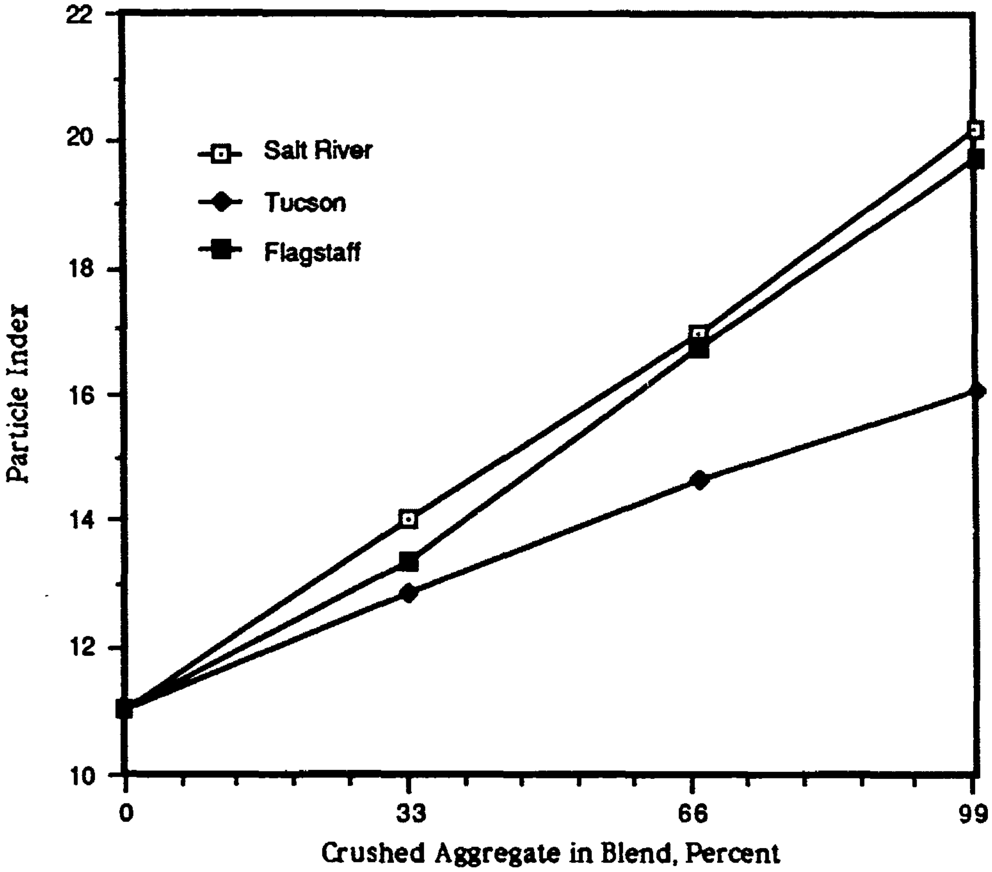

FIGURE 2 ASTM D3398-81 PARTICLE INDEX

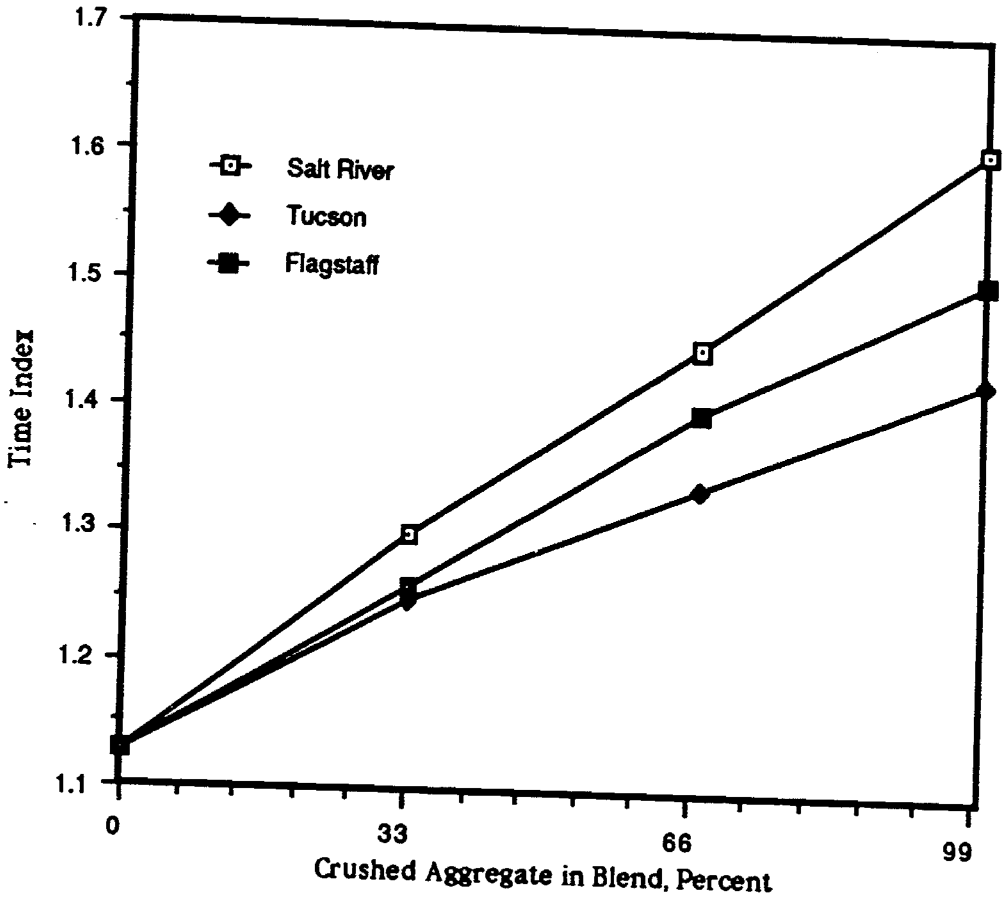

FIGURE 3 REX AND PECK TIME INDEX

Table 6 gives the time index for each combination of aggregates used. Table B-2 in Appendix B gives the analysis of variance. This analysis had three different aggregate sources and three percentages of crushed material. There were three trials of the test performed for each combination of variables. By use of the analysis of variance and the F-test, it was concluded that the type of aggregate and the percent crushed aggregate each produced significant effects on the time index.

TABLE 6. REX AND PECK TIME INDEX

Test Results - Time Index

Aggregate Pit	Trial	Percent Crushed 100	Percent Crushed 67	Percent Crushed 33	Percent Crushed 0
Salt River	1	1.61	1.45	1.30	1.10
	2	1.60	1.44	1.29	1.13
	3	1.61	1.45	1.30	1.15
	Avg	1.61	1.45	1.30	1.13
Tucson	1	1.42	1.34	1.25	Same as Salt River
	2	1.44	1.34	1.24	
	3	1.44	1.35	1.25	
	Avg	1.43	1.34	1.25	
Flagstaff	1	1.50	1.39	1.26	Same as Salt River
	2	1.51	1.41	1.27	
	3	1.51	1.39	1.26	
	Avg	1.51	1.40	1.26	

Void Ratio by Western Technologies

In order to determine the void ratio of a fine aggregate, a testing procedure was developed by Western Technologies Inc. This test was performed on crushed fine aggregate from the three different sources and three percentages of crushed fine aggregate. Three sieve groups were used (No.4 to No.8, No.20 to No.30 and No.100 to No.200) and three complete trials were performed.

Test results show definite relationship between the void ratio and percent crushed fine aggregate for the three aggregate sources. Significantly different relationships are evident for each aggregate source. Average values of the test data are plotted in Figure 4.

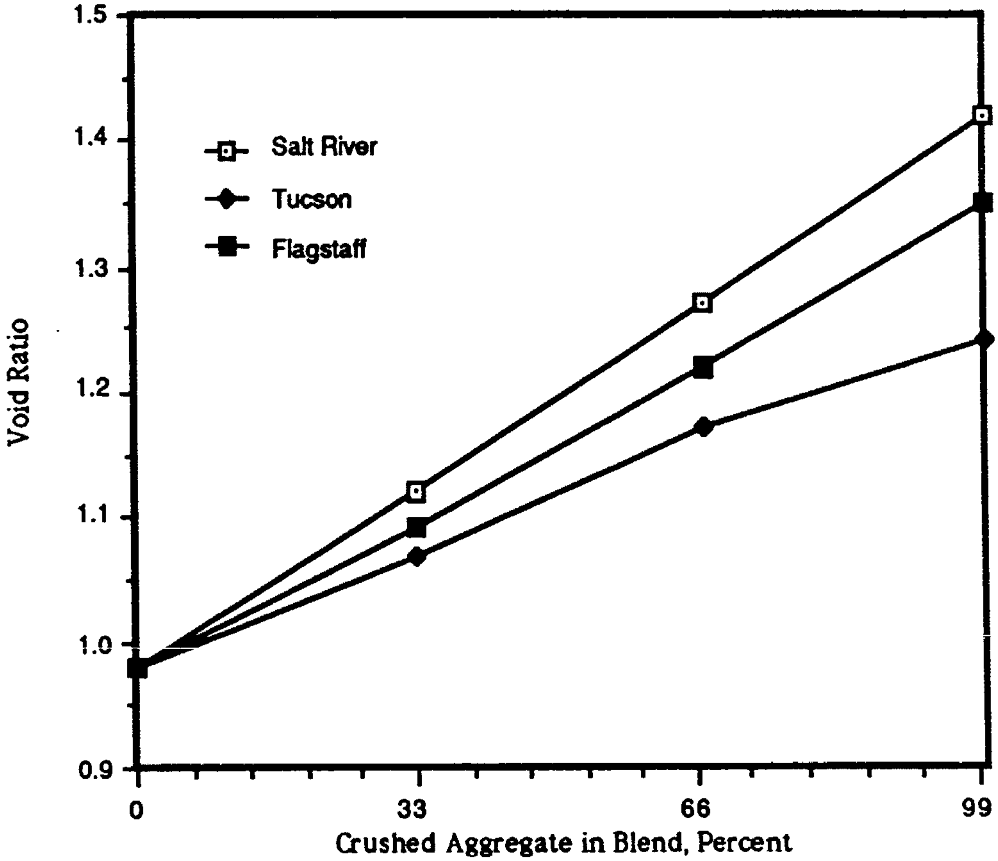

FIGURE 4 WESTERN TECHNOLOGIES VOID RATIO

Table 7 gives the void ratio for each combination of aggregates used. Table B-3 in Appendix B gives the analysis of variance. The analysis used three different aggregate sources and three percentages of crushed fine aggregate. There were three trials of the test performed for each combination of variables. By use of the analysis of variance and F-test, it was concluded that there were significant differences between the test results for both the type of aggregate used and the three percentages of crushed fine aggregate.

Florida Bearing Value

The three aggregate sources and three percentages of crushed fine aggregate were tested using the Florida Bearing Ratio test apparatus. Many of the tests exceeded the capacity of the apparatus. In those cases, the tests were discontinued and the test results recorded as the maximum value reached.

Figure 5 shows the relationship between the percent crushed, the type of aggregate and the Florida Bearing Value. Only the 33 percent crushed fine aggregate value achieved results for all aggregate sources. The Florida Bearing apparatus used in the test had a maximum capacity of 298 psi. Values above 298 psi could only be recorded as 298 psi plus. See Table 8. Because of the inability to evaluate test results at all test levels, an analysis of variance could not be performed.

To become a useful test for the determination of fine aggregate texture, the Florida Bearing apparatus would have to be redesigned. With a redesigned apparatus, test values greater than 298 psi could most likely be accurately determined and evaluated. The Florida Bearing Value test has the advantage over all other test procedures studied that it evaluates a graded fine aggregate rather than fractions of the total material.

TABLE 7. WESTERN TECHNOLOGIES VOID RATIO

Test Results - Void Ratio

Aggregate	Percent	Sieve		Trial			
Pit	Crushed	Fraction	1	2	3	Average	Average
Salt River	100	# 4-# 8	1.38	1.37	1.34	1.36	
		# 20-# 30	1.45	1.46	1.45	1.45	1.42
		#100-#200	1.45	1.45	1.46	1.45	
	67	# 4-# 8	1.21	1.21	1.24	1.22	
		# 20-# 30	1.29	1.28	1.28	1.28	1.27
		#100-#200	1.31	1.31	1.31	1.31	
	33	# 4-# 8	1.07	1.07	1.07	1.07	
		# 20-# 30	1.11	1.11	1.11	1.11	1.12
		#100-#200	1.20	1.17	1.19	1.19	
Tucson	100	# 4-# 8	1.14	1.11	1.11	1.12	
		# 20-# 30	1.26	1.26	1.26	1.26	1.24
		#100-#200	1.36	1.35	1.34	1.35	
	67	# 4-# 8	1.09	1.07	1.07	1.08	
		# 20-# 30	1.17	1.14	1.16	1.16	1.17
		#100-#200	1.27	1.26	1.26	1.26	
	33	# 4-# 8	1.00	1.03	1.00	1.01	
		# 20-# 30	1.05	1.07	1.04	1.05	1.07
		#100-#200	1.17	1.15	1.15	1.16	
Flagstaff	100	# 4-# 8	1.40	1.43	1.41	1.41	
		# 20-# 30	1.38	1.37	1.37	1.37	1.35
		#100-#200	1.28	1.27	1.27	1.27	
	67	# 4-# 8	1.22	1.24	1.24	1.23	
		# 20-# 30	1.24	1.22	1.24	1.23	1.22
		#100-#200	1.20	1.20	1.20	1.20	
	33	# 4-# 8	1.05	1.09	1.06	1.07	
		# 20-# 30	1.09	1.09	1.10	1.09	1.09
		#100-#200	1.13	1.11	1.11	1.12	
Tucson	0	# 4-# 8	0.97	0.97	0.94	0.96	
		# 20-# 30	0.92	0.94	0.93	0.93	0.98
		#100-#200	1.08	1.05	1.06	1.06	

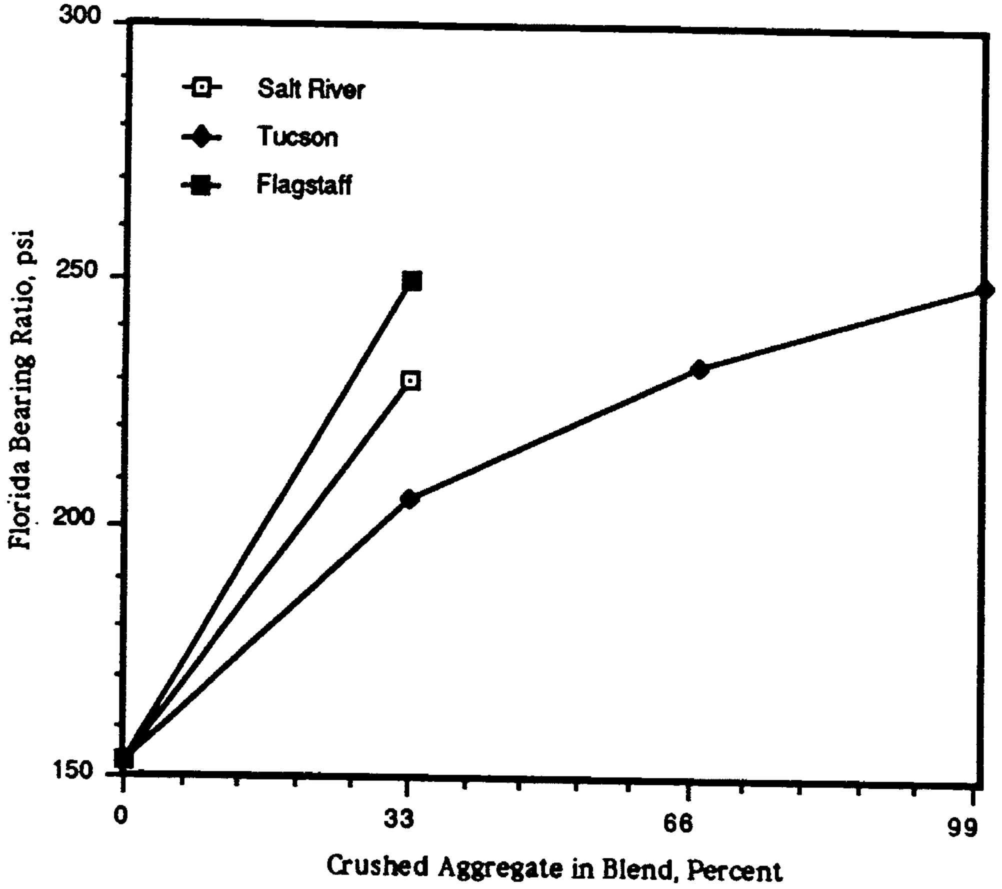

FIGURE 5 FLORIDA BEARING RATIO

TABLE 8. FLORIDA BEARING VALUE

Test Results - psi

Aggregate Pit	Trial	Percent Crushed			
		100	67	33	0
Salt River	1	298 +	298 +	191	136
	2	190	298 +	228	144
	3	298 +	298 +	271	180
	Avg	298 +	298 +	230	153
Tucson	1	234	268	196	Same as Salt River
	2	222	216	192	
	3	293	216	230	
	Avg	250	233	206	
Flagstaff	1	270	191	205	Same as Salt River
	2	298 +	298 +	298 +	
	3	298 +	298 +	247	
	Avg	298 +	298 +	250	

NOTE: If two of the three trials gave a Florida Bearing Value greater than the capacity of the test apparatus (298+), the average Florida Bearing Value was given as 298+.

Direct Shear Test

This test was performed on three different sources of crushed fine aggregate and three percentages of crushed fine aggregate. Three trials were performed for each group.

Test results show no distinct relationship between the specific aggregate used, the percent crushed and the interior friction angle. See Figure 6. The differences between friction angles measured are quite small.

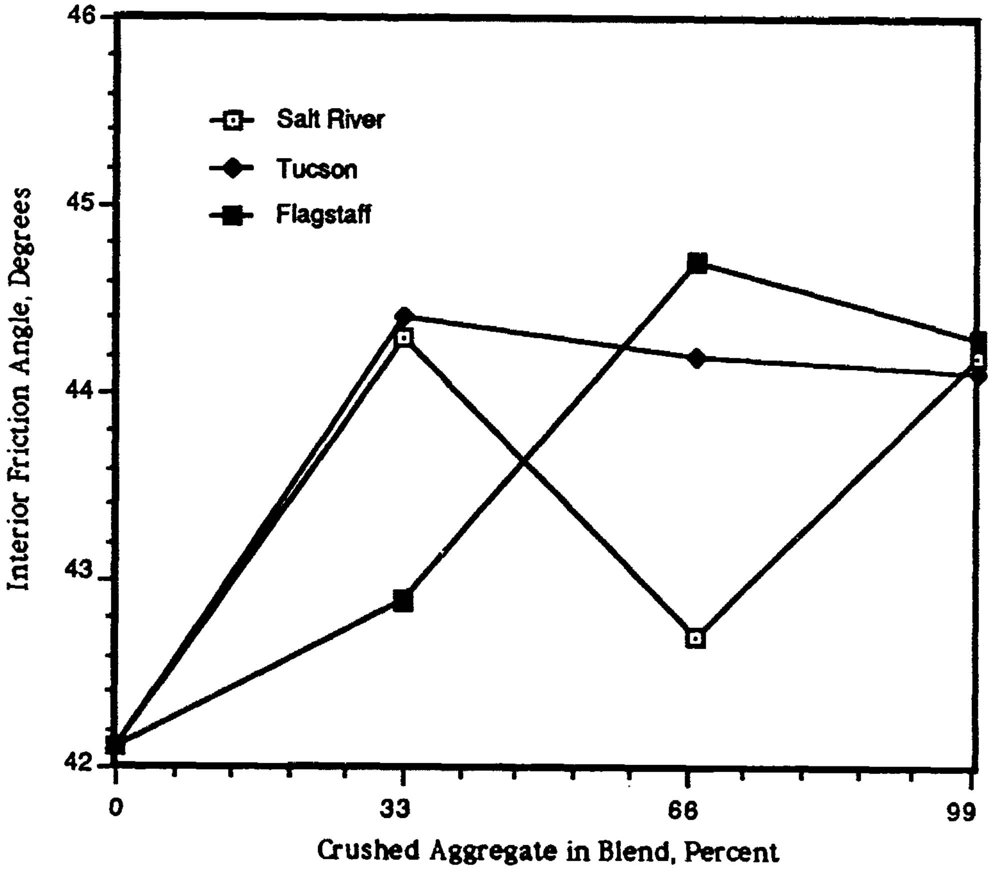

FIGURE 6 DIRECT SHEAR

Table 9 gives the interior friction angle for each combination of aggregates used. Table B-4 in Appendix B gives the analysis of variance. The analysis had three different aggregate sources and three percentages of crushed aggregate. There were three trials of the test performed for each combination of variables. By use of the analysis of variance and F-test, it was concluded that there were no significant differences between the test results for either the type of aggregate or the percent crushed aggregate.

TABLE 9. DIRECT SHEAR

Test Results - Interior Friction Angle

Aggregate Pit	Trial	Percent Crushed 100	67	33	0
Salt River	1	44.3	44.0	42.7	41.4
	2	45.5	41.9	45.5	42.6
	3	42.9	42.3	44.6	42.2
	Avg	44.2	42.7	44.3	42.1
Tucson	1	44.6	43.8	45.3	Same as Salt River
	2	43.7	43.5	44.0	
	3	44.0	45.4	43.8	
	Avg	44.1	44.2	44.4	
Flagstaff	1	45.6	44.4	42.8	Same as Salt River
	2	43.3	44.8	42.9	
	3	44.1	45.0	43.1	
	Avg	44.3	44.7	42.9	

Specific Rugosity by Packing Volume

The pouring test developed by Ishai and Tons was performed on three sources of crushed fine aggregate and three percentages of crushed fine aggregate. Four sieve groups were used (No.8 to No.10, No.20 to No.30, No.60 to No.80 and No.200 to No.270) and three trials were performed for each group.

Figure 7 is a graphical representation of the packing specific gravity for various percentages of crushed fine aggregate for the three aggregate sources studied. Unique relationships between the packing specific gravity and the percentage of crushed aggregate appear to exist for each aggregate source.

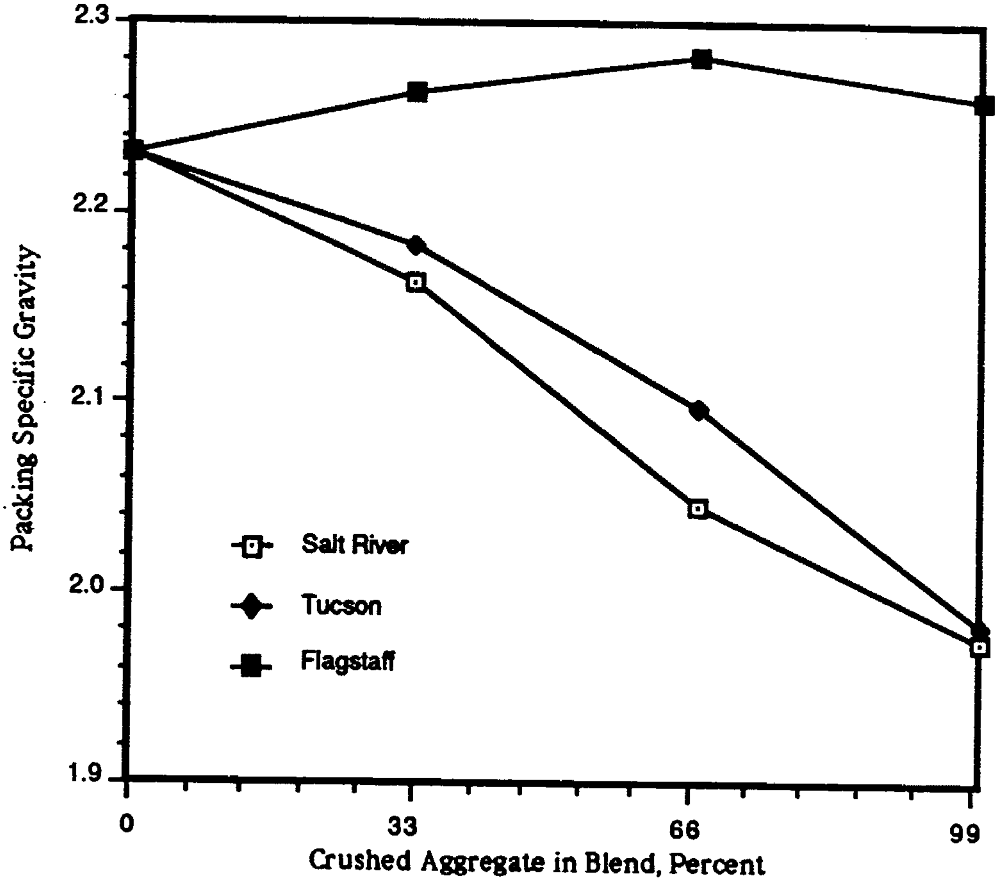

FIGURE 7 POURING TEST

Table 10 gives the packing specific gravity for each combination of aggregates used. Table B-5 in Appendix B give the analysis of variance. The analysis had three different aggregate sources and three percentages of crushed aggregate. There were three trials of the test performed for each combination of variables. By use of the analysis of variance and F-test, it was concluded that there were highly significant differences between the test results for both the sources of crushed fine aggregate used and the percent of crushed aggregate.

The percent macrosurface and microsurface voids can be calculated from the packing specific gravity for an aggregate. The macrosurface voids are the surface voids between the bulk and packing volume membranes. The microsurface voids are the surface voids between the bulk and apparent volume membranes. The percent specific rugosity is the summation of the macrosurface and microsurface voids.

Figure 8 graphically displays the relationships between the aggregate source used, the percent crushed fine aggregate and the percent macrosurface and microsurface voids.

Table 11 contains data for the percent macrosurface and microsurface voids for each combination of aggregates used. Table B-5A and B-5B in Appendix B gives the analyses of variance. Each analysis had three different aggregate sources and three percentages of crushed aggregate. There were three trials of the test performed for each combination of variables. By use of the analyses of variance and F-tests, it was concluded that there were highly significant differences for the test results of both the source of aggregate used and the percent crushed aggregate.

The sum of the macrosurface surface voids and the microsurface voids is defined as the specific rugosity. The specific rugosities were calculated for these data and are shown in Table 12. The mean values for each of the aggregate combinations

TABLE 10. POURING TEST

Test Results - Packing Specific Gravity

Aggregate Pit	Percent Crushed	Sieve Fraction	Trial 1	Trial 2	Trial 3	Average
Salt River	100	# 8-# 10	1.989	1.990	1.992	
		# 20-# 30	2.011	2.003	2.030	
		# 60-# 80	1.937	1.921	1.950	
		#200-#270	1.984	1.952	1.946	
		Average	1.980	1.966	1.980	1.975
	67	# 8-# 10	2.053	2.078	-	
		# 20-# 30	2.110	2.100	2.140	
		# 60-# 80	2.017	1.993	2.018	
		#200-#270	1.980	2.008	2.008	
		Average	2.040	2.045	2.055	2.047
	33	# 8-# 10	2.216	2.211	2.217	
		# 20-# 30	2.289	2.243	2.265	
		# 60-# 80	2.093	2.069	2.104	
		#200-#270	2.058	2.089	2.097	
		Average	2.164	2.153	2.174	2.163
Tucson	100	# 8-# 10	2.089	2.142	2.098	
		# 20-# 30	2.073	1.888	2.096	
		# 60-# 80	1.922	2.062	1.912	
		#200-#270	1.817	1.855	1.848	
		Average	1.975	1.987	1.988	1.983
	67	# 8-# 10	2.147	2.174	2.176	
		# 20-# 30	2.196	2.168	2.196	
		# 60-# 80	2.003	1.985	2.006	
		#200-#270	2.013	2.045	2.053	
		Average	2.090	2.093	2.108	2.097
	33	# 8-# 10	2.242	2.275	2.248	
		# 20-# 30	2.305	2.284	2.308	
		# 60-# 80	2.092	2.070	2.082	
		#200-#270	2.072	2.109	2.105	
		Average	2.178	2.184	2.186	2.183

TABLE 10. POURING TEST - Page 2

Test Results - Packing Specific Gravity

Aggregate	Percent	Sieve	Trial			
Pit	Crushed	Fraction	1	2	3	Average
Flagstaff	100	# 8-# 10	2.199	2.215	2.207	
		# 20-# 30	2.283	2.275	2.304	
		# 60-# 80	2.262	2.226	2.252	
		#200-#270	2.277	2.324	2.306	
		Average	2.255	2.260	2.267	2.261
	67	# 8-# 10	2.240	2.269	2.251	
		# 20-# 30	2.317	2.309	2.334	
		# 60-# 80	2.003	2.221	2.252	
		#200-#270	2.374	2.416	2.417	
		Average	2.234	2.304	2.314	2.284
	33	# 8-# 10	2.292	2.307	2.283	
		# 20-# 30	2.368	2.340	2.369	
		# 60-# 80	2.092	2.198	2.222	
		#200-#270	2.209	2.260	2.235	
		Average	2.240	2.276	2.277	2.264
Tucson	0	# 8-# 10	2.308	2.346	2.334	
		# 20-# 30	2.412	2.386	2.433	
		# 60-# 80	2.185	2.151	2.185	
		#200-#270	1.981	2.039	2.027	
		Average	2.222	2.230	2.245	2.232

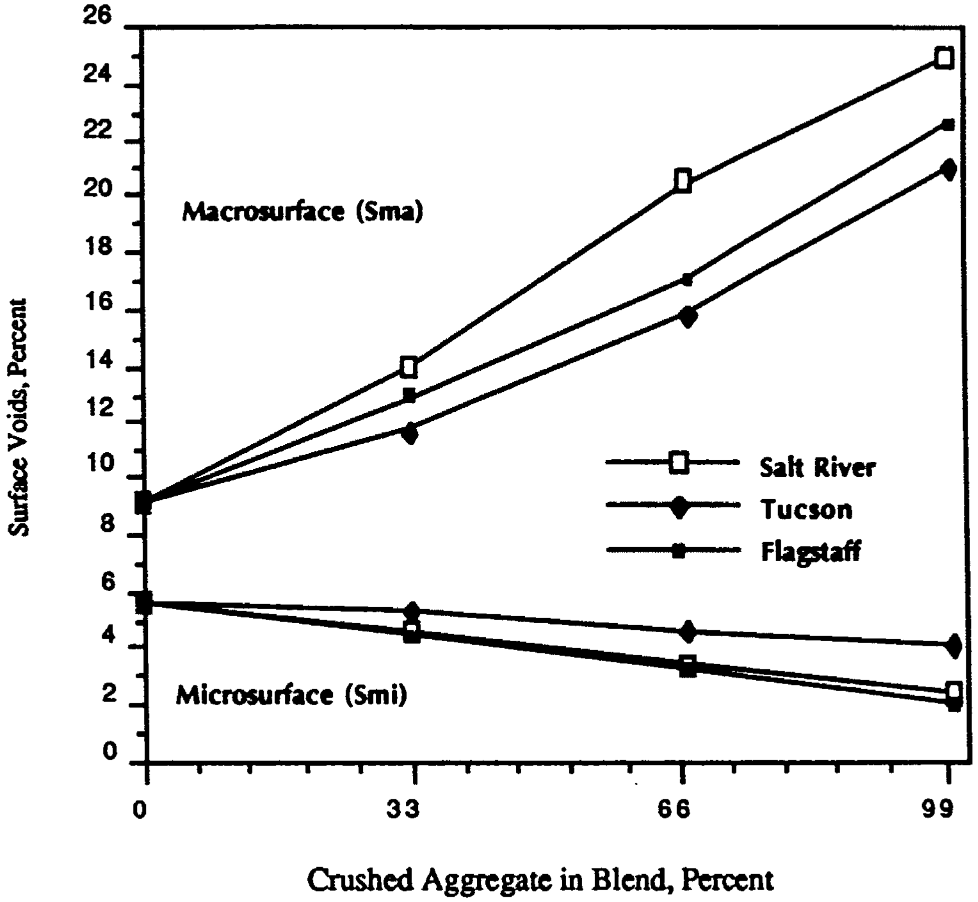

FIGURE 8 MICROSURFACE & MACROSURFACE VOIDS

TABLE 11. MACROSURFACE VOIDS, MICROSURFACE VOIDS

Test Results - Percent

Aggregate Pit	Percent Crushed	Surface Voids	Trial 1	Trial 2	Trial 3	Average
Salt River	100	Sma	24.77	25.30	24.77	24.95
		Smi	2.41	2.39	2.41	2.40
	67	Sma	20.65	20.46	20.07	20.39
		Smi	3.37	3.38	3.39	3.38
	33	Sma	13.82	14.26	13.54	13.87
		Smi	4.58	4.56	4.60	4.58
Tucson	100	Sma	21.32	20.84	20.80	20.99
		Smi	4.07	4.10	4.10	4.09
	67	Sma	16.13	16.01	15.41	15.85
		Smi	4.64	4.65	4.68	4.66
	33	Sma	11.93	11.69	11.60	11.74
		Smi	5.23	5.24	5.24	5.24
Flagstaff	100	Sma	22.77	22.60	22.36	22.58
		Smi	2.03	2.04	2.04	2.04
	67	Sma	18.73	16.19	15.82	16.91
		Smi	3.24	3.34	3.35	3.31
	33	Sma	13.65	12.26	12.22	12.71
		Smi	4.42	4.49	4.50	4.47
Tucson	0	Sma	9.53	9.20	8.59	9.11
		Smi	5.66	5.68	5.72	5.69

Sma = Macrosurface Voids
Smi = Microsurface Voids

are plotted in Figure 9. Table B-6 in Appendix B is the analysis of variance for specific rugosity. Highly significant differences were noted for degree of crushing and between aggregate pits. Examination of Figure 9 indicates the specific rugosity of Salt River aggregate to be different from Tucson and Flagstaff aggregates. Tucson and Flagstaff aggregate specific rugosities are not significantly different from each other.

TABLE 12. SPECIFIC RUGOSITY

Test Results - Specific Rugosity

Aggregate Pit	Percent Crushed	Trial 1	Trial 2	Trial 3	Average
Salt River	100	27.18	27.69	27.18	27.35
	67	24.02	23.84	23.46	23.77
	33	18.40	18.82	18.14	18.45
Tucson	100	25.39	24.94	24.90	25.08
	67	20.77	20.66	20.09	20.51
	33	17.16	16.93	16.84	16.98
Flagstaff	100	24.80	24.64	24.40	24.61
	67	21.97	19.53	19.17	20.22
	33	18.07	16.75	16.72	17.18
Tucson	0	15.19	14.88	14.31	14.79

ASPHALT CONCRETE MIX DESIGN

Mix designs were performed using the Marshall Method with 75 compactive blows per specimen face. Asphalt cement was AC-20. Four mix designs were prepared for each of the three sources of

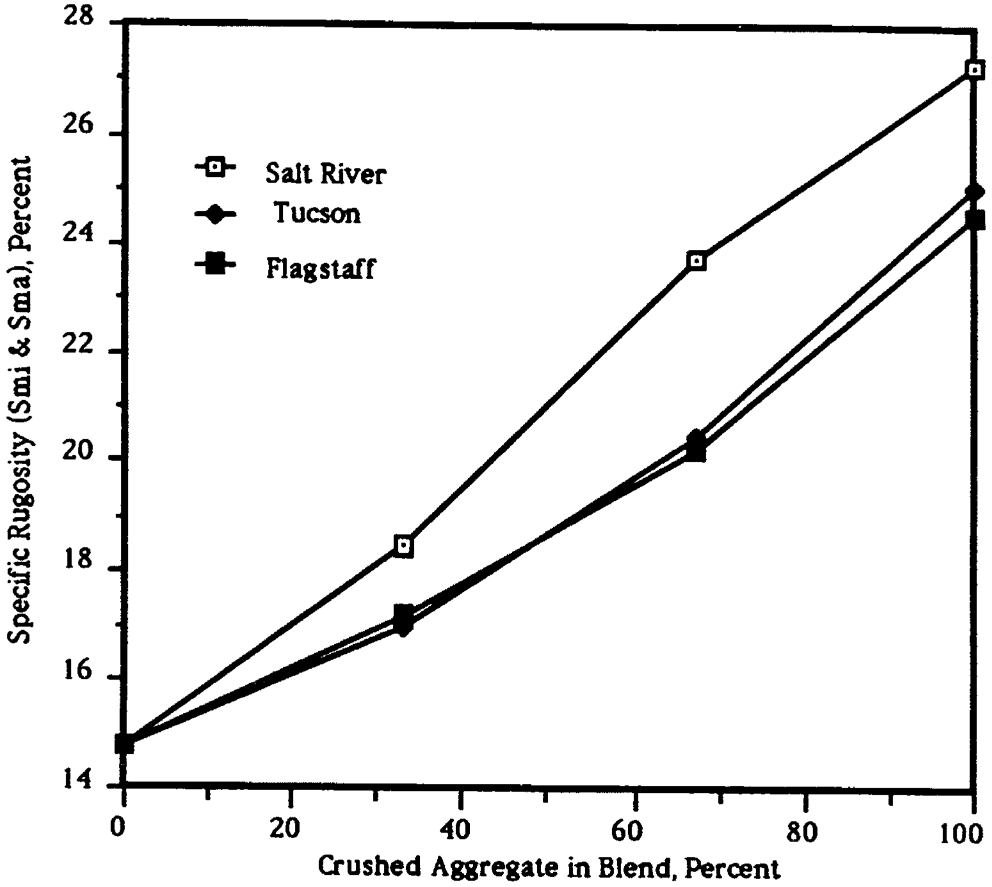

FIGURE 9 SPECIFIC RUGOSITY

aggregate using that source's coarse aggregate and four different combinations of crushed and non-crushed aggregate. Crushed fine aggregate was the same source as the coarse aggregate and uncrushed fine aggregate was from the Tucson source. Aggregate combinations were adjusted for bulk specific gravity to provide a constant gradation by volume. A summary of the combinations used and the percent by weight for each of the aggregates is shown in Table 3.

Mixtures were prepared and compacted at four or more asphalt contents for each aggregate combination. Test results from these mix designs appear in Tables C-1 through C-12 in Appendix C. The percent air voids at the different asphalt contents for each of the mixtures are plotted in Figures 10 through 12. Asphalt contents were selected for use in further mixture testing at approximately 4 percent air voids. These values are referred to as the optimum asphalt contents for the remainder of this work.

The asphalt contents selected as optimum and the physical properties of the mixtures at those values are shown in Tables 13 through 15.

ASPHALT CONCRETE STRENGTH AND DEFORMATION TESTS

A series of tests were performed using asphalt concrete specimens with the various aggregate combinations selected at the optimum asphalt content and 0.5 percent greater. Specimens for static creep testing at 77F and 140F were compacted by the Marshall Method with 75 compactive blows per specimen face. A series of specimens were compacted with a kneading compactor. These specimens were initially tested for Hveem stability. Later they were tested for resilient modulus at 77F following which they were tested for diametral creep at 140F.

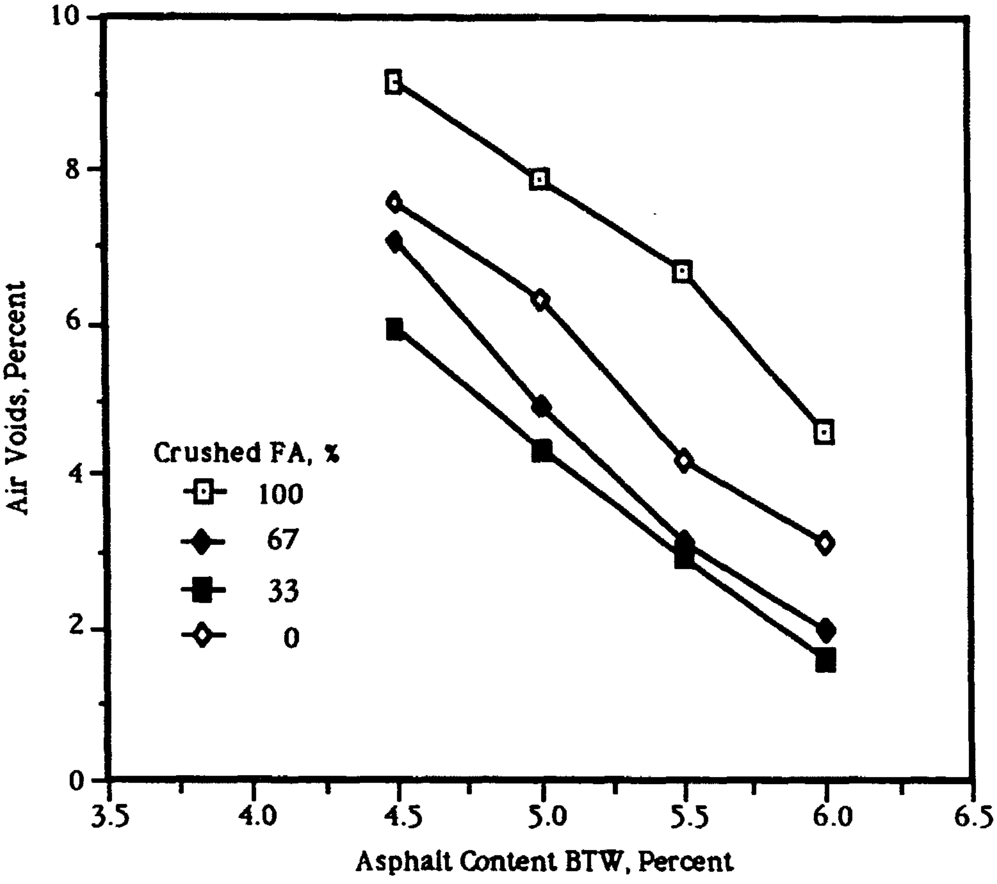

FIGURE 10 VOIDS IN AC MIXTURES, SALT RIVER AGGREGATE

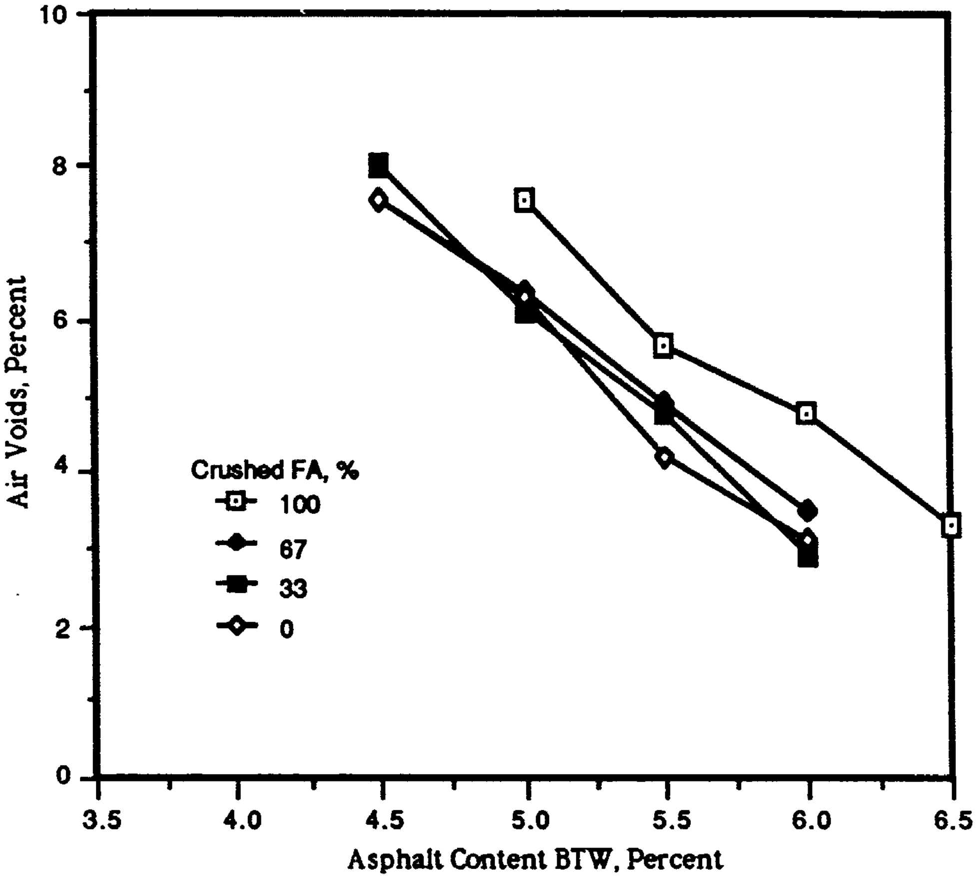

FIGURE 11 VOIDS IN AC MIXTURES, TUCSON AGGREGATE

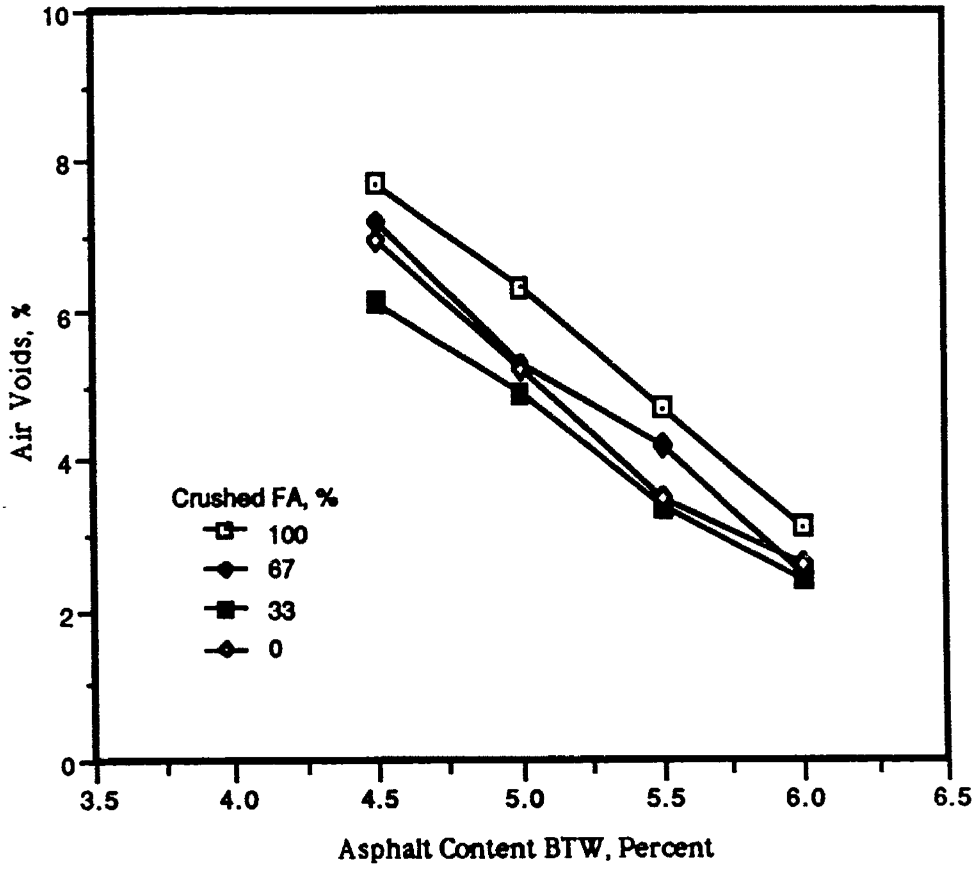

FIGURE 12 VOIDS IN AC MIXTURES, FLAGSTAFF AGGREGATE

TABLE 13. ASPHALT MIX DESIGN PROPERTIES AT 4% AIR VOIDS

SALT RIVER AGGREGATE

Asphalt Mix Properties

Asphalt Mix Proportions	Asphalt Content (%)	Bulk Unit wt (pcf)	Theo Unit wt (pcf)	VMA (%)	Voids Filled (%)	Stability (lbs)	Flow (0.01 in.)
38% CA Salt River 62% FA Salt River Crushed	6.1	146.0	152.5	17.0	76	3340	14
38.5% CA Salt River 41.6% FA Salt River Crushed 19.9% FA Tucson Sand	5.3*	149.2	153.0	14.0	71	3380	10
38.8% CA Salt River 20.9% FA Salt River Crushed 40.3% FA Tucson Sand	5.1	146.0	152.0	14.2	72	3770	11
39.8% CA Salt River 60.2% FA Tucson Sand	5.4*	144.0	150.4	15.0	68	3250	12

* Air Voids at 4.9%

TABLE 14. ASPHALT MIX DESIGN PROPERTIES AT 4% AIR VOIDS

TUCSON AGGREGATE

Asphalt Mix Properties

Asphalt Mix Proportions	Asphalt Content (%)	Bulk Unit wt (pcf)	Theo Unit wt (pcf)	VMA (%)	Voids Filled (%)	Stability (lbs)	Flow (0.01 in.)
38% CA Tucson 62% FA Tucson Crushed	6.2	142.0	147.8	15.3	74	3620	14
38.1% CA Tucson 41.3% FA Tucson Crushed 20.6% FA Tucson Sand	5.8	142.2	148.8	14.6	73	3450	11
38.3% CA Tucson 20.4% FA Tucson Crushed 41.3% FA Tucson Sand	5.7	143.3	149.0	14.2	61	3720	10
38.7% CA Tucson 61.3% FA Tucson Sand	5.4*	145.7	149.8	14.6	66	3920	10

* Air Voids at 4.7%

TABLE 15. ASPHALT MIX DESIGN PROPERTIES AT 4% AIR VOIDS

FLAGSTAFF AGGREGATE

Asphalt Mix Properties

Asphalt Mix Proportions	Asphalt Content (%)	Bulk Unit wt (pcf)	Theo Unit wt (pcf)	VMA (%)	Voids Filled (%)	Stability (lbs)	Flow (0.01 in.)
37.4% CA Flagstaff 62.6% FA Flagstaff Crushed	5.7	159.8	167.5	16.5	76	3800	12
38.4% CA Flagstaff 43.1% FA Flagstaff Crushed 18.5% FA Tucson Sand	5.5	157.2	162.9	15.5	73	3400	11
39.5% CA Flagstaff 22.1% FA Flagstaff Crushed 38.4% FA Tucson Sand	5.4	152.4	158.1	15.0	74	3700	10
41.4% CA Flagstaff 58.6% FA Tucson Sand	5.3	149.2	155.5	14.0	71	3380	10

Static Creep, 77F

The results of static creep testing at 77F are shown in Table 16. The analysis of variance of these data is given in Table B-7 in Appendix B. There were no significant differences in test results for the asphalt contents, aggregate pits or percent of crushed fine aggregate.

TABLE 16. CREEP 77F

Test Results - Creep Modulus, psi

Aggregate Pit	Trial	Percent Crushed							
		100		67		33		0	
		I	II	I	II	I	II	I	II
Salt River	1	1602	3060	2998	2127	2895	3860	3451	3735
	2	3816	2072	3406	2659	2510	4102	3723	3863
	3	744	2108	3588	2582	4144	5784	2582	2734
	Avg	2054	2413	3331	2456	3183	4582	3252	3444
Tucson	1	2620	2693	2312	2836	2158	2727	2749	1918
	2	2811	2113	2339	2097	2347	3555	3027	3700
	3	9737*	1292	2327	2169	2528	1099	5130	3329
	Avg	2716	2032	2326	2367	2344	2460	3635	2982
Flagstaff	1	1644	1733	4487	4809	4580	3992	4851	2644
	2	3260	3059	1955	2457	555*	2442	3193	3947
	3	2389	5107	4746	2408	3193	2883	2454	3308
	Avg	2431	3300	3729	3225	3886	3106	3499	3300

Notes: (1) I - Optimum asphalt content at 4% voids
(2) II - Optimum asphalt content plus 0.5%
(3) * - Outlier not used in average calculation

Static Creep, 140F

The results of static creep testing at 140F are shown in Table 17. The analysis of variance of these data is given in Table B-8 in Appendix B. There were no significant differences in test results for the asphalt contents, aggregate pits or percent of crushed aggregate.

TABLE 17. STATIC CREEP 140F

Test Results - Creep Modulus, psi

Aggregate Pit	Trial	Percent Crushed							
		100		67		33		0	
		I	II	I	II	I	II	I	II
Salt River	1	2163	1210	3984	678	5368	*	1345	1791
	2	2627	1343	5567	*	1129	841	2984	1082
	3	1391	2148	1214	3690	1019	1090	1427	837
	Avg	2060	1567	3588	2184	2505	966	1919	1237
Tucson	1	3880	3385	2254	2388	2294	2416	2821	1162
	2	*	1144	1081	1885	*	7223*	1720	1615
	3	2392	1706	1911	7554*	3156	3154	1144	3574
	Avg	3136	2078	1749	2136	2725	2785	1895	2117
Flagstaff	1	1380	1394	1304	1813	2769	1239	1789	1720
	2	6814*	2789	1972	4061	974	1330	764	1784
	3	509	565	3837	1874	1694	1889	*	4157
	Avg	945	1583	2371	2583	1812	1486	1276	2554

Notes: (1) I - Optimum asphalt content at 4% air voids

(2) II - Optimum asphalt content plus 0.5%

(3) * - Outlier or no data, not used when computing mean

Hveem Stability

Hveem stability test results are tabulated in Table 18. The analysis of variance of these data appears in Table B-9 of Appendix B. The analysis of variance indicates a highly significant effect for both the percent of crushed aggregate and between aggregate pits. Although not highly significant, a significant difference between asphalt contents is apparent.

TABLE 18. HVEEM STABILITY

Test Results - Hveem Stability

Aggregate		Percent Crushed							
		100		67		33		0	
Pit	Trial	I	II	I	II	I	II	I	II
Salt	1	31	18	30	24	31	31	28	21
River	2	35	23	31		20	34	29	20
	3	27	26	35	35	31	24	21	25
	Mean	31	22	32	30	27	30	26	22
Tucson	1	31	36	29	33	19	24	22	19
	2	47	29	31	31	22	22	24	30
	3	42	33	29	27	28	23	22	25
	Mean	40	33	30	30	23	23	23	25
Flagstaff	1	42	32	37	44	32	30	34	31
	2	38	34	34	32	24	21	26	23
	3	44	33	32	25	27	31	32	21
	Mean	41	33	34	34	28	27	31	25

Notes: (1) I - Optimum asphalt content at 4% air voids

(2) II - Optimum asphalt content plus 0.5%

Resilient Modulus, 77F

Test results of Resilient Modulus appear in Table 19 and the analysis of variance for the data in Table B-10 of Appendix B. The analysis of variance indicates a highly significant effect for the percent of crushed fine aggregate. Percent asphalt and aggregate pits showed no significant differences.

TABLE 19. RESILIENT MODULUS

Test Results - 10^5 psi

Aggregate Pit	Trial	Percent Crushed							
		100		67		33		0	
		I	II	I	II	I	II	I	II
Salt	1	3.79	3.54	6.56	3.34	5.20	5.66	5.80	5.58
River	2	3.57	4.92	7.10	3.34	3.18	6.03	5.54	4.74
	3	3.52	5.19	5.81	4.49	5.16	6.00	4.94	4.72
	Mean	3.63	4.55	6.49	3.72	4.51	5.90	5.43	5.01
Tucson	1	4.08	3.94	4.06	4.18	4.52	4.52	6.52	4.24
	2	4.00	4.00	4.72	4.68	4.60	4.62	6.18	4.78
	3	4.80	4.23	4.32	4.12	5.06	5.20	7.56	4.94
	Mean	4.29	4.06	4.37	4.33	4.73	4.78	6.75	4.65
Flagstaff	1	4.44	4.16	4.74	5.44	3.02	5.02	5.84	4.68
	2	4.20	4.44	5.18	5.29	4.19	4.62	6.24	5.11
	3	4.48	4.42	5.20	4.58	4.44	5.47	5.86	4.98
	Mean	4.37	4.34	5.04	5.10	3.88	5.04	5.98	4.92

Notes: (1) I - Optimum asphalt content at 4% air voids

(2) II - Optimum asphalt content plus 0.5%

Diametral Creep, 140F

Diametral creep test results appear in Table 20. Many of the tests had final deformations that exceeded the measuring capacity of the test apparatus. These tests yielded a low creep modulus and are shown as less than 883 psi which was calculated from the maximum deformation measured by the test device. The analysis of variance for the data is shown in Table B-11 of Appendix B. The analysis of variance indicates the amount of crushed fine aggregate to be highly significant while asphalt content and aggregate pits data indicated no significance. The analysis of variance, of course, is flawed as many data points are shown at the minimum test value achieved at the maximum range of the apparatus.

DISCUSSION

Aggregate Shape and Surface Texture

Table 21 is a summary of the analyses of variance for the several tests of aggregate particle shape and surface texture. The ASTM D3398-81 Particle Index and the Florida Bearing Value results are not included as there were no analyses of variance performed for those data. The ability of a test to distinguish between aggregates of different degrees of crushing is most important with differentiation between aggregate sources important, but secondary. Degree of crushing is defined by the percent of aggregate whose particles have crushed faces.

The National Crushed Stone Association and Time Index test results indicated highly significant differences between both aggregate sources and degree of crushing when analyzed by the F-Test. The Western Technologies Void Test did not indicate a significant effect for the degree of crushing, but did measure significant difference for the aggregate sources studied. The Direct Shear Test showed no significant effects for either of the test variables.

TABLE 20. DIAMETRAL CREEP AT 140F

Test Results - Creep Modulus, psi

Aggregate Pit	Trial	Percent Crushed							
		100		67		33		0	
		I	II	I	II	I	II	I	II
Salt River	1	1107	3774	2177	2169	833	833	1724	1251
	2	2962	1836	1853	1831	883	833	1396	1403
	3	1046	2572	883	833	1661	883	1187	883
	Mean	1705	2727	2015	2000	1142	883	1436	1327
Tucson	1	1847	1918	1113	909	883	1548	883	883
	2	883	1027	883	1397	883	883	883	1102
	3	1840	947	1290	1265	883	883	1518	883
	Mean	1844	1297	1202	1190	883	1105	1095	956
Flagstaff	1	1993	2022	901	883	1279	909	1375	883
	2	1955	1058	3080	883	883	883	1189	907
	3	1145	935	2721	2010	959	1444	1246	1946
	Mean	1698	1338	2234	1259	1119	1176	1270	1426

Notes: (1) I - Optimum asphalt content at 4% air voids

(2) II - Optimum asphalt content plus 0.5%

The other four tests for which the F-Test results are tabulated, Pouring Test, Microsurface Voids, Macrosurface Voids and Specific Rugosity, all indicate significant effects for both of the test variables. These four test values are all dependent and have the results of the pouring test and aggregate specific gravity as a basis. The microsurface and macrosurface voids indicate a higher significance for the aggregate source variable for degree of crushing. However, specific rugosity, which is the sum of the two, indicates a higher significance for degree of crushing than aggregate source. Because the degree of crushing was considered the more important variable in this research, the specific rugosity was used for further analyses in this report.

One of the objectives of this research was to relate fine aggregate shape and surface texture to permanent deformation properties of asphalt concrete. The tests and test results discussed here were studied to select those tests most promising for this purpose. The ASTM Particle Index test was not used as it was considered to be an impractical test for routine use. The Florida Bearing Value test was not used as a number of the tests performed exceeded the capacity of the equipment and a full data set for all variables could not be developed. The Western Technologies Void Ratio test and the Direct Shear test did not indicate a significant enough effect from degree of aggregate crushing to be used.

TABLE 21. ANALYSES OF VARIANCE SUMMARY FOR AGGREGATE TESTS

F Test Result

	Aggregate Crushed		F-Statistic	
Aggregate Test	Pit	FA%	$\alpha=0.05$	$\alpha=0.05$
National Crushed Stone	18697	3863	3.55	6.01
Time Index	2465	483	3.55	6.01
Western Technologies	28	6	3.55	6.01
Direct Shear	0.4	0.6	3.55	6.01
Pouring Test	124	374	3.55	6.01
Microsurface	10603	6561	3.55	6.01
Macrosurface	541	69	3.55	6.01

The remaining tests performed were selected to be correlated to asphalt concrete properties. These tests are the Specific Rugosity, the National Crushed Stone Association and the Time Index. The Specific Rugosity was selected at the one test from the four dependent tests relating to the Pouring Test to be used for these purposes. The National Crushed Stone Association and the Specific Rugosity tests have the advantage that they make use of a number of different sized fractions of the fine aggregate whereas the Time Index test used only a single aggregate function. The use of multiple fractions is considered to be advantageous in that a better representation of a composite aggregate is achieved than when only a single fraction is evaluated.

ASPHALT CONCRETE MIXTURES

There were no significant trends in mix design properties that could be related to the amount of crushed fine aggregate. In general, the voids in mineral aggregate (VMA) and the asphalt content at 4 percent air voids tended to decrease with an increase in the amount of uncrushed fine aggregate. Two notable exceptions were for 100 percent uncrushed fine aggregate for the Salt River and Tucson sources. The Salt River source indicated both an increased asphalt content and VMA from mixtures with a combination of crushed and uncrushed fine aggregates. The Tucson source indicated a decrease in asphalt content for the mix design with all fine aggregate uncrushed as expected; however, a slight increase in VMA which was not expected also occurred.

No trend could be noted in Marshall stabilities, however, flow appeared to decrease with increasing amounts of uncrushed fine aggregate. Once again the Salt River mixture with all fine aggregate uncrushed was an exception with a slight increase in flow. The increases in flow noted for all mixtures might well be related to increases in asphalt content required to maintain constant air voids.

ASPHALT CONCRETE STRENGTH AND DEFORMATION TESTS

Strength and deformation tests for the various asphalt concrete mixtures were performed for the optimum asphalt content and at the asphalt content plus 0.5 percent. Three-way analyses of variance were performed for each of the tests using variables of two asphalt contents, three aggregate sources and four levels of crushed fine aggregate. These analyses of variance are shown in Appendix B and the results of the F-test for these data are summarized in Table 22.

TABLE 22. ANALYSES OF VARIANCE SUMMARY FOR MIX TESTS

F Test Results

Variable	Static Creep @77F	Static Creep @140F	Hveem Stability	Resilient Modulus	Diemetral Creep	F Statistic	
						$\alpha=0.05$	$\alpha=0.01$
Asphalt Content	0.07	0.78	6.19	4.75	0.31	4.05	7.22
Aggregate Pit	3.49	1.33	5.49*	0.63	3.22	3.20	5.10
Crushed FA %	3.11	1.13	13.58*	18.97*	5.70*	2.81	4.24

* Significant at $\alpha=0.01$

Results of the F-test indicate the Hveem Stability to be the test most responsive to the three variables studied. These test results indicate significant differences at $\alpha=0.01$ for the source of aggregate and degree of crushing of the fine aggregate. The asphalt content was indicated as significant at $\alpha=0.05$ but not at $\alpha=0.01$.

The analyses of variance for results of the Static Creep tests at both 77F and 140F indicate none of the variables studied to have significant effects at $\alpha=0.01$ and few to be significant at $\alpha=0.05$. This is primarily a result of a failure to repeat test results causing considerable scatter in test data. The Resilient Modulus and Diametral Creep tests indicate the degree of crushing of the fine aggregate to be significant at $\alpha=0.01$. The Diametral Creep test data, however, is biased because those tests yielding deformation beyond the test equipment's range are reported at the minimum test result that could be measured. This condition resulted in greater repetition of test data than is true.

CORRELATION OF AGGREGATE AND ASPHALT CONCRETE TEST DATA

The Hveem Stability and Resilient Modulus were selected as the tests displaying the most significant indicators of effects from varying the amount of crushed fine aggregate. The Specific Rugosity, National Crushed Stone Association and the Time Index were selected as the aggregate tests preferred for the measurement of shape and surface texture effects for fine aggregate. The mean test values for each of these tests and for all twelve aggregate combinations are shown in Table 23. The fine aggregate tests for all uncrushed aggregate are the same for all three aggregate sources as the samples tested were 100 percent Tucson uncrushed material. The same is not true for the asphalt concrete mixtures as the coarse aggregate will be unique for each aggregate source.

Table 23. AGGREGATE AND MIXTURE TEST DATA FOR CORRELATION

Test Property	Nominal Percent Crushed Fine Aggregate			
	100	67	33	0
Salt River Aggregate				
Time Index	1.61	1.45	1.30	1.13
National Crushed Stone	57.6	54.2	50.4	46.2
Specific Rugosity	27.35	23.77	18.45	14.79
Hveem Stab, Opt AC	31**	32	27	26
Hveem Stab, Opt AC+0.5	22**	30	30	22
Resilient Mod, Opt AC*	3.63	6.49	4.51	5.43
Resilient Mod, Opt AC+0.5*	4.55	3.72	5.90	5.01
Tucson Aggregate				
Time Index	1.43	1.34	1.25	1.13
National Crushed Stone	53.8	51.3	48.7	46.2
Specific Rugosity	25.08	20.51	16.98	14.79
Hveem Stab, Opt AC	40	30	23	23
Hveem Stab, Opt AC+0.5	33	30	23	25
Resilient Mod, Opt AC*	4.29	4.37	4.73	6.75
Resilient Mod, OPT AC+0.5*	4.06	4.33	4.78	4.65
Flagstaff Aggregate				
Time Index	1.51	1.40	1.26	1.13
National Crushed Stone	56.6	53.4	49.8	46.2
Specific Rugosity	24.61	20.22	17.18	14.79
Hveem Stab, Opt AC	41	34	28	31
Hveem Stab, Opt AC+0.5	33	34	27	25
Resilient Mod, Opt AC*	4.37	5.04	3.88	5.98
Resilient Mod, Opt AC+0.5*	4.34	5.10	5.04	4.92

*Units of 10^5 psi

** Considered to be an outlier

To measure the correlation between aggregate tests and asphalt concrete tests, each of the three aggregate tests was paired with each of the four asphalt concrete tests. A linear regression analysis was performed using each of the sets of paired data. Hveem stability using Salt River aggregate and 100 percent crushed fine aggregate was judged to be an outlier and data for both optimum asphalt content and optimum plus 0.5 percent were eliminated from the analyses. The results of the regression analyses and a graphical representation for the Hveem stability data paired with the various aggregate test results are shown in Figures 13, 14 and 15.

The linear regression analyses performed produced similar relationships for all data sets. In all cases, the Hveem stabilities demonstrated significant increases with increased aggregate shape and surface texture characteristics of the fine aggregate. Coefficients of determination (r^2) for these data sets varied from 0.61 to 0.78. These indicate a good to strong correlation between the variables studied. Therefore, with other factors equal, any of these three aggregate shape and surface texture evaluations would provide good predictions of the Hveem stability.

All of the relationships developed indicate the Hveem stability to be reduced by increasing the optimum asphalt content by 0.5 percent. However, contrary to anticipated results, the decrease in Hveem stability accompanying this ashphalt content increase is greater for the high proportions of crushed aggregate than lower percentages. The decrease in Hveem stability is less than 1 point at the low values for aggregate shape and surface texture and greater than 4 points for higher values of that property. These correspond to decreases in Hveem stability of approximately 4 and 12 percent, respectively.

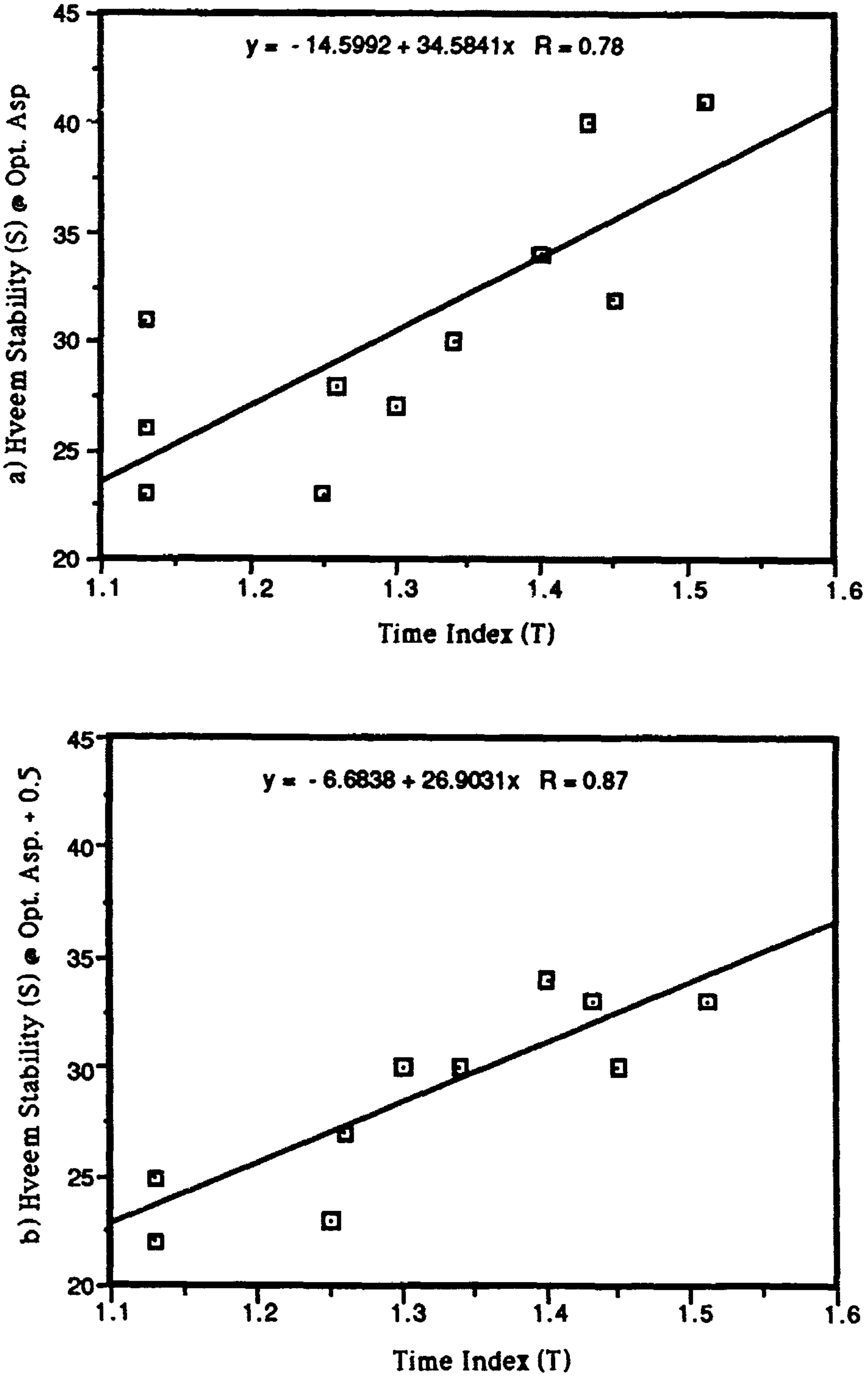

FIGURE 13. HVEEM STABILITY - TIME INDEX RELATIONSHIPS

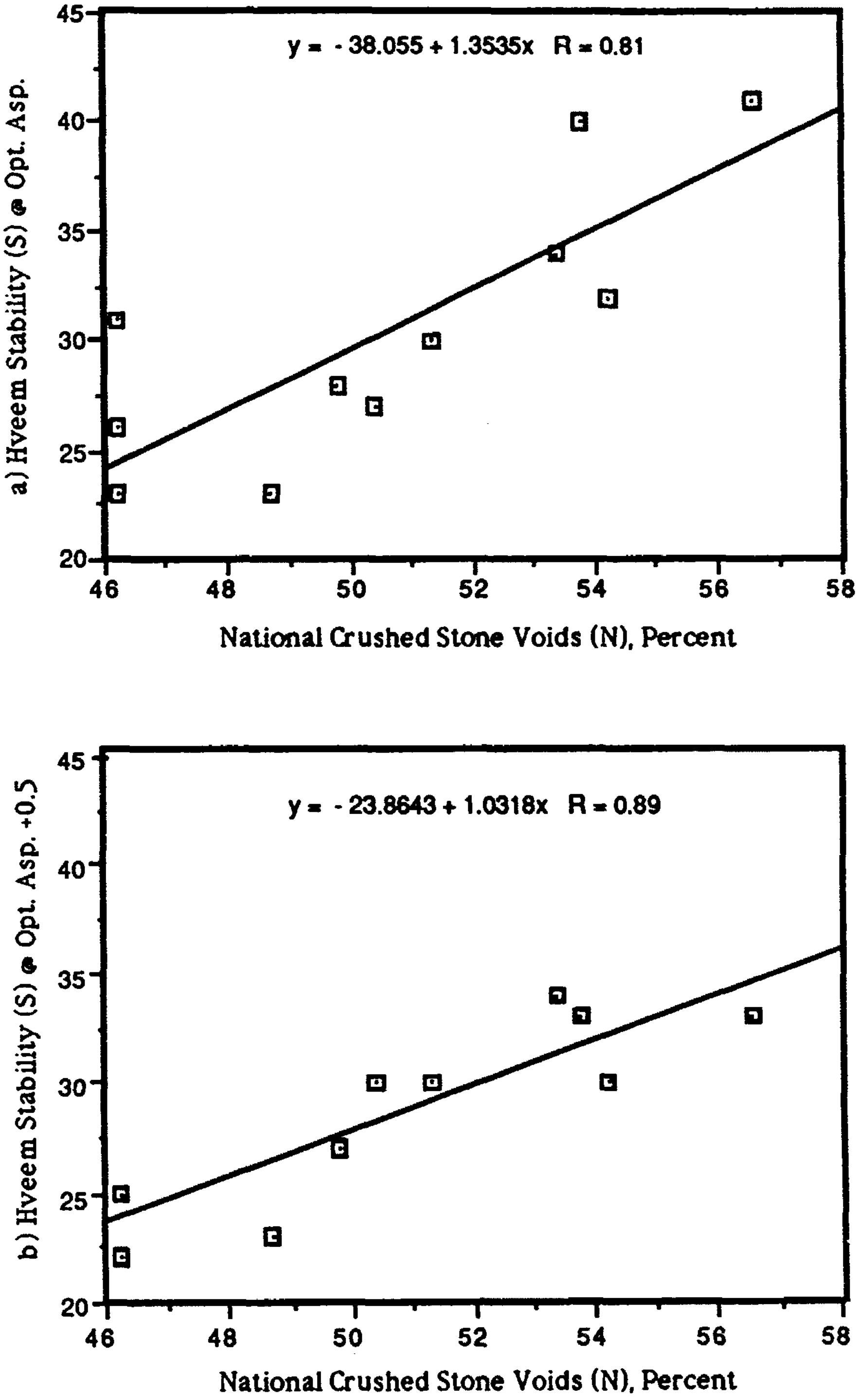

FIGURE 14. HVEEM STABILITY - NATIONAL CRUSHED STONE RELATIONSHIPS

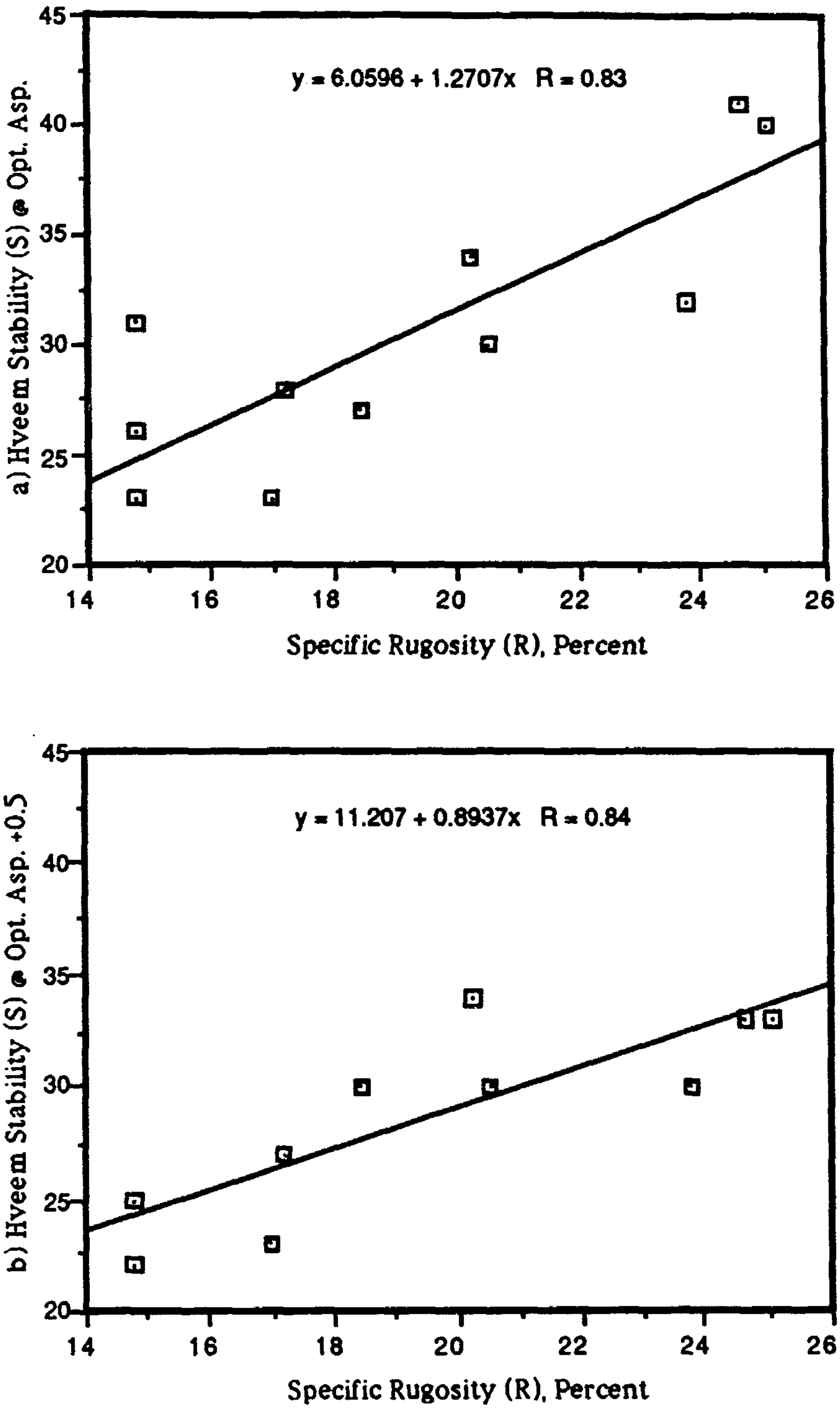

FIGURE 15. HVEEM STABILITY - SPECIFIC RUGOSITY RELATIONSHIPS

A similar analysis of the resilient modulus data was performed to correlate it to aggregate shape and surface texture test results. The analysis of variance for resilient modulus data indicated a significant effect for amount of crushed fine aggregate; however, these same data have a poor correlation to fine aggregate shape and surface texture test results. Linear regression analysis for paired data of resilient modulus and aggregate tests yielded coefficients of determination varying between 0.19 and 0.31. Although overall means for resilient modulus indicate an upward trend as the amount of crushed fine aggregate is decreased, the individual paired data points do not indicate a significant correlation between the test results.

The resilient modulus as tested here did not respond to aggregate surface and texture characteristics. The small strains generated during the test are probably not sufficient to be affected by aggregate interaction and results in a measurement primarily influenced by the asphalt binder's properties. Consequently, there is no significant correlation between the resilient modulus and the aggregate shape and surface texture properties.

A minimum Hveem stability of 35 is often considered necessary for an asphalt concrete mix design. This corresponds to a Time Index of 1.45, a National Crushed Stone Association void value of 54 and a Specific Rugosity of 23. These would be reasonable values to be considered for a specification value for mineral aggregate for use in asphalt concrete mixtures.

CONCLUSIONS

Seven test procedures for evaluating aggregate shape and surface texture were performed. The Direct Shear and Void Ratio by Western Technologies were concluded to have low correlation with aggregate surface properties. The Index of Aggregate Shape and Texture was felt to be too labor intensive to be practical as a routine aggregate test. The Florida Bearing Value could not be fully evaluated as several of the planned tests exceeded the capacity of the equipment. The National Crushed Stone Association, Time Index and Specific Rugosity by Packing Volume tests were found to be the preferred tests for evaluating aggregate shape and surface texture. The Time Index test is felt to be an inferior test because it uses only a single fraction of aggregate, whereas, the other two tests use a number of different sized aggregate fractions.

Asphalt concrete mix designs were prepared for different combinations of crushed and non-crushed fine aggregates by the Marshall method. Asphalt contents were selected for each at approximately 4 percent air voids. This asphalt content and an asphalt content 0.5 percent greater were used for preparing specimens for further mixture testing.

A series of tests evaluating asphalt concrete strength and/or deformation properties were performed. Tests were conducted with mixtures at the optimum asphalt content and 0.5 percent greater. Tests were:

- Static Creep at 77F
- Static Creep at 140F
- Hveem Stability
- Resilient Modulus at 77F
- Diametral Creep at 140F

Static Creep tests at both 77F and 140F had a great deal of scatter and did not correlate well with the mixture variables being studied. It is felt that the static creep test should be applicable to this type of evaluation and that the test procedure, apparatus or techniques in obtaining data were at fault in obtaining consistent test results.

Diametral Creep tests at 140F had deformations, even at the lowest possible sustained load, that often exceeded the maximum that could be measured by the test apparatus. It was not possible to judge whether the test would provide consistent results due to these incomplete data.

Resilient Modulus did not correlate well with aggregate shape and surface texture properties. It is concluded that resilient modulus at low strains does not provide a good evaluation of the effect of aggregate properties.

Hveem stability was found to be a good indicator of the effect of aggregate shape and surface on asphalt concrete mixtures. A good correlation existed between Hveem stability and the three aggregate tests selected as the preferred tests. Linear relationships were developed between these aggregate shape and surface texture test results and Hveem stability. An increase of 0.5 percent in asphalt content from the optimum asphalt content caused a decrease in Hveem stability. However, contrary to anticipated results, this decrease was greater for high percentages of crushed fine aggregate than for low percentages.

The relationships established indicate that a Hveem stability of 35 was achieved in asphalt concrete mixtures when aggregate shape and surface texture values of a time index of 1.45, a National Crushed Stone Association value of 54 and a specific rugosity of 23 were achieved.

RECOMMENDATIONS FOR FURTHER RESEARCH

The work performed and reported here leaves a number of areas to be researched or to be researched in further depth. It is recommended that research in those areas be pursued to supplement these data and conclusions.

Further studies of aggregate shape and surface texture with other aggregates and aggregate combinations is desired. The three tests of Time Index, National Crushed Stone Association and Specific Rugosity are recommended for study. If Florida Bearing Value apparatus was revised to allow measurement of the full range of aggregate properties, the test procedure is felt to have merit and justifies further study. The Florida Bearing Value test is valuable in that it was the one test procedure that used the entire graded fine aggregate whereas all other tests used only selected portions of the aggregate.

Static creep tests either axial or diametral are still felt to be tests that should be most responsive to aggregate shape and surface texture and that will relate this aggregate property to asphalt concrete mixture properties. In as much as the creep testing performed here was unsuccessful, it is recommended that further work with the creep test and its relation to aggregate properties be pursued. It is felt that a more positive method of measuring the creep deformation than was used here may assist in obtaining better repeatability of the test results.

The conclusion that the fine aggregate with more crushed material was more sensitive to an increase in asphalt as measured by the Hveem stability is questioned. Further research should be performed to either verify or dispute this conclusion. Supplementing this work with successful creep tests would also provide information regarding the validity of that conclusion.

A program should be established to provide for the routine evaluation of aggregate shape and surface texture by all or some of the three test procedures successfully performed during this work. These test results should be compared to asphalt concrete mixture properties and field performance. Aggregate shape and surface texture properties for recovered aggregate from samples of good and poor performing pavements is also recommended for study. Research results of this type are felt to be necessary before any of these test procedures would be ready for incorporation as an aggregate specification requirement.

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APPENDIX A

TEST PROCEDURES

NATIONAL CRUSHED STONE ASSOCIATION
(now NATIONAL STONE ASSOCIATION)

Proposed Method of Test for Voids in Individual Size Fractions of Manufactured Stone Fine Aggregate for Concrete.

Scope

This method of test describes a procedure for determining voids in individual size fractions of sand fine aggregate.

Apparatus

A cylindrical tube having an inside diameter of 3 in. and a height of 5 1/2 in. mounted on a metal base 3 1/2 in. square.

A truncated metal cone having an overall height of 4 in., inside diameters of 5 1/2 in. for the large opening and 1 in. for the small opening.

Samples

A sample of the fine aggregate obtained by standard methods shall be washed thoroughly, dried and separated into the following sizes:

Passing	Retained on
No. 8	No. 16
No. 16	No. 30
No. 30	No. 50

Procedure

One of the blends of fine aggregate shall be poured into the cone while a stiff piece of metal is held against the bottom aperture. After the cone is filled, the piece of metal used to close the bottom of the cone is quickly withdrawn in a horizontal movement and the sand permitted to flow freely into the cylinder beneath until it overflows.

The cylinder shall be carefully struck off, level with the top of the cylinder.

Weigh the cylinder and sand to the nearest 0.1g.

All the sand from the test is recombined and two additional determinations made. An average of three determinations having a maximum range of 4 g shall constitute a test.

Calculations

The percent voids of each size shall be determined by the following formula:

$$\text{Percent voids} = \left(1 - \frac{W}{VG}\right)$$

W = Weight of sand in cylinder
V = Volume of cylinder in cc
G = Bulk specific gravity of the fine aggregate blend

Report

The percent voids obtained from the arithmetical average of the percent voids of the three sizes tested shall be reported.

STANDARD TEST METHOD FOR INDEX OF AGGREGATE ARTICLE SHAPE AND TEXTURE

(ASTM D3398-81)

This test was performed in accordance with the procedure specified in the ASTM test, except for a reduced size mold of 3 in. by 3.5 in. and a tamping rod 5/16 inch in diameter, about 12 inches long, with a mass of 115 to 117.5 g, with the tamping end rounded to a hemispherical end.

This equipment was developed by Norman W. McLead and J. Keith Davidson of McAsphalt Engineering Services, Toronto, Ontario, Canada and is reported in a paper entitled "Particle Index Evaluation of Aggregates for Asphalt Paving Mixtures."[6]

TIME INDEX BY REX AND PECK

A Laboratory Test to Evaluate the Shape and Surface Texture of Fine Aggregate Particles by the Bureau of Public Roads

Scope

This method of test describes a procedure for determining the rate of flow for a fine aggregate.

Apparatus

A one-pint Mason jar and an aluminum cap in the shape of a frustum of a cone fitted with a dimensional orifice an cork stopper. See Figure 1A page A-5.

Samples

A sample of the fine aggregate obtained by standard methods shall be washed, dried, sieved (-No. 20, +No. 30) and blended.

Procedure

Determine the bulk specific gravity of the sample and compute the solid volume of the sample.

Place 500 g of the dry sample in a Mason jar and assemble apparatus.

Remove stopper and start timing simultaneously. Determine the time between the removal of the stopper and the passage of the last sand particles through the orifice. Make a minimum of three determinations and report the average as the time of flow.

Determine the flow rate for standard Ottawa sand.

Calculations

Compute the flow rate in terms of seconds per 100 cc of solid volume for the sample and Ottawa sand.

Compute the time index of the sample by dividing its flow rate by the flow rate of Ottawa sand.

Report

The time index obtained from the arithmetical average of the three trials shall be reported.

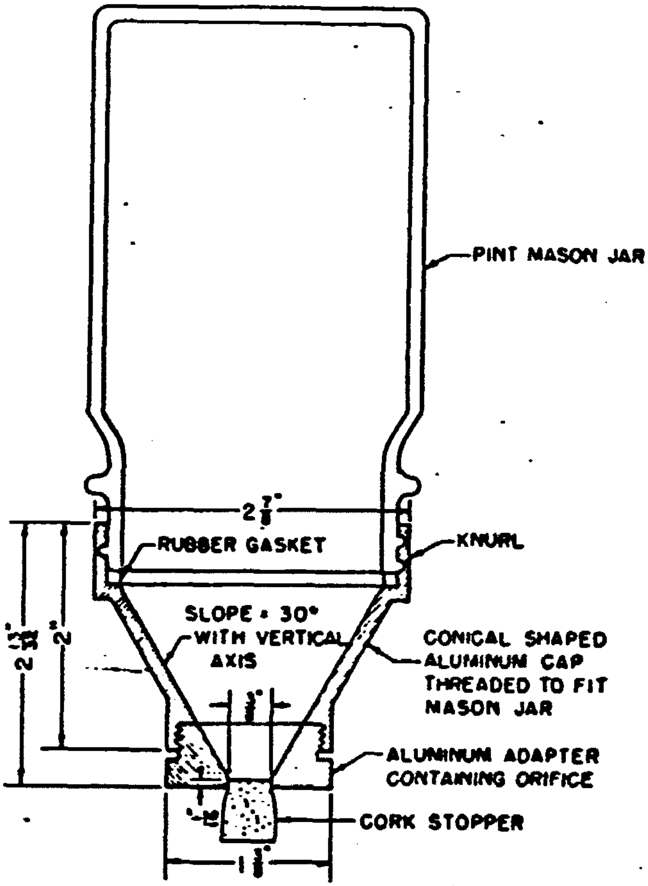

FIGURE 1A. TEST APPARATUS

WESTERN TECHNOLOGIES TEST PROCEDURE
For Void Ratio Determination

Scope

This method of test describes a procedure for determining the void ratio of individual size fractions of fine aggregate.

Apparatus

Balance. A balance having a capacity of 200g or more and sensitive to 0.1g or less

Containers of at least 200g capacity suitable for drying samples

A 250, 100 and 25ml graduated cylinder

Sieves with square openings conforming to Specifications for Sieves for Testing Purposes (ASTM Designation E11) of the following sizes are required:

No. 4, No. 8, No. 20, No. 30, No. 100, No. 200.

Samples

Samples of fine aggregate for testing shall be obtained by the method of quartering or by use of a sample splitter. The sample shall be thoroughly washed, dried to constant weight at 100 to 105 C (220 to 230 F), and separated into the following sizes:

Passing	Retained on	Amount Required (g)
No. 4	No. 8	200
No. 20	No. 30	100
No. 100	No. 200	25

Procedure

Each of the aggregate fractions is tested by the following method

The fine aggregate fraction to be tested shall be weighed to the nearest 0.1g.

The sample to be tested shall be poured into a suitable graduated cylinder. With the palm of the hand covering the top of the graduated cylinder, tip the graduated cylinder and aggregate sample upside down and then upright. This procedure is performed three times.

Carefully place the graduated cylinder on a hard, flat surface and read the aggregate level to the nearest ml.

The sand shall be removed from the graduated cylinder, thoroughly mixed, and two additional determinations made.

Calculations

The specific volume of each size shall be determined by the following formula:

$$\text{Specific volume} = \frac{W}{SG}$$

W = weight of sand in graduated cylinder
SG = specific gravity

The void ratio of each size shall be determined by the following formula:

$$\text{Void ratio} = \frac{Vm - Vs}{Vs}$$

Vm = measured volume
Vs = specific volume

Report

The void ratio obtained from the arithmetical average of the void ratio of the three sizes tested shall be reported.

FLORIDA BEARING VALUE OF FINE AGGREGATE

Test Method No. Ind. 201-72, Indiana State Highway Commission

Scope

This method of test covers the determination of the Florida Bearing Value of Fine Aggregate.

Apparatus

Soil Bearing Cup, a cylindrical brass cup 3 3/16 in. in height with an outside diameter of 3 1/4 in. (inside diameter of 3 1/16 in.).

Bearing Plates, a large brass circular bearing plate 3 in. diameter and a small brass circular plate 1 sq in. in area.

Spring Tester, Rimac Spring Tester or equivalent capable of applying a total load of 100 pounds uniformly at the rate of 20 pounds per second.

Compression Testing Machine, capable of applying a total load of 1500 pounds at a rate of 2.4 inches per minute.

Bearing Value Machine

Samples

A sample of the fine aggregate obtained by standard methods shall be washed, dried, sieved through the No. 4 sieve and blended.

Procedure

Add 1.75 percent water to a known weight of oven-dry material and thoroughly mix.

Fill the soil bearing cup with the mixed material. Place the 3 in. diameter bearing plate on top of the coned material. Place the soil bearing cup in a compression testing machine and apply a load of 100 pounds at a rate of 20 pounds per second for 5 seconds. Add additional material to the cup and repeat loading process. Remove excess material with a straight edge.

Replace the 3 in. diameter bearing plate on the material and apply a load at a rate of 2.4 inches per minute to a total load of 1500 pounds. Remove the bearing plate and place the 1 sq. in. bearing plate in the center of the upper surface of the compressed sample. Place the compressed sample in the Bearing Value Machine. Adjust equipment to obtain an initial reading.

Apply a constant increasing load to the specimen by opening the valve on the funnel and allowing the shot to enter the bucket at the rate of 454g in 7.5 seconds, until the pressure on the bearing plate is great enough to cause a deformation of 0.01 in. in 5 seconds. When this rate of deformation is reached, immediately close the valve on the funnel. Weight the shot in the bucket to the nearest gram and record the weight.

Calculations

Calculate the Florida Bearing Value in pounds per square inch by the following formula:

$$\text{Florida Bearing Value} = \frac{W}{454} \times L$$

W = weight of shot (g)
L = lever arm ratio

Report

Report the Florida Bearing Value obtained from the arithmetical average of the percent voids of three tests.

DIRECT SHEAR TEST

Modified from ASTM D3080-72 Standard Method for Direct Shear Test of Soils Under Consolidated Drained Conditions

Scope

This method of test describes a procedure for determining the internal friction angle of a fine aggregate.

Apparatus

Shear Device - Wykeham Farrance Limited

Samples

Fine aggregate were prepared by standard washing, drying and sieving procedures. Various combinations of fine aggregates were used as test samples.

Procedure

A pre-weighed, pre-mixed sample is poured into the direct shear mold from a height of approximately two inches and leveled.

With the upper sample platens in place, the shear box housing was dropped five times from an approximate height of one-half inch onto the sample.

The shear box housing and sample were then placed in the shearing apparatus and a vertical dial reading taken in a no-load condition.

A pre-determined normal load is then applied to the sample for approximately two minutes. After two minutes, another vertical dial reading is taken.

Unlock the shear box platens and separate them slightly so that the specimen can be sheared. Read the vertical dial again and record results.

Apply the shearing force (strain rate of 1.2 mm/min.) until the sample has completely sheared. Record all necessary dial readings.

Remove sample, clean equipment and repeat the procedure for the next sample.

Calculations

Calculate the shearing stress for each normal stress.

Plot the maximum shear stress vs. normal stress and determine the internal friction angle.

Report

The internal friction angle obtained from the arithmetical average of the internal friction angle of three trials shall be reported.

SPECIFIC RUGOSITY BY POURING TEST

Concept and Test Method for a Unified Characterization of Geometric Irregularity fo Aggregate Particles

Scope

This method of test describes a procedure for determining the packing specific gravity of one-size aggregate particles.

Apparatus

Pouring setup consisting of a supporting bin with adjustable orifice funnel and stainless steel containers (standard volumes).

Uniform, clean, smooth, spherical glass beads in different sizes.

Samples

A sample of the fine aggregate obtained by standard methods shall be washed, dried, sieved (pass the top sieve and retained on the bottom sieve) and blended.

Procedure

Fill the conical bin with the one-size glass beads. Open the funnel orifice to allow free pouring of all particles into the stainless steel container.

Level the particle pile to the top of the container and weigh the contents of the container.

Collect all particles and repeat the same procedure for the number of replications desired.

Repeat the same procedure for all comparative aggregate fractions.

Calculations

The packing specific gravity for each aggregate fraction shall be determined by the following formula:

$$Gpx = \frac{Gps}{*Ws} *Wx \qquad * = \text{Summation Sign}$$

Gpx = packing specific gravity of the aggregate tested
Gps = packing specific gravity of the glass beads
*Ws = weight of the glass beads which filled the container
*Wx = weight of the aggregates which filled the container

Report

The packing specific gravity obtained from the arithmetical average of the packing specific gravity of the three trials shall be reported.

ASPHALT CONCRETE MIX DESIGN PROCEDURE

The standard test method for resistance to plastic flow of Bituminous mixtures using Marshall apparatus, ASTM D1559-76 was used for preparation and testing of mixtures. Analysis methods were those given in The Asphalt Institute, Manual Series No.2, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types."

CREEP TEST, 77F and 140F

Scope

This method of test describes a procedure as developed by J.F. Hill[19], for determining the creep of prepared Marshall samples at two different temperatures.

Apparatus

The creep apparatus is a modified version of a soil consolidation apparatus manufactured by Wykeham Farrance Engineering, Inc. A load is placed on the end of a lever and the load is then transmitted to a 3/4 inch diameter ball bearing. The apparatus has a lever arm ratio that results in a specimen load four times the load applied. A load platen is centered under the ball bearing and the load is transmitted to the specimen.

Samples

Three specimens were prepared for each bituminous mixture to be tested for each specified test temperature.

Procedure, Test Temperature 77F

Stabilized a room to 77F

Measure the diameter of the specimen in the X and Y directions and the height. This should be done twice.

Center the specimen on the bottom platen and place the top platen on the center of the specimen. Place the 3/4 in. ball bearing on the top platen and lower the loading bar.

Apply a weight (45.56 lbs) to the loading bar for 30 seconds. After 30 seconds, remove the weight for 30 seconds and repeat the cycle.

Position and set a 0.0001 in. graduated dial gauge directly over the center of the sample.

Apply a 5 lb weight and after 5 minutes, observe and record the dial reading. Remove the 5 lb weight and re-attach the 45.56 lb weight.

Observe and record the dial reading after 22 hours. Remove the 45.56 lb weight and apply the 5 lb weight to the loading bar. After 30 seconds, observe and record the dial reading.

Procedure, Test Temperature 140F

Stabilize an environmental room to 140F

Perform specimen measuring and positioning as given in the 77F temperature test procedure.

Apply a 5 lb weight to the loading bar for 15 seconds and take an initial reading.

Remove the 5 lb weight and apply the 45.56 lb weight to the loading bar. Observe and record the dial reading after 5 minutes.

Observe and record the dial reading after 22 hours. Remove the 45.56 lb weight and apply the 5 lb weight to the loading bar. After 15 seconds, observe and record the dial reading.

Calculations

S = Unit Stress = P/A

P = Specimen Load = 45.56 X 4 = 182.24 lb

A = Specimen Area = 12.57 sq in.

S = 182.24/12.57 = 14.5 psi

D = Unit Deformation = Measured Deformation/Specimen Height

Creep Modulus, psi S/d = 14.5/d

HVEEM STABILITY

Hveem stability was measured in accordance with Standard Test Methods for Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveen Apparatus, ASTM Designation D1560-80a and Preparation of Bituminous Mixture Test Specimens by Means of California Kneading Compactor, ASTM Designation D1561-81a. The specimen cohesion was not measured.

RESILIENT MODULUS, 77F

Resilient Modulus was tested according to the standard method of indirect tension test for resilient modulus of bituminous mixtures, ASTM Designation D4123-82. Specimens were prepared and tested for Hveem stability in accordance with ASTM D1561 and D1562 prior to testing for resilient modulus. Testing was performed by applying a 70 lb pulse for 0.15 sec across the vertical diameter of the specimen and sensing the resultant deformation across the horizontal diameter 0.05 sec after the beginning of the specimen deformation.

DIAMETRAL CREEP, 140F

Scope

This test method describes a procedure for determining the diametral creep of asphalt concrete specimens using the resilient modulus apparatus. The procedure is a modification of ASTM Designation D4123-82.

Apparatus

The resilient modulus device functions as a load apparatus for application of a constant sustained load across the vertical diameter of a specimen. The permanent, unrecovered deformation across the horizontal diameter following unloading is measured by transducers.

Specimens

Specimens were made with the kneading compactor by procedures given within ASTM Designation D1561-81a . Specimens were tested for Hveem stability and resilient modulus at 77F prior to being tested for diametral creep at 140F.

Procedure

Prepare the test room by stabilizing the air temperature at 140F.

Glue 7/16 in. dia paper caps to the specimen at mid-height and diametrically opposite points.

Bring the specimen to temperature by placing in the 140F test room for at least 2 hr but no more than 3 hr prior to the start of the test.

Place the specimen in the test yoke with transducer contacts on the paper caps. Gently tighten the side supporting screws.

Adjust transducer tips to make contact with the specimen to produce a reading of 100 micro inches on the meter. Set the meter to zero.

Preset the loading strip and apply a vertical load of 7 lb with the thumb screw. Maintain this load by use of air pressure for 1,000 sec. Record the horizontal deformation at intervals of time during the loading period.

Remove the load and continue recording the horizontal deformation until the specimen displacement has stabilized. The permanent deformation following stabilization of the unloaded specimen is recorded and used for computation of the creep modulus.

Calculations

The diametral creep modulus in psi reported was calculated from the magnitude of the sustained load and the resulting permanent deformation at the end of the test.

$$\text{Creep Modulus} = (v + 0.2734)\ P/td$$

P = Load, lb
t = Specimen height, inc.
d = Deflection, μ-in
v = Poisson's ratio = 0.35

APPENDIX B

ANALYSES OF VARIANCE AND F-TEST FOR FINE AGGREGATE

TABLE B-1. NATIONAL CRUSHED STONE

Columns are percentages of crushed fine aggregate
Rows are aggregate sources

```
SOURCE OF VARIATION       DF     SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS            2        180.05                 90.02
BETWEEN ROWS               2         37.20                 18.60
INTERACTION                4          3.73                  0.93
WITHIN                    18          0.09                  0.00
TOTAL                     26
COLUMN F = 18696.976079
     SIGNIFICANCE = 0.000000
ROW F = 3863.148925
     SIGNIFICANCE = 0.000000
INTERACTION F =193.922807
     SIGNIFICANCE = 0.000000
               RANDOM EFFECTS RESULTS
COLUMN F = 96.414529
     SIGNIFICANCE = 0.001397
ROW F = 19.921065
     SIGNIFICANCE = 0.010212
```

TABLE B-2. TIME INDEX

Columns are percentages of crushed fine aggregate

Rows are aggregate sources

```
SOURCE OF VARIATION       DF     SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS            2          0.27                  0.14
BETWEEN ROWS               2          0.05                  0.03
INTERACTION                4          0.01                  0.00
WITHIN                    18          0.00                  0.00
TOTAL                     26
COLUMN F = 2464.799867
     SIGNIFICANCE = 0.000000
ROW F = 482.599976
     SIGNIFICANCE = 0.000000
INTERACTION F =52.699996
     SIGNIFICANCE = 0.000001
               RANDOM EFFECTS RESULTS
COLUMN F = 46.770400
     SIGNIFICANCE = 0.003148
ROW F = 9.157496
     SIGNIFICANCE = 0.033672
```

TABLE B-3. WESTERN TECHNOLOGIES VOID RATIO

Columns are percentages of crushed fine aggregate
Rows are aggregate sources

```
SOURCE OF VARIATION      DF    SUM OF SQUARES      MEAN SQUARE
BETWEEN COLUMNS           2         0.26                0.13
BETWEEN ROWS              2         0.05                0.03
INTERACTION               4         0.01                0.00
WITHIN                   18         0.08                0.00
TOTAL                    26
COLUMN F = 27.854101
     SIGNIFICANCE = 0.000026
ROW F = 5.813092
     SIGNIFICANCE = 0.011227
INTERACTION F =0.676656
     SIGNIFICANCE = 0.619220
               RANDOM EFFECTS RESULTS
COLUMN F = 41.164336
     SIGNIFICANCE = 0.003701
ROW F = 8.590909
     SIGNIFICANCE = 0.037142
```

TABLE B-4. DIRECT SHEAR

Columns are percentages of crushed fine aggregate
Rows are aggregate sources

```
SOURCE OF VARIATION      DF    SUM OF SQUARES      MEAN SQUARE
BETWEEN COLUMNS           2         0.72                0.36
BETWEEN ROWS              2         1.08                0.54
INTERACTION               4         9.35                2.34
WITHIN                   18        16.75                0.93
TOTAL                    26
COLUMN F = 0.387187
     SIGNIFICANCE = 0.689247
ROW F = 0.578193
     SIGNIFICANCE = 0.575605
INTERACTION F =2.510943
     SIGNIFICANCE = 0.077564
               RANDOM EFFECTS RESULTS
COLUMN F = 0.154200
     SIGNIFICANCE = 0.861247
ROW F = 0.230269
     SIGNIFICANCE = 0.804394
```

TABLE B-5. POURING TEST PACKING SPECIFIC GRAVITY

Columns are percentages of crushed fine aggregate

Rows are aggregate sources

```
SOURCE OF VARIATION      DF     SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS           2          0.08                 0.04
BETWEEN ROWS              2          0.23                 0.12
INTERACTION               4          0.04                 0.01
WITHIN                   18          0.01                 0.00
TOTAL                    26
COLUMN F = 124.237995
     SIGNIFICANCE = 0.000000
ROW F = 374.085924
     SIGNIFICANCE = 0.000000
INTERACTION F =31.195150
     SIGNIFICANCE = 0.000004
               RANDOM EFFECTS RESULTS
COLUMN F = 3.982606
     SIGNIFICANCE = 0.112439
ROW F = 11.991798
     SIGNIFICANCE = 0.022185
```

TABLE B-5A. POURING TEST MACROSURFACE VOIDS

Columns are percentages of crushed fine aggregate

Rows are aggregate sources

```
SOURCE OF VARIATION      DF     SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS           2         455.66               227.83
BETWEEN ROWS              2          58.48                29.24
INTERACTION               4           6.07                 1.52
WITHIN                   18           7.58                 0.42
TOTAL                    26
COLUMN F = 541.109726
     SIGNIFICANCE = 0.000000
ROW F = 69.451918
     SIGNIFICANCE = 0.000001
INTERACTION F =3.604264
     SIGNIFICANCE = 0.024826
               RANDOM EFFECTS RESULTS
COLUMN F = 150.130415
     SIGNIFICANCE = 0.000925
ROW F = 19.269373
     SIGNIFICANCE = 0.010732
```

TABLE B-5B. POURING TEST MICROSURFACE VOIDS

Columns are percentages of crushed fine aggregate
Rows are aggregate sources

```
SOURCE OF VARIATION      DF    SUM OF SQUARES       MEAN SQUARE
BETWEEN COLUMNS           2       16.57                8.29
BETWEEN ROWS              2       10.25                5.13
INTERACTION               4        1.42                0.36
WITHIN                   18        0.01                0.00
TOTAL                    26
COLUMN F = 10603.028061
     SIGNIFICANCE = 0.000000
ROW F = 6561.118251
     SIGNIFICANCE = 0.000000
INTERACTION F =454.284344
     SIGNIFICANCE = 0.000000
               RANDOM EFFECTS RESULTS
COLUMN F = 23.340069
     SIGNIFICANCE = 0.008085
ROW F = 14.442757
     SIGNIFICANCE = 0.016641
```

TABLE B-6. SPECIFIC RUGOSITY

Columns are percentages of crushed fine aggregate
Rows are aggregate sources

```
SOURCE OF VARIATION      DF    SUM OF SQUARES       MEAN SQUARE
BETWEEN COLUMNS           2      298.48              149.24
BETWEEN ROWS              2       35.56               17.78
INTERACTION               4        4.51                1.13
WITHIN                   18        6.95                0.39
TOTAL                    26
COLUMN F = 386.407811
     SIGNIFICANCE = 0.000000
ROW F = 46.036277
     SIGNIFICANCE = 0.000004
INTERACTION F =2.918250
     SIGNIFICANCE = 0.050005
               RANDOM EFFECTS RESULTS
COLUMN F = 132.410811
     SIGNIFICANCE = 0.001033
ROW F = 15.775304
     SIGNIFICANCE = 0.014533
```

TABLE B-7. STATIC CREEP AT 77F

Columns are percentages of crushed fine aggregate
Rows are aggregate sources
Levels are asphalt content

```
SOURCE OF VARIATION       DF     SUM OF SQUARES       MEAN SQUARE
BETWEEN COLUMNS            3      8273326.11            2757775.37
BETWEEN ROWS               2      6177618.86            3088809.43
BETWEEN LEVELS             1      64680.06            64680.06
INTERACTION R X C          6      6074264.14            1012377.36
INTERACTION R X L          2      1032637.69            516318.85
INTERACTION C X L          3      1466817.39            488939.13
INTERACTION R X C X L      6      5618165.53            936360.92
WITHIN                    48      42531546.67            886073.89
TOTAL                     71
COLUMN F = 3.112354
     SIGNIFICANCE = 0.034136
ROW F = 3.485950
     SIGNIFICANCE = 0.037484
LEVEL F =0.072996
     SIGNIFICANCE = 0.784373
COLUMN-ROW INTERACTION = 1.142543
     SIGNIFICANCE = 0.352433
COLUMN-LEVEL INTERACTION = 0.551804
     SIGNIFICANCE = 0.653464
ROW-LEVEL INTERACTION = 0.582704
     SIGNIFICANCE = 0.567344
COLUMN-ROW-LEVEL INTERACTION = 1.056753
     SIGNIFICANCE = 0.401795
```

TABLE B-8. STATIC CREEP AT 140F

Columns are percentages of crushed fine aggregate
Rows are aggregate sources
Levels are asphalt content

```
SOURCE OF VARIATION       DF    SUM OF SQUARES       MEAN SQUARE
BETWEEN COLUMNS            3     3952023.39            1317341.13
BETWEEN ROWS               2     3104855.44            1552427.72
BETWEEN LEVELS             1     915755.56            915755.56
INTERACTION R X C          6     10207049.44            1701174.91
INTERACTION R X L          2     6719938.78            3359969.39
INTERACTION C X L          3     1789876.33            596625.44
INTERACTION R X C X L      6     3418893.67            569815.61
WITHIN                    48     56024838.00            1167184.12
TOTAL                     71
COLUMN F = 1.128649
     SIGNIFICANCE = 0.347113
ROW F = 1.330062
     SIGNIFICANCE = 0.273311
LEVEL F =0.784585
     SIGNIFICANCE = 0.616102
COLUMN-ROW INTERACTION = 1.457503
     SIGNIFICANCE = 0.212301
COLUMN-LEVEL INTERACTION = 0.511167
     SIGNIFICANCE = 0.680580
ROW-LEVEL INTERACTION = 2.878697
     SIGNIFICANCE = 0.064353
COLUMN-ROW-LEVEL INTERACTION = 0.488197
     SIGNIFICANCE = 0.814998
```

TABLE B-9. HVEEM STABILITY

Columns are percentages of crushed fine aggregate
Rows are aggregate sources
Levels are asphalt content

```
SOURCE OF VARIATION         DF    SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS              3       860.82               286.94
BETWEEN ROWS                 2       231.75               115.87
BETWEEN LEVELS               1       130.68               130.68
INTERACTION R X C            6       397.81                66.30
INTERACTION R X L            2        22.03                11.01
INTERACTION C X L            3       199.49                66.50
INTERACTION R X C X L        6        41.31                 6.88
WITHIN                      48      1014.00                21.12
TOTAL                       71
COLUMN F = 13.582950
     SIGNIFICANCE = 0.000018
ROW F = 5.485207
     SIGNIFICANCE = 0.007322
LEVEL F =6.186062
     SIGNIFICANCE = 0.015604
COLUMN-ROW INTERACTION = 3.138505
     SIGNIFICANCE = 0.011257
COLUMN-LEVEL INTERACTION = 3.147710
     SIGNIFICANCE = 0.032781
ROW-LEVEL INTERACTION = 0.521368
     SIGNIFICANCE = 0.602484
COLUMN-ROW-LEVEL INTERACTION = 0.325882
     SIGNIFICANCE = 0.919759
```

TABLE B-10. RESILIENT MODULUS

Columns are percentages of crushed fine aggregate
Rows are aggregate sources
Levels are asphalt content

SOURCE OF VARIATION	DF	SUM OF SQUARES	MEAN SQUARE
BETWEEN COLUMNS	3	14.11	4.70
BETWEEN ROWS	2	0.31	0.16
BETWEEN LEVELS	1	1.18	1.18
INTERACTION R X C	6	4.51	0.75
INTERACTION R X L	2	1.14	0.57
INTERACTION C X L	3	12.52	4.17
INTERACTION R X C X L	6	11.43	1.90
WITHIN	48	11.90	0.25
TOTAL	71		

COLUMN F = 18.973196
SIGNIFICANCE = 0.000003
ROW F = 0.626094
SIGNIFICANCE = 0.543729
LEVEL F =4.751571
SIGNIFICANCE = 0.032193
COLUMN-ROW INTERACTION = 3.034882
SIGNIFICANCE = 0.013439
COLUMN-LEVEL INTERACTION = 16.838300
SIGNIFICANCE = 0.000005
ROW-LEVEL INTERACTION = 2.295147
SIGNIFICANCE = 0.109802
COLUMN-ROW-LEVEL INTERACTION = 7.683011
SIGNIFICANCE = 0.000042

TABLE B-11. DIAMETRAL CREEP

Columns are percentages of crushed fine aggregate
Rows are aggregate sources
Levels are asphalt content

```
SOURCE OF VARIATION        DF    SUM OF SQUARES        MEAN SQUARE
BETWEEN COLUMNS             3     5178087.83              1726029.28
BETWEEN ROWS                2     1937965.86               968982.93
BETWEEN LEVELS              1     98864.22               98864.22
INTERACTION R X C           6     1866362.92               311060.49
INTERACTION R X L           2     642670.19               321335.10
INTERACTION C X L           3     496145.00               165381.67
INTERACTION R X C X L       6     2347241.25               391206.87
WITHIN                     48     14641146.67               305023.89
TOTAL                      71
COLUMN F = 5.658669
     SIGNIFICANCE = 0.002447
ROW F = 3.176744
     SIGNIFICANCE = 0.049251
LEVEL F =0.324120
     SIGNIFICANCE = 0.578561
COLUMN-ROW INTERACTION = 1.019791
     SIGNIFICANCE = 0.424572
COLUMN-LEVEL INTERACTION = 0.542193
     SIGNIFICANCE = 0.659830
ROW-LEVEL INTERACTION = 1.053475
     SIGNIFICANCE = 0.357781
COLUMN-ROW-LEVEL INTERACTION = 1.282545
     SIGNIFICANCE = 0.282526
```

APPENDIX C

ASPHALT CONCRETE MIX DESIGNS

TABLE C-1. ASPHALT CONCRETE MIX DESIGN NO. 1

Aggregate Data:	Coarse:	38% Crushed Salt River
	Fine:	62% Crushed Salt River (100%)

Asphalt Data: AC-20

Asphalt Content (%)	4.0	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	139.9	142.0	142.9	143.9	145.8
VMA (%)	18.3	17.5	17.4	17.5	16.7
Air Voids (%)	11.2	9.2	7.9	6.7	4.6
Voids Filled (%)	39.0	47.8	54.9	61.4	72.5
Stability (lbs)	2766	2902	3081	3292	3322
Flow (.01 in.)	11	11	11	13	14

Note: Test Results based on average of three specimens

TABLE C-2 ASPHALT CONCRETE MIX DESIGN NO. 2

Aggregate Data:	Coarse:	38% Crushed Tucson
	Fine:	62% Crushed Tucson (100%)

Asphalt Data: AC-20

Asphalt Content (%)	5.0	5.5	6.0	6.5
Bulk Unit Weight (pcf)	138.8	140.6	140.9	142.2
VMA (%)	16.0	15.3	15.5	15.2
Air Voids (%)	7.6	5.7	4.8	3.3
Voids Filled (%)	52.2	62.5	69.0	78.6
Stability (lbs)	4064	3680	3688	3589
Flow (.01 in.)	13	14	14	14

Note: Test Results based on average of three specimens

TABLE C-3. ASPHALT CONCRETE MIX DESIGN NO. 3

Aggregate Data: Coarse: 38% Crushed Flagstaff
Fine: 62% Crushed Flagstaff (100%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	156.8	157.9	159.1	160.3
VMA (%)	16.8	16.7	16.5	16.3
Air Voids (%)	7.7	6.3	4.7	3.1
Voids Filled (%)	54.2	62.5	71.5	80.7
Stability (lbs)	4359	4365	4048	3390
Flow (.01 in.)	9	11	11	12

Note: Test Results based on average of three specimens

TABLE C-4. ASPHALT CONCRETE MIX DESIGN NO. 4

Aggregate Data: Coarse: 38% Crushed Salt River
Fine: 62% Uncrushed Tucson (100%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	141.8	142.8	144.9	145.4
VMA (%)	15.5	15.4	14.6	14.7
Air Voids (%)	7.6	6.3	4.2	3.1
Voids Filled (%)	51.0	59.2	71.2	78.7
Stability (lbs)	3046	3046	3226	3008
Flow (.01 in.)	10	10	11	10

Note: Test Results based on average of three specimens

TABLE C-5. ASPHALT CONCRETE MIX DESIGN NO. 5

Aggregate Data: Coarse: 38% Crushed Tucson
Fine: 62% Uncrushed Tucson (100%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	140.8	142.0	142.3	144.1
VMA (%)	14.6	14.4	14.7	14.0
Air Voids (%)	7.2	5.8	4.9	3.0
Voids Filled (%)	50.5	59.6	66.4	78.5
Stability (lbs)	3775	3804	3413	3724
Flow (.01 in.)	9	10	10	10

Note: Test Results based on average of three specimens

TABLE C-6. ASPHALT CONCRETE MIX DESIGN NO. 6

Aggregate Data: Coarse: 38% Crushed Flagstaff
Fine: 62% Uncrushed Tucson (100%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	146.6	148.2	149.6	149.9
VMA (%)	14.9	14.4	14.0	14.3
Air Voids (%)	6.9	5.2	3.5	2.6
Voids Filled (%)	53.4	64.0	75.0	81.9
Stability (lbs)	3261	3162	3363	3318
Flow (.01 in.)	9	9	10	12

Note: Test Results based on average of three specimens

TABLE C-7. ASPHALT CONCRETE MIX DESIGN NO. 7

Aggregate Data: Coarse: 38% Crushed Salt River
Fine: 41.5% Crushed Salt River (67%)
20.5% Uncrushed Tucson (33%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	143.5	145.9	147.5	148.1
VMA (%)	16.6	15.7	15.2	15.3
Air Voids (%)	7.1	4.9	3.1	2.0
Voids Filled (%)	57.0	68.7	79.4	86.7
Stability (lbs)	3779	3508	3210	3822
Flow (.01 in.)	11	11	11	13

Note: Test Results based on average of three specimens

TABLE C-8. ASPHALT CONCRETE MIX DESIGN NO. 8

Aggregate Data: Coarse: 38% Crushed Salt River
Fine: 20.5% Crushed Salt River (33%)
41.5% Uncrushed Tucson (67%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	144.3	145.7	146.8	147.7
VMA (%)	14.7	14.4	14.2	14.1
Air Voids (%)	5.9	4.3	2.9	1.6
Voids Filled (%)	59.7	69.9	79.7	88.7
Stability (lbs)	3681	3791	3697	3627
Flow (.01 in.)	10	11	11	11

Note: Test Results based on average of three specimens

TABLE C-9. ASPHALT CONCRETE MIX DESIGN NO. 9

Aggregate Data:			
	Coarse:	38%	Crushed Tucson
	Fine:	41.5%	Crushed Tucson (67%)
		20.5%	Uncrushed Tucson (33%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	139.8	140.7	141.9	142.9
VMA (%)	15.1	15.0	14.8	14.6
Air Voids (%)	7.6	6.4	4.9	3.5
Voids Filled (%)	49.7	57.8	67.0	75.9
Stability (lbs)	3760	3540	3489	3646
Flow (.01 in.)	10	10	10	12

Note: Test Results based on average of three specimens

TABLE C-10 ASPHALT CONCRETE MIX DESIGN NO. 10

Aggregate Data:			
	Coarse:	38%	Crushed Tucson
	Fine:	20.5%	Crushed Tucson (33%)
		41.5%	Uncrushed Tucson (67%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	139.5	141.2	142.2	144.0
VMA (%)	15.3	14.+	14.6	13.9
Air Voids (%)	8.0	6.1	4.8	2.9
Voids Filled (%)	47.9	58.2	66.9	79.1
Stability (lbs)	3296	3539	3648	3709
Flow (.01 in.)	10	10	10	11

Note: Test Results based on average of three specimens

TABLE C-11. ASPHALT CONCRETE MIX DESIGN NO. 11

Aggregate Data: Coarse: 38% Crushed Flagstaff
Fine: 41.5% Crushed Flagstaff (67%)
20.5% Uncrushed Tucson (33%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	153.8	155.6	156.1	157.6
VMA (%)	15.8	15.3	15.5	15.1
Air Voids (%)	7.2	5.3	4.2	2.5
Voids Filled (%)	54.7	65.5	72.8	83.5
Stability (lbs)	4326	4440	4065	4127
Flow (.01 in.)	10	10	11	12

Note: Test Results based on average of three specimens

TABLE C-12. ASPHALT CONCRETE MIX DESIGN NO. 12

Aggregate Data: Coarse: 38% Crushed Flagstaff
Fine: 20.5% Crushed Flagstaff (33%)
41.5% Uncrushed Tucson (67%)

Asphalt Data: AC-20

Asphalt Content (%)	4.5	5.0	5.5	6.0
Bulk Unit Weight (pcf)	150.8	151.4	152.6	152.9
VMA (%)	14.9	15.0	14.8	15.1
Air Voids (%)	6.1	4.9	3.4	2.4
Voids Filled (%)	59.3	67.4	77.0	83.9
Stability (lbs)	3214	3593	3362	3712
Flow (.01 in.)	10	10	11	12

Note: Test Results based on average of three specimens

APPENDIX D

F TEST

The F test is commonly used in conjunction with an analysis of variance to measure the significance of the effect of individual test variables. The analysis of variance partitions the variation of test data from an overall mean. The F statistic is obtained by comparing the variation attributed to an individual test variable to variation attributed to a failure to obtain the same results for test replications (error). The larger the variation attributed to the test variable when compared to test error, the larger the F statistic and the more significant the variable's effect. The F statistic is compared to values of F tabulated for different probabilities to obtain a measure of the significance of a variable's effect.

The analyses of variance for the work were obtained by use of a Wang computer and an analysis of variance program. Tabulated values for the F statistic can be obtained from most commonly used statistic books.