SYNTHETIC AGGREGATES FOR ASPHALT CONCRETE MIXES

by

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Synthetic Aggregates for Asphaltic Concrete Mixtures

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ABSTRACT

Included in this report are the descriptions and findings resulting from laboratory and field investigations of the use of four manufactured aggregates for the production of asphaltic concrete. The information consists of basic design data for the inclusion of synthetic aggregates in asphaltic concrete mixes, the results obtained from a comprehensive program of laboratory testing of the synthetic aggregates and asphaltic concrete mixes containing the synthetic aggregates. Descriptions of field performance characteristics of asphaltic concrete mixes containing synthetic aggregates are also included.

The laboratory test data were obtained from standard or well established test procedures designed for the evaluation of the physical and engineering properties of the aggregates and asphaltic concrete mixes. The test data relating to the physical properties of synthetic aggregates reflect gradation, specific gravity, unit weight, abrasion, freeze-thaw and absorption of water, of the four synthetic aggregates included in the study. The laboratory test data relating to rational mix combinations reflect asphalt absorption by the aggregate, surface area, asphalt film thickness, air permeability, unconfined compressive strength, swell characteristic, Hveem stability, cohesiometer values, degradation of aggregates during compaction and surface abrasion.

The information relating to field tests reflects test methodology and short term evaluations of the field performance of asphaltic concrete mixes containing manufactured aggregates for both hot-mix hot-laid and hot-mix cold-laid designs. Brief descriptions of previous field tests conducted by the Texas Highway Department also are included to establish the field performance characteristics of this new type of aggregate for the construction of bituminous pavements. The tests that were conducted consist of small scale field tests of cold mixes and a large scale test of the use of the lightweight aggregates for the production of open graded plant mixed seal coats. Open graded mixes as used in this report refer to field void contents in the range of 12 to 24 percent.

The findings reported herein furnish the highway construction industry with basic design criteria for the inclusion of synthetic aggregates in asphaltic concrete mixes as well as laboratory and field test data supporting favorable performance of this new aggregate used as a substitute for natural aggregates. This report also points up a very meaningful characteristic of lightweight synthetic aggregates, namely, the friction textured characteristics are superior to natural aggregates. Extensive field data present ample proof that lightweight aggregate used as the coarse aggregate fraction in bituminous mixes provides long lasting high skid resistance.

IMPLEMENTATION STATEMENT

The significant findings resulting from this study consist of the development of basic design criteria for the inclusion of synthetic aggregates in asphaltic concrete mixes, and test data supporting favorable performance characteristics of this new material used as a substitute for natural aggregates. The study also served to point up some of the material properties and performance characteristics of the synthetic aggregates that are superior to the corresponding properties and characteristics reflected in natural aggregates. The implementation of these findings must reflect acceptance by the sponsor and an effectuation of programs of instruction designed to familiarize the Texas Highway Department personnel (design, maintenance, and construction) with the peculiarities and advantages associated with the use of synthetic aggregates for asphaltic concrete pavement construction.

A suggested program of instruction for the implementation of the significant findings resulting from this study is outlined as follows:

1. Dissemination of significant and applicable findings in the form of technical or instructional memoranda.
2. Revise design and construction manuals to reflect design criteria that are applicable to asphaltic concrete containing blends of lightweight aggregates and natural aggregates.
3. Sponsor special conferences or programs of instruction designed to familiarize the design, construction, and maintenance personnel with engineering practices that are applicable to asphaltic concrete containing blends of synthetic aggregates.

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INTRODUCTION

This report contains a description of a comprehensive investigation of the use of synthetic aggregates for the production of asphaltic concrete mixes. Research work in this area has been stimulated by the increased rate of aggregate consumption and the scarcity of natural aggregates in certain areas. The synthetic aggregate referred to in this report is produced by subjecting material selected from natural deposits of clay or shale to elevated temperatures for the purpose of expanding and hardening the structure of the parent raw material. All materials studied were produced by the rotary kiln method. The term synthetic aggregate is used to describe the aggregates manufactured by the rotary kiln method; whereas, the term lightweight is only used to describe aggregates that have a significant reduction in unit weight resulting from the internal bleb structure.

The research work described in this report consisted of an analysis of the basic design criteria, a determination of the physical properties of the aggregates, and a study of the performance characteristics of asphaltic concrete mixes containing these aggregates. The study of asphaltic concrete mixes included an investigation of the use of manufactured aggregates for the preparation of hot mixes as well as cold mixes. Well established laboratory tests and small scale field tests were used for the study of performance characteristics of the asphaltic concrete mixes containing synthetic aggregates. Serviceability studies of full scale field sections are also included particularly as related to skid resistance.

Synthetic Aggregates and Physical Properties

The synthetic aggregates used for this investigation represent four different sources. Three of the aggregates are presently being produced by plants located in Texas. These plants are located near Clodine, Dallas, and Ranger, Texas. The fourth material, a Sulphur Springs, Texas, material is not classed as a lightweight aggregate due to the lack of expansion of the parent material during the burning process. The other three aggregates reflect a significant expansion within the parent material and may be classed as lightweight aggregates[1] (dry loose unit weight less than 55 lbs. per cubic foot). This report will contain no further disclosure of the identity of the four aggregates under consideration. A confidential code established by the researcher is used for the reporting of all of the other test data included in this report.

It was necessary to blend two grades of the three lightweight aggregates in order to obtain the gradation desired for asphaltic concrete mixes. The physical properties of these two grades are reported separately. However, only one grade of the material from Sulphur Springs was required in order to satisfy the gradation requirements for the asphaltic concrete mixes.

The four aggregates were subjected to a comprehensive program of laboratory testing to determine the significant physical properties. The significant physical properties are the properties of the aggregates that furnish indices of performance when used in asphalt concrete mixes. The following laboratory tests were used to determine the physical properties of the four material:

1. Gradation—ASTM C-117-67—wet sieve analysis.
2. Bulk specific gravity, percent absorption, and aggregate absorption factor—Bryant test.[2]
3. Unit Weight—ASTM C-29-67T.
4. Los Angeles Abrasion — ASTM C-131-66, and Los Angeles Abrasion as modified by the Texas Highway Department (3).
5. Test for degradation of aggregates due to cycles of freezing and thawing by Gallaway (4).

Additional information pertaining to the above test procedures is included in the following sections. In addition to the supplementary information pertaining to

TABLE 1. GRADATION OF SYNTHETIC AGGREGATES
(Percent Passing)

Sieves	Aggregate No. 1		Aggregate No. 2		Aggregate No. 3		Aggregate No. 4
	Coarse	Medium	Coarse	Medium	Coarse	Medium	
½″	100	100	100	100	100	100	100
⅜″	51	100	81	100	61	99	99
4	2	21	5	32	1	46	48
8	1	1	1	1	0	1	23
16	0	0	0	0	0	0	11
30	0	0	0	0	0	0	7
50	0	0	0	0	0	0	5
100	0	0	0	0	0	0	3
200	0	0	0	0	0	0	2

TABLE 2. BULK SPECIFIC GRAVITY, PERCENT ABSORPTION, AND AGGREGATE ABSORPTION FACTOR

Material Identification	Bulk Spec. Grav.	Percent Absorption 1 day	7 days	14 days	Aggregate Absorption Factor
Aggregate No. 1 (Coarse)	1.61	11.5	16.6	18.4	4.3
	1.60	11.8	16.7	18.2	4.7
	1.60	11.5	17.3	18.9	4.7
Aggregate No. 1 (Medium)	1.56	12.9	18.8	20.4	5.2
	1.58	12.6	18.4	19.8	5.4
	1.58	12.7	18.6	20.0	5.3
Aggregate No. 2 (Coarse)	1.28	16.8	23.7	26.5	6.7
	1.27	16.9	23.6	26.6	6.3
	1.34	15.5	22.2	25.2	6.0
Aggregate No. 2 (Medium)	1.26	17.1	24.1	27.0	5.3
	1.27	13.9	23.4	26.6	4.0
	1.27	17.1	24.3	27.5	6.9
Aggregate No. 3 (Coarse)	1.48	4.9	7.8	9.2	2.4
	1.51	5.5	8.3	9.9	1.7
	1.48	5.6	8.4	9.9	2.4
Aggregate No. 3 (Medium)	1.52	6.9	10.5	12.2	2.8
	1.57	5.7	9.1	10.5	2.7
	1.56	5.8	9.4	11.0	2.6
Aggregate No. 4	2.37	3.0	3.6	3.9	0.2
	2.35	3.3	3.4	3.6	0.6
	2.34	3.6	3.8	4.0	0.5

test procedure, the following five subsections contain a summary of test data relating to the significant physical properties of the four aggregates under consideration.

Gradation. The four aggregates were tested for particle size and gradation by the wet sieve analysis—ASTM C-117-67. The wet sieve analysis was used for an accurate account of dust and agglomerations of fines that may be found in highly textured kiln fired aggregates. The gradation test data for these four aggregates are included in Table 1. The aggregates will hereinafter be identified as Aggregates Nos. 1, 2, 3, and 4.

Bulk Specific Gravity, Percent Absorption, and Aggregate Absorption Factor. A test procedure developed by Bryant[1] was used for the determination of the bulk specific gravity, percent absorption, and aggregate absorption factor for the four aggregates. An abstracted version of this test procedure is included in Appendix A for convenient reference. Figure 1 shows the laboratory equipment used for a precise measurement of the weight of water absorbed by a sample of this type of aggregate.

TABLE 3. UNIT WEIGHTS OF THE SYNTHETIC AGGREGATES

Material Identification	Unit Weight, pcf (Rodding Procedure)	Unit Weight, pcf Shoveling Procedure
Aggregate No. 1—Coarse	50.7	52.3
Aggregate No. 1—Medium	49.7	50.9
Aggregate No. 2—Coarse	43.6	42.5
Aggregate No. 2—Medium	45.2	42.1
Aggregate No. 3—Coarse	51.0	49.8
Aggregate No. 3—Medium	56.2	50.9
Aggregate No. 4	76.0	73.1

Table 2 contains a summary of test data relating to bulk specific gravity, percent absorption, and aggregate absorption factor.

Unit Weight. Unit weights of the aggregates were determined by the rodding and shoveling procedures described in ASTM C-29-67T. The unit weights as determined by both test methods (rodding and shoveling) are listed in Table 3.

Los Angeles Abrasion and Los Angeles Abrasion as Modified by the Texas Highway Department. The four synthetic aggregates were tested for abrasion in accordance with the Los Angeles Abrasion Test (ASTM C-131-

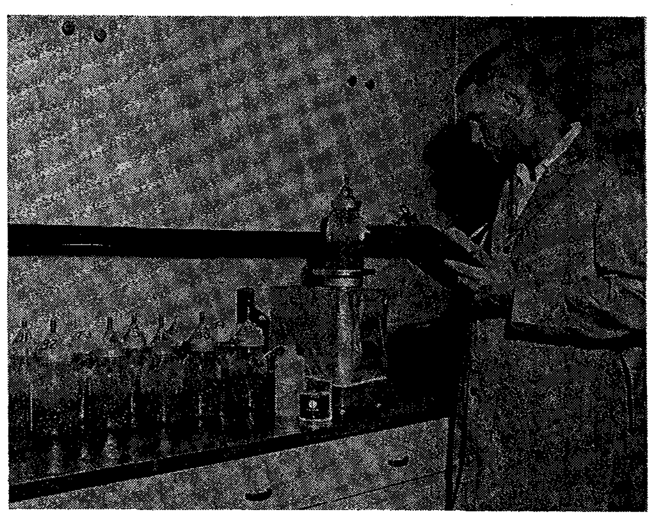


Figure 1. Laboratory testing for absorption and specific gravity.

TABLE 4. ABRASION BY LOS ANGELES TEST AND TEXAS HIGHWAY METHOD

Material Identification	L. A. Abrasion (percent)		THD Abrasion (percent)	
	B-C Grading	C-Grading	B-C Grading	C-Grading
Aggregate No. 1	33.2	27.9	16.4	17.4
Aggregate No. 2	26.3	20.1	17.2	13.5
Aggregate No. 3	27.6	24.8	15.8	15.8
Aggregate No. 4	49.9	42.5	31.7	33.2

66) and the Los Angeles Abrasion Test as modified by the Texas Highway Department[3] for the testing of lightweight aggregates. These abrasion test data are reported in Table 4. The "B-C" grading shown in Table 4 is a nonstandard grading but because this grading is more nearly representative of the materials under test, Los Angeles Abrasion values for this grading are included. A "B-C" grading includes the smaller size of the standard B grading and the larger size of the C grading in the regular amounts.

Degradation of Aggregates Due to Cycles of Freezing and Thawing. Representative samples of the synthetic aggregates were subjected to a test procedure developed by Gallaway[4] for the measurement of aggregate degradation due to cycles of freezing and thawing. An abstracted version of this test procedure is included in Appendix A for convenient reference. The test data reflecting the susceptibility of the synthetic aggregates to degradation under cycles of freezing and thawing are reported in Table 5.

TABLE 5. AGGREGATE DEGRADATION AFTER FIFTY CYCLES OF FREEZE-THAW

Synthetic Aggregate	Weighted Loss After 50 Cycles (percent)
Aggregate No. 1	27.7
Aggregate No. 2	32.1
Aggregate No. 3	8.9
Aggregate No. 4	70.2

The test data obtained from this program of laboratory testing were used for a classification of the four synthetic aggregates. The aggregates were classed according to a classification system prepared for this purpose by a staff of researchers at the Texas Transportation Institute.[1] The aggregates are classed as follows:

Aggregate No. 1	I B-C
Aggregate No. 2	I C
Aggregate No. 3	I A
Aggregate No. 4	II C

Design Criteria for Bituminous Mixes Containing Synthetic Aggregates

Bituminous mix design consists of a rational determination of the optimum gradation of aggregates and the optimum percentage of asphalt for an economical production of asphaltic concrete with an acceptable level of stability. The design criteria and empirical guidelines that have been established for the determination of the optimum gradation of aggregates and optimum percentage of asphalt reflect many years of coordinated laboratory and field research work by highway departments and other organizations. The design criteria and empirical guidelines that have been established from the coordinated laboratory and field research work are based on weight measurements of typical aggregates from natural sources. These well established weight-volume relations are distorted by the use of lightweight aggregate as a substitute for natural aggregates. The effects of these distorted weight-volume relations are reflected in the asphalt-aggregate relations, gradation analyses, and the spread rate or lay-down rate (lbs. per sq. yd.) for a predetermined pavement thickness. It is, therefore, necessary for the design criteria for bituminous mixes containing lightweight aggregates to reflect a complete volumetric analysis of the materials in addition to the conventional weight analysis.

A complete volumetric analysis of the material components will reflect a more accurate and theoretical relationship for the basic parameters for bituminous mix design. However, the factors of primary concern are an accurate reflection of asphalt-aggregate relations, gradation analyses, and laydown volume. The need for a volumetric analysis for an accurate reflection of the basic information in these three areas is described as follows:

Asphalt-Aggregate Relations. The optimum percentage of asphalt is normally determined from a laboratory investigation of surface area, absorption characteristics, and a study of the variations in stability associated with changes in asphalt content. This optimum asphalt content is then expressed as a percentage of the total weight of the bituminous mixture. However, for preliminary laboratory investigations, the asphalt content is frequently based on the weight of the aggregate combination.

The inclusion of varying amounts of a lightweight aggregate in a bituminous mixture destroys the significance of weight measures for the design and control of asphalt content. For this reason, it is necessary to base asphalt content on percent by volume in order to establish reliable indices of the asphalt content for bituminous mixtures containing lightweight aggregates.

Gradation Analyses. The optimum gradation of aggregates for a bituminous mixture is normally determined from a series of laboratory tests conducted on aggregate blends or combinations that hold promise for an economical production of high stability mixes. A gradation curve is prepared for a graphical analysis of the various grade fractions contained in the total aggregate volume. The established methodology for gradation analyses and blending operations is based on weight measurements of the grade fractions of natural aggregates.

The conventional weight measurements of the various grade fractions may be expressed as relative percentages of the total aggregate volume when the aggregates have a common specific gravity. However, these weight measurements fail to reflect an accurate measure of the various grade fractions when a lightweight aggregate is included in the aggregate combination.

A simplified procedure was developed by Hargett for the determination of a theoretical gradation analysis of a combination of aggregates having different specific gravities. The basic data required for this theoretical gradation analysis consist of the gradation data and blend ratios for each of the aggregates included in the combination. This simplified procedure for the blending of aggregates having different specific gravities to obtain a desired gradation is described in detail in Appendix A.

Laydown Rate. When bituminous concrete is applied to the highway surface, the laydown or coverage rate is normally reported in pounds per square yard. A rule of thumb that has been established for rate of coverage is 100 lbs. per sq. yd. (conventional mix) will yield one inch of pavement thickness.[5] The reliability of such a coverage rate is destroyed by the use of lightweight or synthetic aggregates in asphaltic concrete mixes. This problem of determining the laydown rate for a predetermined pavement thickness further emphasizes the need for a thorough evaluation of the weight per unit volume of asphaltic concrete mixes containing lightweight aggregates.

Two basic formulas were developed for a thorough evaluation of material components and the weight per unit volume of asphaltic concrete mixes containing synthetic aggregates. The two basic formulas are described as follows:

$$Vmx = Vb + Vna + Vsa + Vv. \qquad (1)$$

$$\gamma mx = \frac{(\gamma b)\ (Vb) + (\gamma na)\ (Vna) + (\gamma sa)\ (Vsa)}{Vmx}. \qquad (2)$$

Vmx = Volume of bituminous mix.

Vb = Volume of bituminous material.

Vna = Volume of natural aggregate.

Vsa = Volume of synthetic aggregate.

Vv = Volume of voids.

γmx = Unit weight of bituminous mix.

γb = Unit weight of bituminous material.

γna = Unit weight of natural aggregate.

γsa = Unit weight of synthetic aggregate.

Bituminous Mixes and Weight-Volume Analysis of the Constituents

The bituminous mixes were designed to reflect rational blends of the four synthetic aggregates with two natural aggregates. The mixes were designed to satisfy the Texas Highway Department's gradation specifications for a Class "A" Type "D" hot mix for fine graded surface course construction. Manufactured aggregates were used to satisfy the requirement for coarse graded particles, whereas natural aggregates were used to satisfy the gradation requirements for intermediate and fine graded particles. Sand and limestone chips were used as the two sources of fine graded natural aggregates. The gradation data for the three natural aggregates are reported in Table 6. The specific gravities of the bituminous mix constituents are reported in Table 7.

The aggregates were blended to satisfy the Texas Highway Department specifications by a simplified blending procedure developed by Hargett. An abstracted version of this simplified blending procedure is included in Appendix A for convenient reference. The aggregates were blended by volume in view of the significant differences in the specific gravities of the lightweight aggregate and natural aggregates. The synthetic aggregates (1 through 4) were blended with sand (S) and limestone screenings (L) and then mixed with predetermined percentages of asphalt cement for laboratory investigation. The laboratory investigation included a total of forty aggregate blends. The synthetic aggregates in these blends were increased by five percent increments

TABLE 6. NATURAL AGGREGATE GRADATIONS

Percent Passing - Retained	Coarse Limestone Chips	Medium Limestone Chips	Field Sand
½ - ⅜			
⅜ - 4	1		
4 - 8	10	2	2
8 - 16	15	47	0
16 - 30	13	18	2
30 - 50	11	12	13
50 - 100	10	10	52
100 - 200	7	7	20
200 - Pan	33	4	11

TABLE 7. SPECIFIC GRAVITIES OF THE CONSTITUENTS OF THE BITUMINOUS MIXES

Constituents of the Bituminous Mixes	Specific Gravity
Lightweight Aggregate No. 1	1.65
Lightweight Aggregate No. 2	1.28
Lightweight Aggregate No. 3	1.52
Synthetic Aggregate No. 4	2.36
Limestone Chips - Coarse	2.71
Natural Aggregate—Limestone Chips—Medium (blend)	2.69
Field Sand	2.64
Asphalt Cement—AC-10 (at 77°F)	1.01

TABLE 8. MIX IDENTIFICATION, AGGREGATE BLENDS, AND ASPHALT CONTENT

Mix Identification	Synthetic Aggregate (percent by volume)	Limestone Screenings (percent by volume)	Sand (percent by volume)	Asphalt (percent of aggregate weight)
1-4/L::40/60 + 7A	40	60		7
1-4/S::40/60 + 7A	40		60	7
1-4/L::45/55 + 5A & 9A	45	55		5,9
1-4/S::45/55 + 5A & 9A	45		55	5,9
1-4/L::50/50 + 7A	50	50		7
1-4/S::50/50 + 7A	50		50	7
1-4/L::55/45 + 5A & 9A	55	45		5,9
1-4/S::55/45 + 5A & 9A	55		45	5,9
1-4/L::60/40 + 7A	60	40		7
1-4/S::60/40 + 7A	60		40	7

(by volume) between limits of 40 and 60 percent. The following form is used for mix identifications: type of synthetic aggregate (coded)/type of natural aggregates (S or L) :: percentage of synthetic aggregate by volume/ percentage of natural aggregate by volume + percentage of asphalt cement (A) based on the weight of the aggregate combination. Table 8 shows a summary of the aggregate blends, asphalt content, and mix identification expressed in the above form.

The gradation differences associated with the five percent increases in the volume of synthetic aggregate are reflected in a family of five gradation curves. Figures 2 through 9 show a family of five gradation curves for each source of synthetic aggregate (1 through 4).

The asphalt content for preliminary design and batching was based on the weight of the aggregate combination. Since the aggregates were blended to yield a unit volume of solids, the total volume of the mix exceeded a unit volume by an amount equal to the volume of asphalt. The following expression reflects the procedure used for the mix preparation and a volumetric analysis of solid constituents included in the mix:

> One cubic foot (absolute volume) of aggregate + asphalt content expressed as a volume (rational percentage based on the weight of the aggregate combination) = minimum volume of mix (volume of solids or theoretical minimum volume).

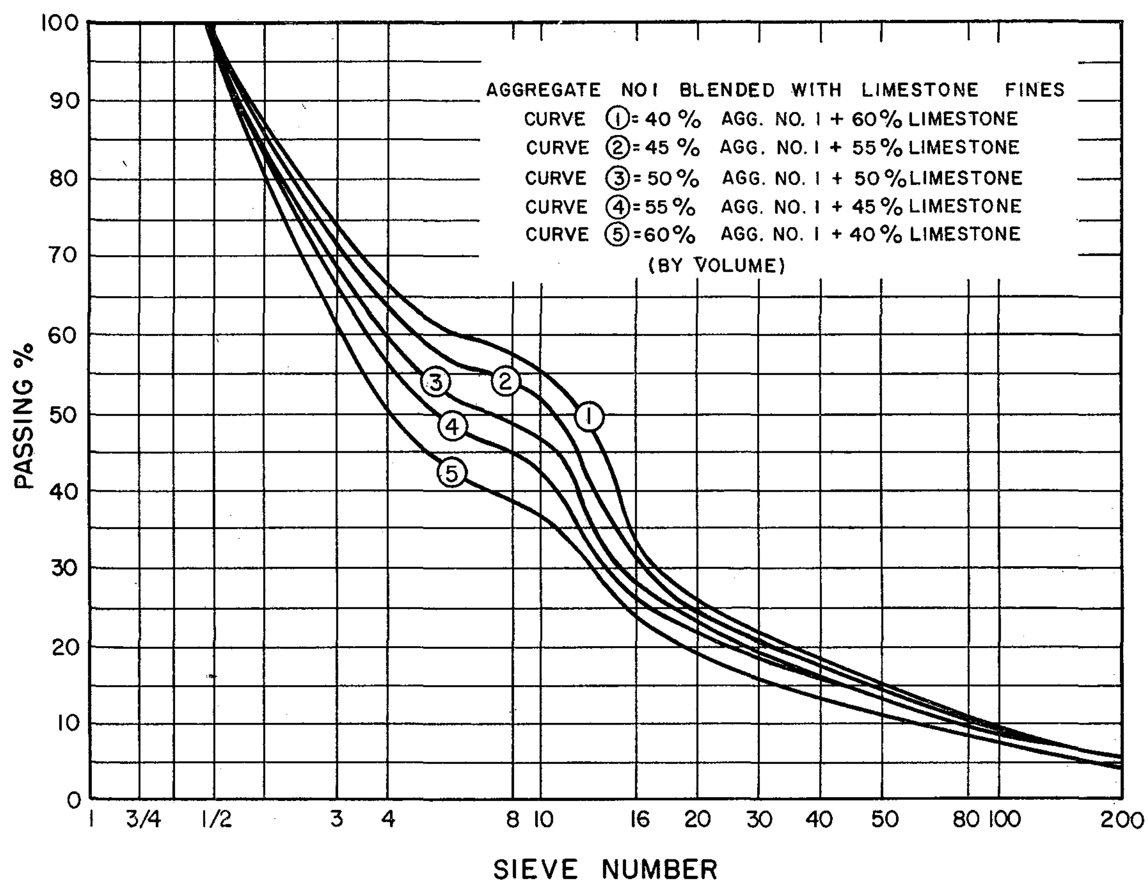


Figure 2. Gradation curves for blends of Aggregate No. 1 with limestone.

The weight and volume measurements of the mix constituents are reported in Table 9. Table 9 shows the asphalt content (by volume and weight) based on the total weight of the aggregate combination. The theoretical maximum density was determined by dividing the total weight of the mix constituents by total mix volume. It is believed that a volumetric analysis of bituminous mixes as described above will simplify the determination of air voids and asphalt absorbed by the aggregate.

Volumetric analyses are considered a necessary part of the comprehensive analyses of the constituents of asphaltic concrete mixes. Such analyses will give rise to simplified determinations of the asphalt absorbed by the aggregate and the air entrained in the uncompacted mix. The basic data for these simplified determinations consist of the theoretical maximum specific gravity and the specific gravity as determined by the Rice Method. Any difference reflected in these two specific gravities is

TABLE 9. WEIGHT AND VOLUMETRIC MEASUREMENTS OF MIX CONSTITUENTS

	Synthetic Aggregate		Natural Aggregate		Asphalt		Theoretical Maximum Density
Mix Identification	Weight (lbs.)	Volume (cu. ft.)	Weight (lbs.)	Volume (cu. ft.)	Weight (lbs.)	Volume (cu. ft.)	(lbs./cu. ft.)
1/L::40/60 + 7A	41.2	0.40	100.7	0.60	9.9	0.158	130.86
1/S::40/60 + 7A	41.2	0.40	99.8	0.60	9.9	0.158	130.08
1/L::45/55 + 5A	46.3	0.45	92.3	0.55	6.8	0.108	129.36
1/L::45/55 + 9A	46.3	0.45	92.3	0.55	12.3	0.196	125.29
1/S::45/55 + 5A	46.3	0.45	90.6	0.55	6.8	0.108	129.45
1/S::45/55 + 9A	46.3	0.45	90.6	0.55	12.3	0.196	125.38
1/L::50/50 + 7A	51.5	0.50	83.9	0.50	9.5	0.151	126.00
1/S::50/50 + 7A	51.5	0.50	82.4	0.50	9.4	0.150	124.60
1/L::55/45 + 5A	56.6	0.55	75.5	0.45	6.6	0.105	124.95
1/L::55/45 + 9A	56.6	0.55	75.5	0.45	11.9	0.189	121.01
1/S::55/45 + 5A	56.6	0.55	74.1	0.45	6.5	0.103	124.72
1/S::55/45 + 9A	56.6	0.55	74.1	0.45	11.8	0.188	119.75
1/L::60/40 + 7A	61.8	0.60	67.1	0.40	9.0	0.143	120.96
1/S::60/40 + 7A	61.8	0.60	65.9	0.40	8.9	0.142	119.82
2/L::40/60 + 7A	31.95	0.40	100.7	0.60	9.3	0.148	123.43
2/S::40/60 + 7A	31.95	0.40	99.8	0.60	9.2	0.146	122.57
2/L::45/55 + 5A	35.94	0.45	92.3	0.55	6.4	0.102	122.40
2/L::45/55 + 9A	35.94	0.45	92.3	0.55	11.5	0.183	118.42
2/S::45/55 + 5A	35.94	0.45	90.6	0.55	6.3	0.100	120.76
2/S::45/55 + 9A	35.94	0.45	90.6	0.55	11.4	0.181	116.89
2/L::50/50 + 7A	39.94	0.50	83.9	0.50	8.7	0.138	116.26
2/S::50/50 + 7A	39.94	0.50	82.4	0.50	8.6	0.137	114.86
2/L::55/45 + 5A	43.93	0.55	75.5	0.45	5.9	0.094	114.98
2/L::55/45 + 9A	43.93	0.55	75.5	0.45	10.7	0.170	111.22
2/S::55/45 + 5A	43.93	0.55	74.1	0.45	5.9	0.094	113.94
2/S::55/45 + 9A	43.93	0.55	74.1	0.45	10.6	0.169	109.94
2/L::60/40 + 7A	47.92	0.60	67.1	0.40	8.0	0.127	108.87
2/S::60/40 + 7A	47.92	0.60	65.9	0.40	7.9	0.126	107.72
3/L::40/60 + 7A	37.94	0.40	100.7	0.60	9.7	0.154	128.99
3/S::40/60 + 7A	37.94	0.40	99.8	0.60	9.7	0.154	128.97
3/L::45/55 + 5A	42.68	0.45	92.3	0.55	6.7	0.107	127.64
3/L::45/55 + 9A	42.68	0.45	92.3	0.55	12.1	0.193	123.59
3/S::45/55 + 5A	42.68	0.45	90.6	0.55	6.7	0.107	126.11
3/S::45/55 + 9A	42.68	0.45	90.6	0.55	11.99	0.191	122.07
3/L::50/50 + 7A	47.43	0.50	83.9	0.50	9.2	0.146	122.20
3/S::50/50 + 7A	47.43	0.50	82.4	0.50	9.1	0.145	121.87
3/L::55/45 + 5A	52.17	0.55	75.5	0.45	6.4	0.102	121.88
3/L::55/45 + 9A	52.17	0.55	75.5	0.45	11.5	0.183	117.94
3/S::55/45 + 5A	52.17	0.55	74.1	0.45	6.3	0.100	120.52
3/S::55/45 + 9A	52.17	0.55	74.1	0.45	11.4	0.181	116.67
3/L::60/40 + 7A	56.91	0.60	67.1	0.40	8.7	0.138	116.41
3/S::60/40 + 7A	56.91	0.60	65.9	0.40	8.6	0.137	115.27
4/L::40/60 + 7A	58.9	0.40	100.7	0.60	11.87	0.189	144.09
4/S::40/60 + 7A	58.9	0.40	99.8	0.60	11.10	0.177	143.89
4/L::45/55 + 5A	66.27	0.45	92.3	0.55	11.9	0.189	143.25
4/L::45/55 + 9A	66.27	0.45	92.3	0.55	14.3	0.228	140.50
4/S::45/55 + 5A	66.27	0.45	90.6	0.55	7.8	0.124	147.03
4/S::45/55 + 9A	66.27	0.45	90.6	0.55	14.1	0.224	140.14
4/L::50/50 + 7A	73.63	0.50	83.9	0.50	11.0	0.175	142.82
4/S::50/50 + 7A	73.63	0.50	82.4	0.50	10.9	0.173	142.68
4/L::55/45 + 5A	80.99	0.55	75.5	0.45	7.8	0.124	146.69
4/L::55/45 + 9A	80.99	0.55	75.5	0.45	14.1	0.224	139.83
4/S::55/45 + 5A	80.99	0.55	74.1	0.45	7.8	0.124	145.44
4/S::55/45 + 9A	80.99	0.55	74.1	0.45	13.9	0.221	138.52
4/L::60/40 + 7A	88.36	0.60	67.1	0.40	10.9	0.173	142.19
4/S::60/40 + 7A	88.36	0.60	65.9	0.40	10.8	0.172	141.08

attributed to a change in the unit volume of the mix. Changes in the theoretical or absolute unit volume may result from the aggregate absorbing the asphalt or by the entrainment of air in the uncompacted mix. The units of mass or weight of the mix will not be altered by asphalt absorption or air entrainment. However, the effects of these two factors are reflected in test data regarding theoretical maximum density (absolute volume) and Rice's specific gravity. The absorption of asphalt by the aggregate will yield a specific gravity (Rice's Method) which will be larger than the theoretical maximum specific gravity. The difference between these two specific gravities will reflect a measure of the volume of asphalt absorbed per unit volume of mix. In like manner, when the specific gravity by Rice's method is less than the theoretical maximum specific gravity, the difference will reflect a measure of the volume of air entrained in a unit volume of uncompacted mix.

A volumetric analysis as previously described will also provide basic data for the design and control of voids-density relations of compacted asphalt concrete mixes.

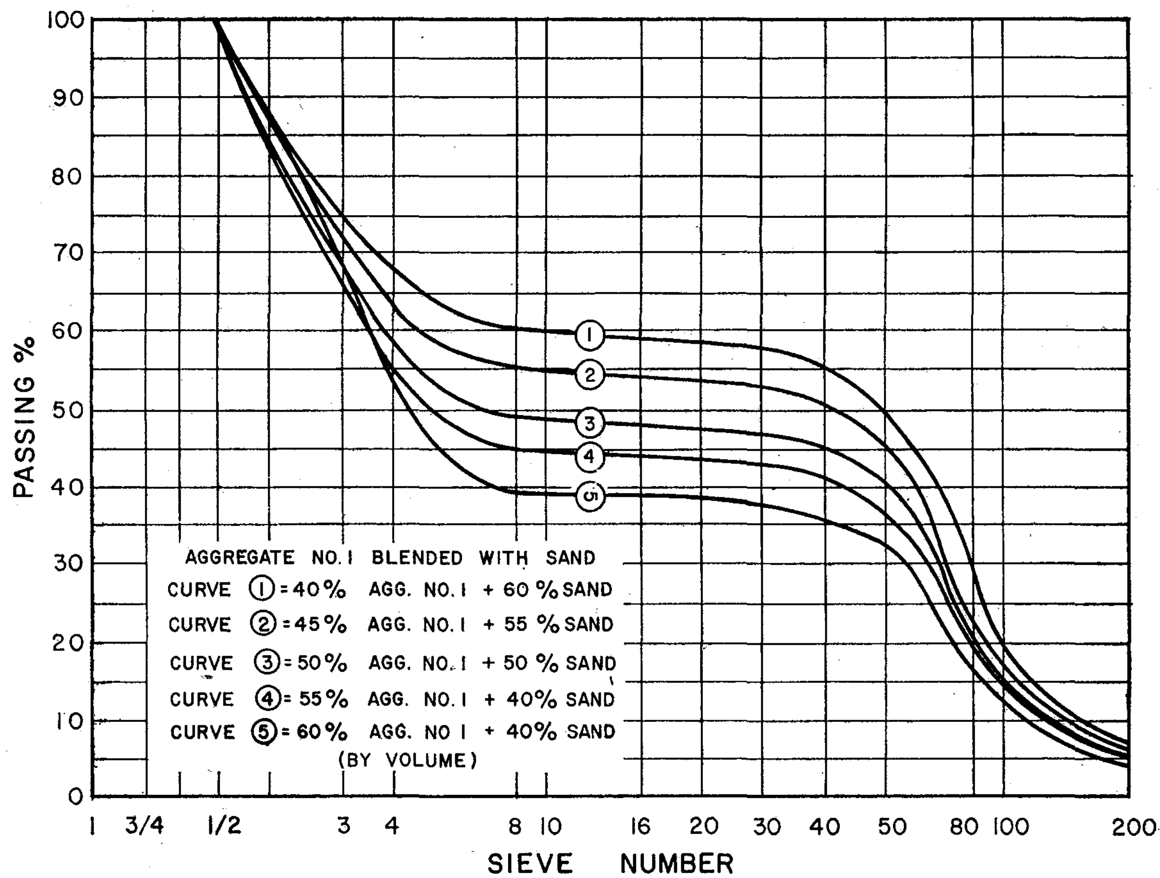


Figure 3. Gradation curves for blends of Aggregate No. 1 with sand.

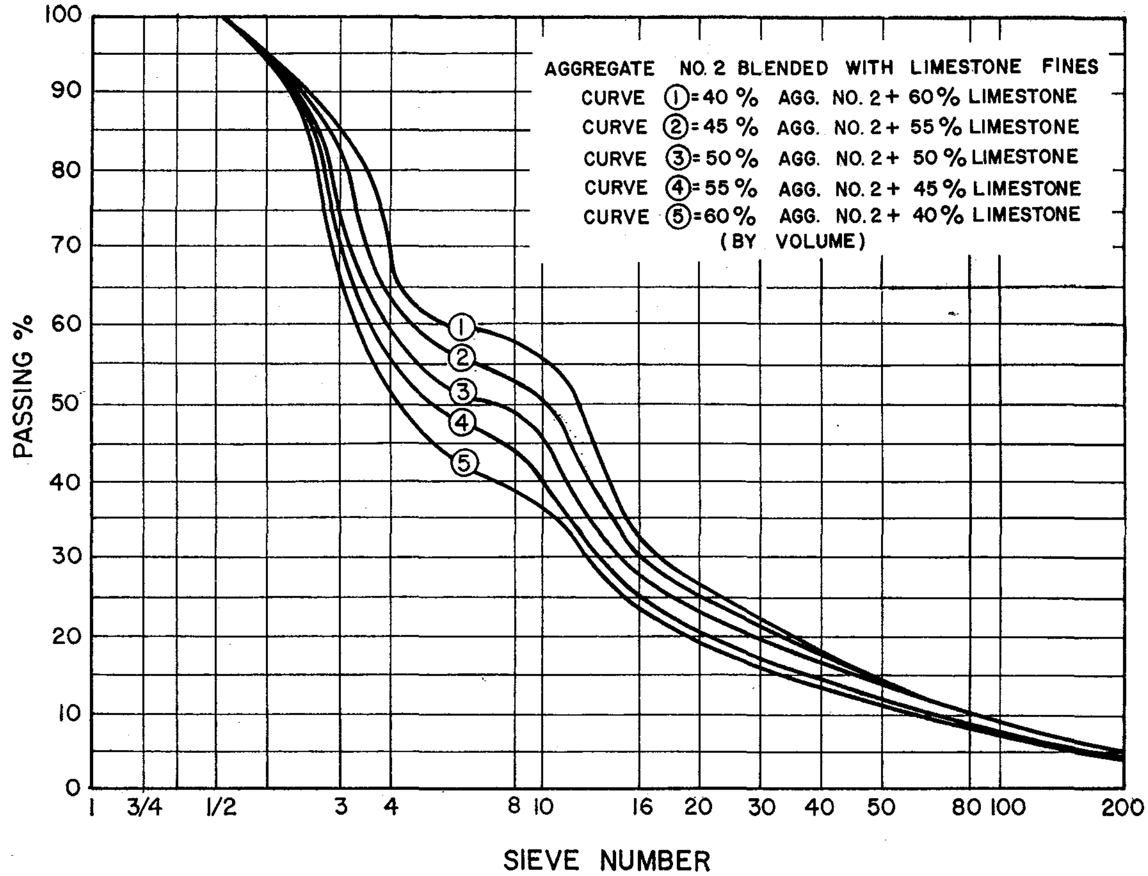


Figure 4. Gradation curves for blends of Aggregate No. 2 with limestone fines.

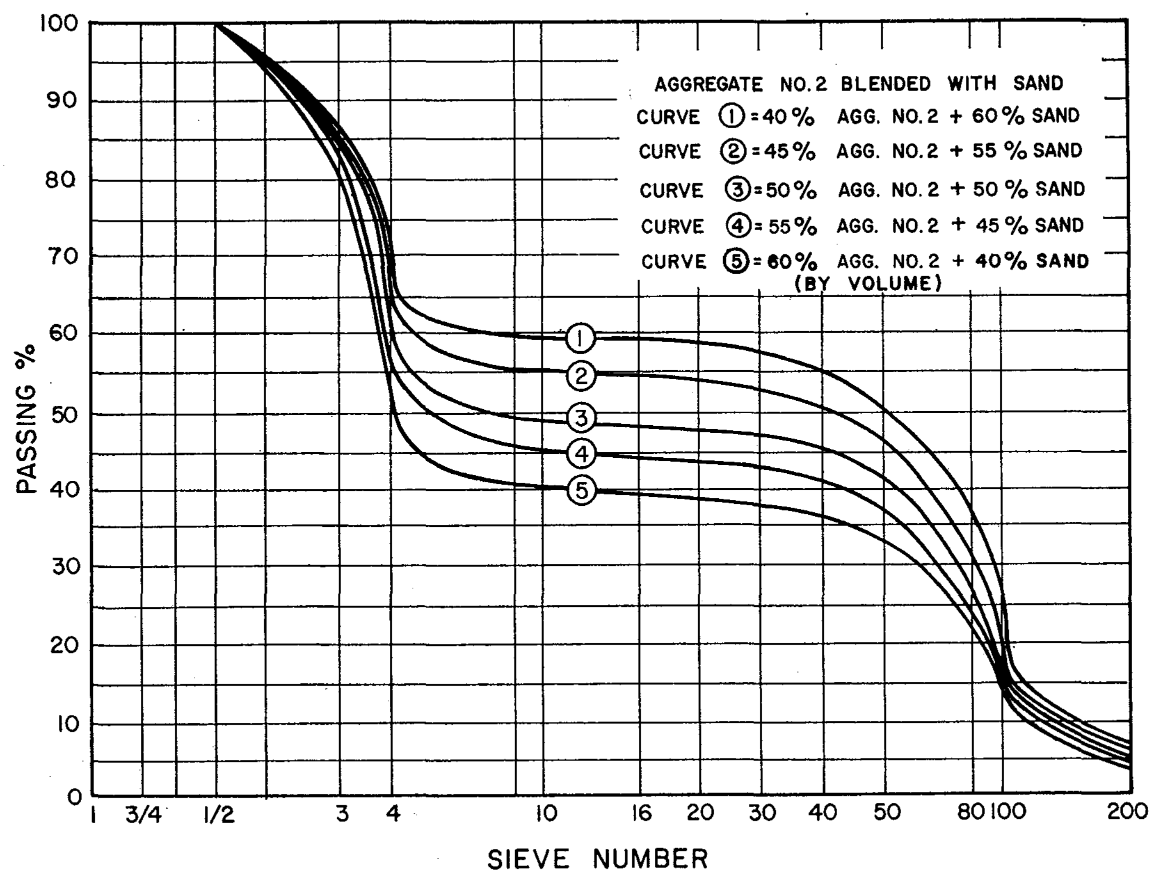


Figure 5. Gradation curves for blends of Aggregate No. 2 with sand.

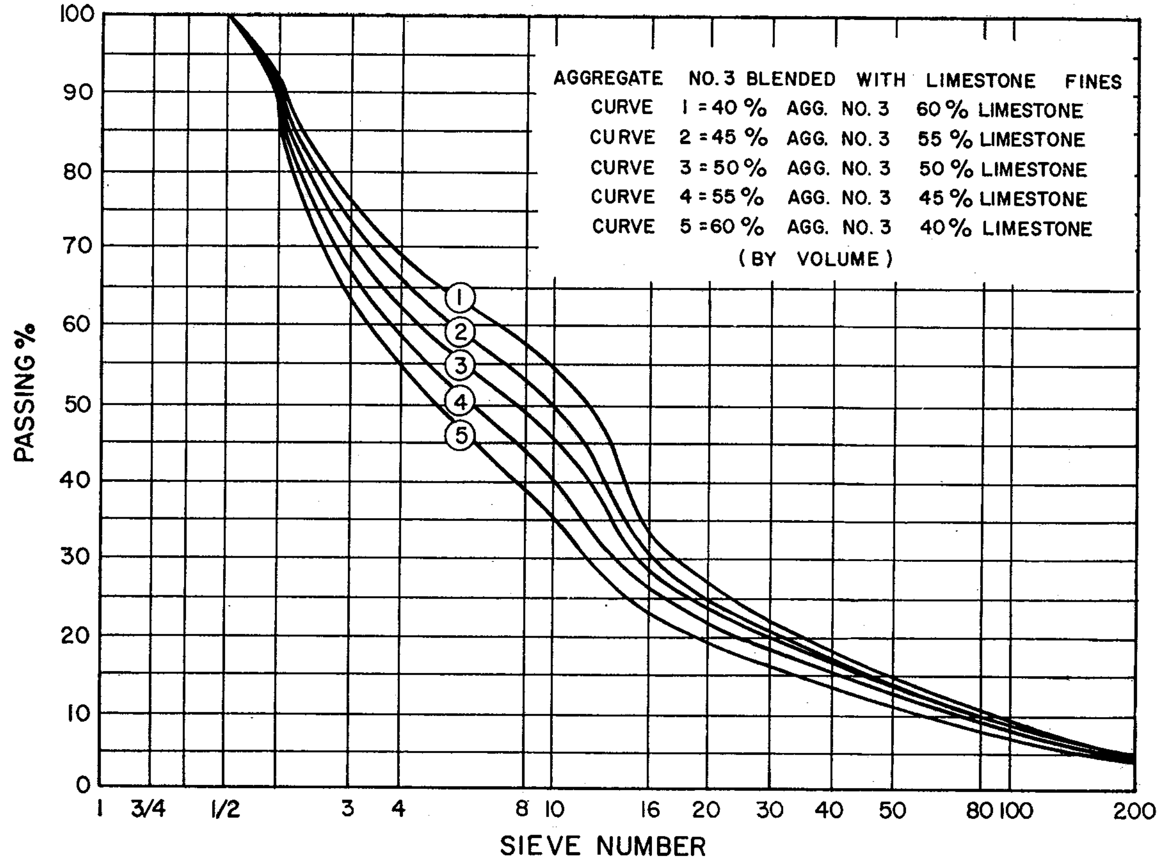


Figure 6. Gradation curves for blends of Aggregate No. 3 with limestone fines.

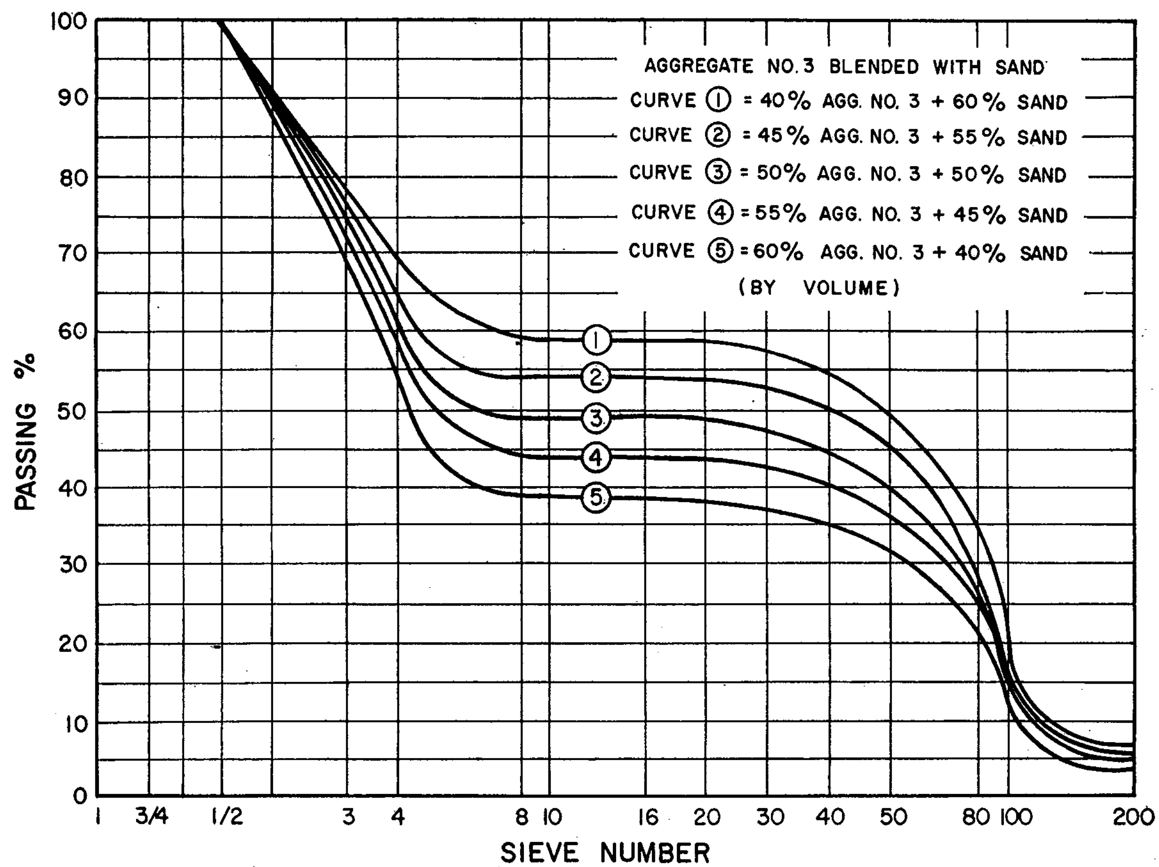


Figure 7. Gradation curves for blends of Aggregate No. 3 with sand.

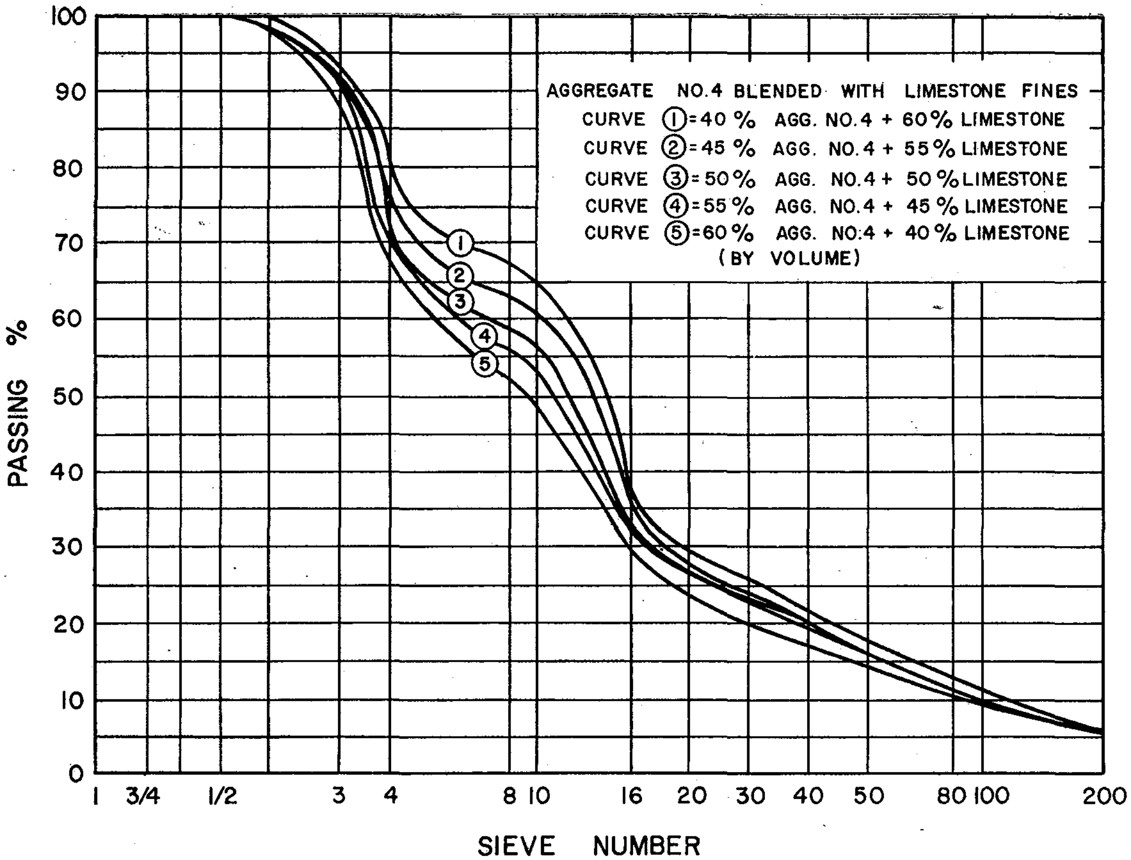


Figure 8. Gradation curves for blends of Aggregate No. 4 with limestone fines.

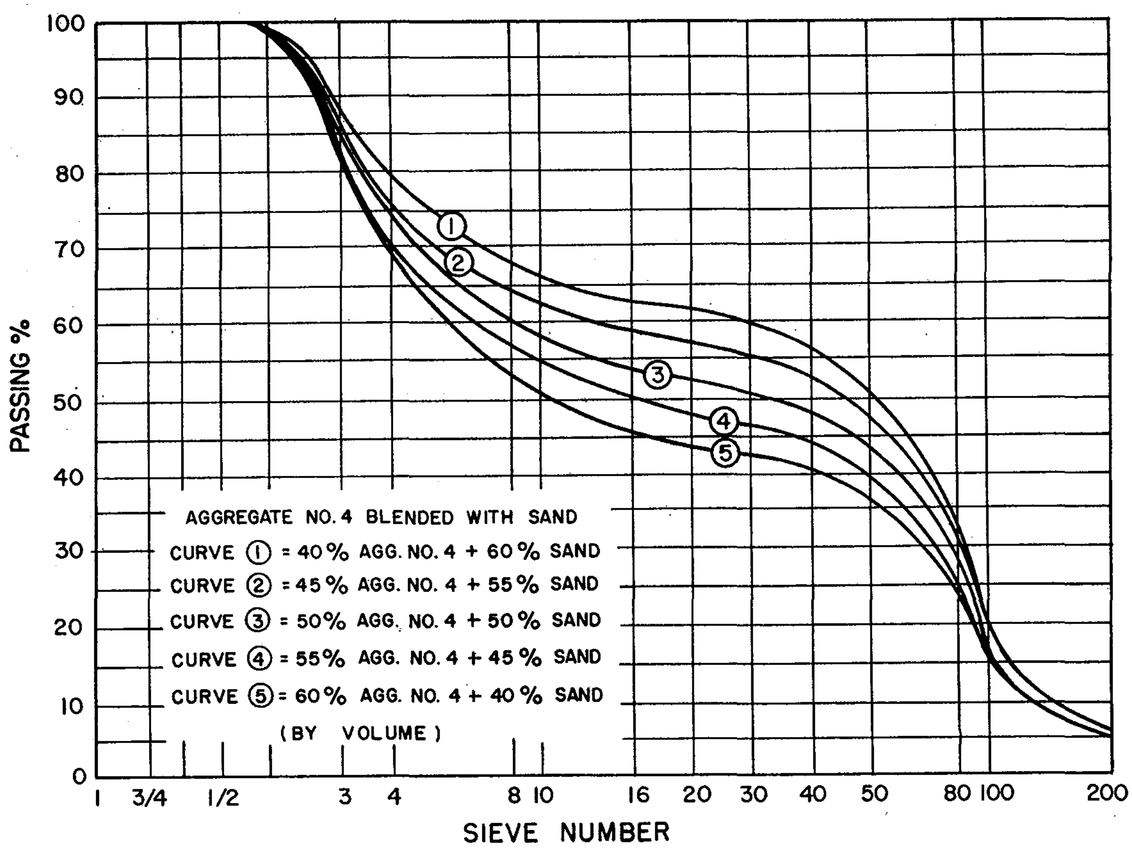


Figure 9. Gradation curves for blends of Aggregate No. 4 with sand.

Laboratory Testing and Analysis of Hot Mixes

A comprehensive program of laboratory testing was considered necessary to establish strength properties and indices of the performance of asphalt concrete containing manufactured aggregates. This program of laboratory testing was designed to furnish the Texas Highway Department and the construction industry with guidelines for the use of lightweight aggregates for the construction of high quality asphaltic concrete pavements. The program of laboratory investigation consisted of laboratory tests and analyses for the establishment of realistic data relating to the following eight factors:

1. Asphalt demand in view of aggregate absorption, surface area, and film thickness.
2. Asphalt absorption as determined from theoretical maximum density (computed) and laboratory density as determined by the test procedure developed by Rice.
3. Permeability of air through laboratory test specimens.
4. Compressive strength and the effects of water on the cohesion of the compacted bituminous mixes.
5. Swell characteristics and expansion pressures.
6. Hveem stability and cohesiometer values.
7. Degradation of aggregates during laboratory compaction.
8. Laboratory abrasion of bituminous mixes.

Asphalt Demand. The asphalt demand for bituminous mixes containing lightweight aggregates is recognized as a design factor of real concern in view of the peculiar physical properties possessed by this new type of aggregate. The peculiar properties of primary concern are attributed to the high porosity and bleb structure possessed by synthetic aggregate particles.

The investigation of asphalt demand included a study of surface area, theoretical film thickness of the asphalt, and the percentage of water absorbed by the aggregate during a two-minute interval (percent by volume). The surface area was determined for each aggregate combination according to the method described by the Asphalt Institute.[6] A theoretical film thickness was then computed for each mix from the predetermined asphalt content and surface area. The computed values for surface area (sq. ft./lb. of aggregate) and film thickness (microns) are reported in Table 10. These values were tabulated for further study and evaluation even though the use of empirical constants for the determination of the surface area of synthetic aggregate combinations is questioned. It is believed that the bleb structure (when exposed) yields a high level of surface area which is not reflected in the surface area constants that have been established for natural aggregates.

It is believed that the volume of water absorbed by the synthetic aggregate during a two-minute interval furnishes an index of asphalt absorption. The average percentages of water absorbed by the synthetic aggregates during two-minute intervals are reported below. The absorptions reported are percentages (by volume) of the aggregate solids.

Synthetic Aggregate	Absorption of Water (percent by volume in two minutes)
Aggregate No. 1	0.76%
Aggregate No. 2	1.29%
Aggregate No. 3	0.73%
Aggregate No. 4	0.97%

In view of the above premise and test data, aggregate No. 2 is expected to absorb more asphalt than any of the three other aggregates under investigation.

TABLE 10. SURFACE AREA AND FILM THICKNESS

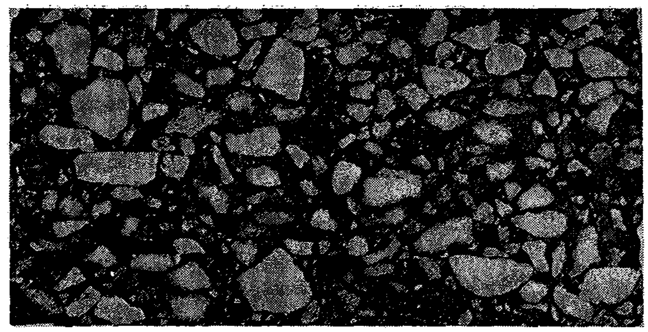
Mix Identification	Synthetic Aggregate No. 1		Synthetic Aggregate No. 2		Synthetic Aggregate No. 3		Synthetic Aggregate No. 4	
	Surface Area (sq. ft./lb.)	Film Thickness (microns)	Surface Area (sq. ft./lb.)	Film Thickness (microns)	Surface Area (sq. ft./lb.)	Film Thickness (microns)	Surface Area (sq. ft./lb.)	Film Thickness (microns)
1-4/L::40/60 + 7A	38.76	9.21	46.64	4.38	41.76	8.55	36.54	9.77
1-4/S::40/60 + 7A	71.95	3.47	87.17	4.10	79.75	4.48	64.28	5.55
1-4/L::45/55 + 5A	38.14	6.55	46.99	5.31	42.58	5.86	35.51	7.02
1-4/L::45/55 + 9A	38.14	12.30	46.99	9.98	42.58	11.02	35.51	13.21
1-4/S::45/55 + 5A	70.85	3.52	85.26	2.93	77.18	3.23	60.44	4.13
1-4/S::45/55 + 9A	70.85	6.62	85.26	5.50	77.18	6.08	60.44	7.76
1-4/L::50/50 + 7A	37.52	9.51	47.28	7.55	42.44	8.41	34.43	10.37
1-4/S::50/50 + 7A	67.29	5.31	83.31	4.29	74.31	4.80	53.47	6.68
1-4/L::55/45 + 5A	36.76	6.79	47.93	5.21	41.63	6.00	33.85	7.36
1-4/L::55/45 + 9A	36.76	12.76	47.93	9.79	41.63	11.27	33.85	13.86
1-4/S::55/45 + 5A	66.94	3.73	80.74	3.09	70.87	3.52	52.84	4.72
1-4/S::55/45 + 9A	66.94	7.01	80.74	5.81	70.87	6.62	52.84	8.88
1-4/L::60/40 + 7A	35.67	10.01	47.63	7.49	41.12	8.68	32.77	10.90
1-4/S::60/40 + 7A	59.18	6.03	77.63	4.60	67.11	5.32	48.88	7.30

Asphalt Absorption. A study was also made to determine the asphalt absorptive characteristics of synthetic aggregate mixes in an attempt to accurately evaluate asphalt demand for these mixes. The study procedure consists of the use of Rice's[7] specific gravity of the mixes to reflect asphalt absorption. The study method is similar to the one recommended by the Asphalt Institute.[6] However, the method used involves the use of a theoretical maximum density of the mix of asphalt and aggregates instead of bulk specific gravity of the aggregate combination designated "G_{ag}" by the Asphalt Institute.

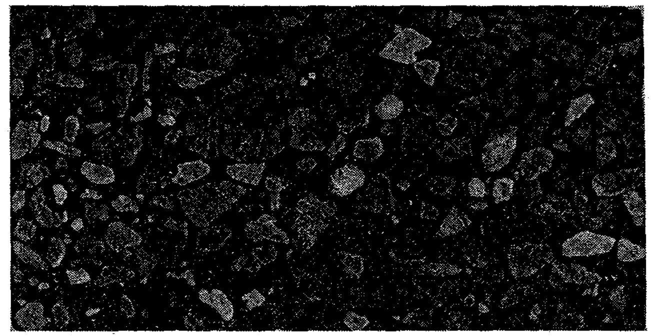
Table 11 contains a summary of theoretical maximum specific gravities (computed) and specific gravities of the mixes as determined in the laboratory by Rice's method.[7] These data show close agreement between the theoretical (computed) specific gravities and the specific gravities of actual mixes as determined in the laboratory.

Absorption of asphalt by the aggregate is reflected by laboratory densities exceeding the theoretical or computed densities.[6] In like manner, air entrainment is reflected by laboratory densities falling below the theoretical maximum density. In view of this analogy, the specific gravities reported in Table 11 reflect asphalt absorption by the aggregates in ten of the mixes. Six out of the ten mixes reflecting asphalt absorption contained synthetic aggregate number two. Seven out of these ten mixes contained limestone chips for the fines. It is therefore concluded that a low level of asphalt absorbed by part of the aggregate combination will not be reflected by the evaluation procedure described above. However, the absorption of asphalt by aggregate number 2 combined with the asphalt absorbed by the limestone fines was enough to be reflected by Rice's specific gravity of the mix.

The test data show that a relatively low level of asphalt is absorbed by synthetic aggregate. This is contrary to the conventional rationalization regarding asphalt absorption and aggregate porosity. High levels of asphalt absorption by lightweight aggregates are precluded by an impervious shell and the bleb structure within the particles. The bleb structure consists of macroscopic cellular air spaces which are not interconnected. Therefor the asphalt absorbed by high quality synthetic aggregates is considered to be of a lower level than the asphalt absorbed by limestones or other porous aggregates (natural aggregates). Figure 10 shows discolorations (halos) at the surface of the particles of natural aggregate (a), whereas the particles of synthetic aggregate (b) show no discoloration at the aggregate-asphalt interface due to asphalt absorption. The natural color of the synthetic aggregate shown in Figure 10 (b) was dark grey before mixing. There was little evidence of a discoloration due to the absorption of asphalt.



(a) Asphalt absorption by natural aggregates.



(b) No evidence of a significant level of asphalt absorption by synthetic aggregates.

Figure 10. Visual inspection of asphalt absorption.

Air Permeability. The air permeability of the bituminous mixes was studied in view of the high level

TABLE 11. SUMMARY OF SPECIFIC GRAVITIES—THEORETICAL AND RICE'S

	Synthetic Aggregate No. 1		Synthetic Aggregate No. 2		Synthetic Aggregate No. 3		Synthetic Aggregate No. 4	
Mix Identification	Theoretical Maximum Sp. G.	Rice's Sp. G.	Theoretical Maximum Sp. G.	Rice's Sp. G.	Theoretical Maximum Sp. G.	Rice's Sp. G.	Theoretical Maximum Sp. G.	Rice's Sp. G.
1-4/L::40/60 + 7A	2.10	2.09	1.98	1.96	2.07	2.01	2.31	2.32
1-4/S::40/60 + 7A	2.08	2.02	1.96	1.94	2.07	2.03	2.31	2.29
1-4/L::45/55 + 5A	2.07	2.09	1.96	2.04	2.05	2.05	2.30	2.37
1-4/L::45/55 + 9A	2.01	2.00	1.90	1.86	1.98	1.96	2.25	2.25
1-4/S::45/55 + 5A	2.07	2.07	1.94	1.97	2.20	2.03	2.36	2.34
1-4/S::45/55 + 9A	2.01	1.98	1.87	1.86	1.96	1.95	2.25	2.22
1-4/L::50/50 + 7A	2.02	2.01	1.86	1.85	1.96	1.96	2.37	2.29
1-4/S::50/50 + 7A	2.00	1.99	1.84	1.83	1.95	1.94	2.29	2.27
1-4/L::55/45 + 5A	2.00	2.01	1.84	1.85	1.95	1.95	2.35	2.34
1-4/L::55/45 + 9A	1.94	1.93	1.78	1.74	1.89	1.88	2.24	2.22
1-4/S::55/45 + 5A	2.01	1.99	1.83	1.88	1.93	1.93	2.33	2.32
1-4/S::55/45 + 9A	1.92	1.84	1.76	1.77	1.87	1.86	2.22	2.20
1-4/L::60/40 + 7A	1.94	1.93	1.75	1.80	1.87	1.87	2.28	2.27
1-4/S::60/40 + 7A	1.92	1.91	1.73	1.68	1.85	1.85	2.26	2.25

TABLE 12. AIR PERMEABILITY AND AIR VOIDS

Mix Identification	Synthetic Aggregate No. 1		Synthetic Aggregate No. 2		Synthetic Aggregate No. 3		Synthetic Aggregate No. 4	
	Air Permea-bility	Air Voids	Air Permea-bility	Air Voids	Air Permea-bility	Air Voids	Air Permea-bility	Air Voids
1-4/L::40/60 + 7A	71	13.6	80	5.1	29	3.0	160	6.3
1-4/S::40/60 + 7A	66	13.8	7	9.8	41	10.2	13	7.7
1-4/L::45/55 + 5A	103	21.1	122	12.7	145	8.0	141	12.0
1-4/L::45/55 + 9A	84	9.3	60	3.2	41	2.0	119	1.0
1-4/S::45/55 + 5A	100	21.7	29	16.8	98	14.8	140	13.6
1-4/S::45/55 + 9A	12	9.0	5	6.5	22	3.1	22	3.7
1-4/L::50/50 + 7A	170	11.8	272	6.5	58	3.6		6.4
1-4/S::50/50 + 7A	41	15.1	4	9.3	39	9.1	20	6.4
1-4/L::55/45 + 5A	206	16.9	252	8.6	77	5.8	127	12.1
1-4/L::55/45 + 9A	149	4.7	70	2.9	37	0.0	65	1.0
1-4/S::55/45 + 5A	105	22.8	21	16.0	112	15.0	166	11.7
1-4/S::55/45 + 9A	12	9.8	7	6.2	17	4.8	44	2.9
1-4/L::60/40 + 7A	207	7.4	119	7.2	101	1.1	229	6.0
1-4/S::60/40 + 7A	43	16.0	5	6.5	17	4.9	27	6.9

of porosity possessed by the synthetic aggregates and the increased demand for open graded and friction textured surfaces. Compacted test specimens from the 14 mixes were tested according to the test procedure developed by Ellis and Schmidt.[8] This test procedure reflects the flow or air (ml/sq. in) through the test specimen under a pressure head of 1 inch of water. Figure 11 shows the laboratory equipment used for the air permeability tests. Table 12 shows a summary of air permeability test data and air voids as determined from theoretical maximum density.

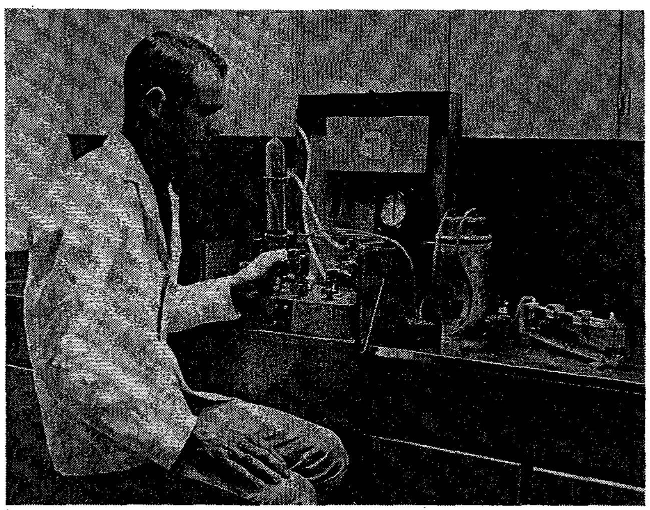


Figure 11. Air permeability test.

Even though the air voids in a bituminous mix furnish an indication of air permeability, there is no well established relationship between these two material properties. The air permeability test actually reflects a measure of the continuity of the air voids within the bituminous mix. Therefore, the flow of air through synthetic aggregate mixes may not be attributed to the bleb structure of the aggregate particles. Since air voids within the aggregate particles are not interconnected, a continuity of air voids must be developed within the structure of the asphalt matrix (asphalt binder and fine aggregate). This premise is supported by the preponderance of air permeability values obtained from mixes containing limestone instead of sand.

Compressive Strength, Strength Index, and Swell Characteristics. The bituminous mixes containing synthetic aggregates were tested to determine the effects of water on cohesion according to ASTM Standards D 1074-60 and ASTM D 1075-54. Table 13 contains a summary of unconfined compressive strengths obtained

TABLE 13. UNCONFINED COMPRESSIVE STRENGTH

Mix Identification	Synthetic Aggregate No. 1 (psi)	Synthetic Aggregate No. 2 (psi)	Synthetic Aggregate No. 3 (psi)	Synthetic Aggregate No. 4 (psi)
1-4/L::40/60 + 7A	401	393	103	373
1-4/S::40/60 + 7A	180	270	629	189
1-4/L::45/55 + 5A	401	388	252	385
1-4/L::45/55 + 9A	492	359	194	350
1-4/S::45/55 + 5A	180	117	425	164
1-4/S::45/55 + 9A	259	152	446	182
1-4/L::50/50 + 7A	470	359	193	342
1-4/S::50/50 + 7A	228	205	423	191
1-4/L::55/45 + 5A	436	431	307	361
1-4/L::55/45 + 9A	457	356	180	416
1-4/S::55/45 + 5A	180	144	459	241
1-4/S::55/45 + 9A	279	166	358	184
1-4/L::60/40 + 7A	429	303	198	331
1-4/S::60/40 + 7A	204	186	492	259

TABLE 14. EFFECTS OF WATER ON COHESION

Mix Identification	Strength Index Aggregate No. 1	Strength Index Aggregate No. 2	Strength Index Aggregate No. 3	Strength Index Aggregate No. 4
1-4/L::40/60 + 7A	88	78	91	78
1-4/S::40/60 + 7A	83	95	98	86
1-4/L::45/55 + 5A	85	62	85	71
1-4/L::45/55 + 9A	95	91	102	101
1-4/S::45/55 + 5A	98	90	89	85
1-4/S::45/55 + 9A	103	104	93	92
1-4/L::50/50 + 7A	90	67	83	78
1-4/S::50/50 + 7A	85	106	96	89
1-4/L::55/45 + 5A	67	62	84	66
1-4/L::55/45 + 9A	95	89	102	89
1-4/S::55/45 + 5A	69	77	93	83
1-4/S::55/45 + 9A	96	92	107	95
1-4/L::60/40 + 7A	77	68	92	63
1-4/S::60/40 + 7A	115	87	102	98

from an average of three test specimens (ASTM D 1074-60). Strength indices reflecting the effects of water on cohesive strengths were determined from the compressive strengths of dry tests and the compressive strengths obtained from samples immersed in 140°F water for 24 hours (ASTM D 1075-54). The effects of water on cohesion are reported in Table 14.

The laboratory test specimens were measured for a determination of swell after a 4-day soaking period. Since the test specimens failed to reflect any significant swelling during the 4-day soaking period, it was concluded that swell pressures were of no concern.

Hveem Stability and Cohesiometer Values. The synthetic aggregate mixes were subjected to a program of laboratory testing for a study of stability and cohesiometer values obtained from these mixes. The test specimens were compacted with the mortorized-shear molding press shown in Figure 12. The laboratory test specimens were prepared in accordance with the Texas Highway Department's[3] test procedure (Tex 208-F). Figure 13 shows the laboratory equipment used for stability testing. The laboratory test data are reported in Table 15. These stability values reflect an average of three test specimens.

After obtaining stabilometer values, the test specimens (same specimens) were heated in an oven for a period of 3½ hours to destroy any stresses induced during the stabilometer test. Cohesiometer tests were then conducted in accordance with the Texas Highway Department's[3] test procedure (Tex 214-F). The cohesiometer values are reported in Table 16. These test data reflect an average of three test specimens.

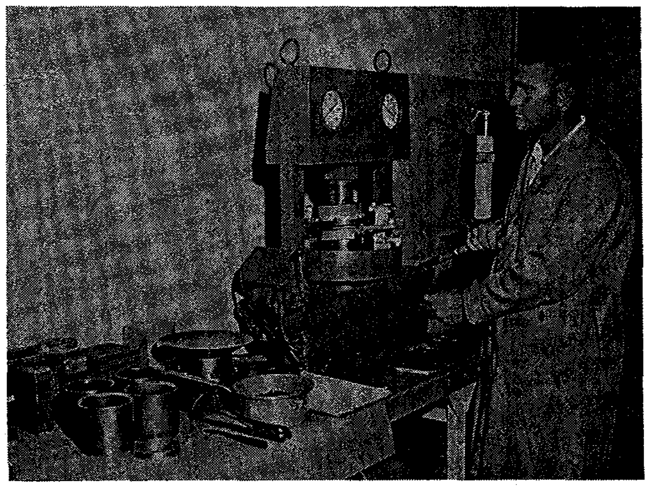


Figure 12. Texas motorized gyratory-shear molding press.

Degradation of Aggregates During Laboratory Compaction. The need for an investigation of aggregate degradation during compaction was recognized in view

TABLE 15. HVEEM STABILOMETER VALUES

Mix Identification	Synthetic Aggregate No. 1	Synthetic Aggregate No. 2	Synthetic Aggregate No. 3	Synthetic Aggregate No. 4
1-4/L::40/60 + 7A	51	52	52	47
1-4/S::40/60 + 7A	31	32	29	33
1-4/L::45/55 + 5A	54	49	57	54
1-4/L::45/55 + 9A	52	39	39	38
1-4/S::45/55 + 5A	36	33	29	32
1-4/S::45/55 + 9A	33	33	28	29
1-4/L::50/50 + 7A	53	51	46	44
1-4/S::50/50 + 7A	35	36	35	33
1-4/L::55/45 + 5A	54	49	55	55
1-4/L::55/45 + 9A	52	37	35	27
1-4/S::55/45 + 5A	49	36	36	39
1-4/S::55/45 + 9A	39	34	32	30
1-4/L::60/40 + 7A	49	45	51	44
1-4/S::60/40 + 7A	49	42	40	38

TABLE 16. COHESIOMETER VALUES

Mix Identification	Synthetic Aggregate No. 1	Synthetic Aggregate No. 2	Synthetic Aggregate No. 3	Synthetic Aggregate No. 4
1-4/L::40/60 + 7A	323	323	502	221
1-4/S::40/60 + 7A	64	123	33	56
1-4/L::45/55 + 5A	157	225	166	225
1-4/L::45/55 + 9A	302	383	366	273
1-4/S::45/55 + 5A	81	35	61	53
1-4/S::45/55 + 9A	106	65	89	133
1-4/L::50/50 + 5A	228	348	310	188
1-4/S::50/50 + 7A	69	75	31	71
1-4/L::55/45 + 5A	106	205	204	260
1-4/L::55/45 + 9A	341	400	361	342
1-4/S::55/45 + 5A	154	41	71	70
1-4/S::55/45 + 9A	175	122	115	193
1-4/L::60/40 + 7A	335	353	502	223
1-4/S::60/40 + 7A	91	95	57	80

of the relatively low crushing strength of synthetic aggregate particles. Such an investigation is complicated by the differences in the specific gravity of the aggregates included in the aggregate blend. The investigation used consists of weight and volume analyses of the grade fractions of aggregate recovered (by extraction test) from the laboratory test specimens.

Theoretical specific gravities were computed for each grade fraction of blended material (grade fractions before compaction). The volumes of the various grade fractions (sieve analysis) of the recovered aggregate were then determined by dividing the weights of the sized material by the appropriate specific gravities. The total volume of the test sample of recovered aggregate was obtained by dividing the dry weight by a weighted average of the specific gravities of the various grade fractions included in the aggregate blend. The total sample volume determined from the use of a weighted specific gravity when compared with the total volume obtained from the sum of various grade fraction volumes furnishes a measure of aggregate degradation. Aggregate degradation is reflected when the recovered aggregate volume (determined by a weighted specific gravity) exceeds the aggregate volume obtained from a summation of the various grade fraction volumes.

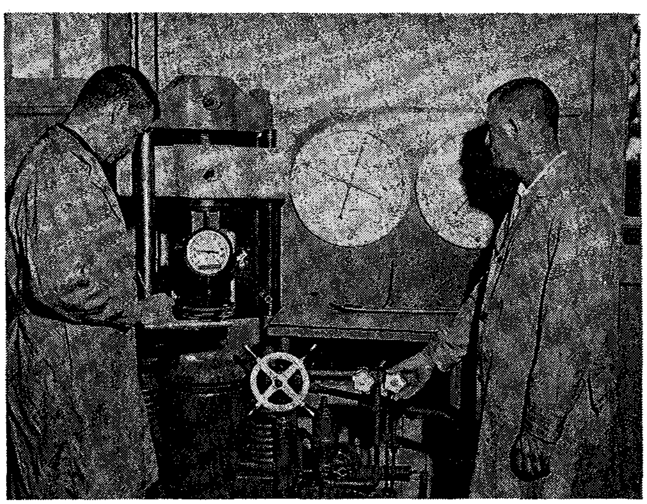


Figure 13. Laboratory equipment for stabilometer test.

An example of the above described investigation of the degradation of a synthetic aggregate blend is included for a further clarification of the procedure. The following tabulation furnishes an example of the basic data and investigative procedure:

TABLE 17. DEGRADATION ANALYSIS OF SYNTHETIC AGGREGATES DURING LABORATORY COMPACTION

Grade Fractions	(1) Grade Fraction Percentages (original)	(2) Specific Gravities	(3) Weight of Extracted Material (grams)	(4) Grade Fraction Volumes (c.c.)
½ - ⅜	13	1.58	48.5	30.7
⅜ - 4	20	1.67	103.9	62.3
4 - 8	7	1.87	48.4	25.9
8 - 16	1	1.72	12.7	7.4
16 - 30	1	2.51	12.2	4.8
30 - 50	8	2.64	85.4	32.3
50 - 100	31	2.64	284.0	107.9
100 - 200	12	2.64	75.2	28.5
200 - Pan	7	2.64	38.6	14.6
	Σ=100%	2.244* *Weighted Average	Σ=708.9 g.	Σ=314.4 cc.

Analysis:

a) Compute a weighted average of the specific gravities of the various grade fractions (2.244).
b) Determine a total of the grade fraction weights of recovered material (708.9 g.).
c) Determine a total of grade fraction volumes (314.4 c.c.).
d) Determine theoretical volume (315.9) by dividing total weight of recovered material (208.9 g.) by the weighted average specific gravity (2.244).
e) Compare the theoretical volume (315.9 c.c.) with the sum of the grade fraction volumes for a measure of degradation.
f) This computation procedure reflects degradation when the sum of the grade fraction volumes (314.4 c.c.) is less than the total theoretical volume (315.9 c.c.).

The above described procedure was applied to the five mixes consisting of synthetic aggregate No. 1 and sand. Three test specimens from each mix were investigated for aggregate degradation. Table 18 contains a summary of the test data reflecting an investigation of aggregate degradation in the five mixes of blends of synthetic aggregate No. 1 and sand.

TABLE 18. A MEASURE OF AGGREGATE DEGRADATION DURING LABORATORY COMPACTION

Mix Identification	Aggregate Volume (Sample Weight ÷ Weighted Sp. G.)	Aggregate Volume (Summary of grade fraction Volumes)	Comments
1/S::40/60	315.9 c.c.	314.3 c.c.	Low Level Degradation
1/S::45/55	314.1 c.c.	320.5 c.c.	No Degradation
1/S::50/50	323.8 c.c.	324.4 c.c.	No Degradation
1/S::55/45	321.7 c.c.	320.9 c.c.	Low Level Degradation
1/S::60/40	329.2 c.c.	325.- c.c.	Low Level Degradation

The above described analysis was not used for an investigation of the remaining three aggregates in view of the time required for the analysis and the low level of degradation revealed by aggregate No. 1. Synthetic aggregates 2 and 3 are not expected to reflect levels of degradation of major concern since the results from the Los Angeles and THD abrasion tests (Table 4) were about the same for aggregates 1 through 3.

Laboratory Abrasion of Bituminous Mixes. Surface abrasion is one of the suspect areas of performance of bituminous mixes containing synthetic aggregates. In response to this area of question, a simplified laboratory test procedure was devised to furnish an index of the wearing or abrasive characteristics of synthetic aggregate mixes. This test consists of rotating or scrubbing the end of a standard 4-inch diameter test specimen on a rubber pad covered with a stream of free flowing water. Supplementary equipment was devised so as to use the Hobart mixer for this test. The supplementary equipment consists of a pan supporting a ¾-inch rubber pad and a cylindrical cup for the rotation of the test specimen on the rubber pad. The operation of this device is similar to that of a conventional lapping machine. The center of the test specimen is rotated through a circular path 3⅓ inches in diameter at a rate of 48 rotations per minute. Figure 14 shows the Hobart mixer as modified for laboratory testing.

The laboratory equipment described above was used to subject one test specimen to 30 hours of abrasion. The test specimen consisted of 60 percent of synthetic aggregate number 2 (by volume), 40 percent Rockdale slag, and 8.5 percent asphalt cement (Texas AC-20). This abrasion test consisted of three ten-hour testing phases. The total weight of the sample was increased for the second and third testing phase (ten-hour testing periods). Metal weights were added to the top of the test specimen to increase the normal force on the friction plane. The weights and normal forces (in psi) used during the three ten-hour intervals are as follows:

Ten hour period	Total sample weight (grams)	Normal Force on Friction plane (psi)
1	1418	0.25
2	2661	0.47
3	3437	0.60

The decrease in the thickness of the test specimen was measured carefully after each ten-hour period of abrasion testing. The thicknesses of bituminous material lost to surface wear during these three levels of abrasion testing are reflected in the data tabulated below:

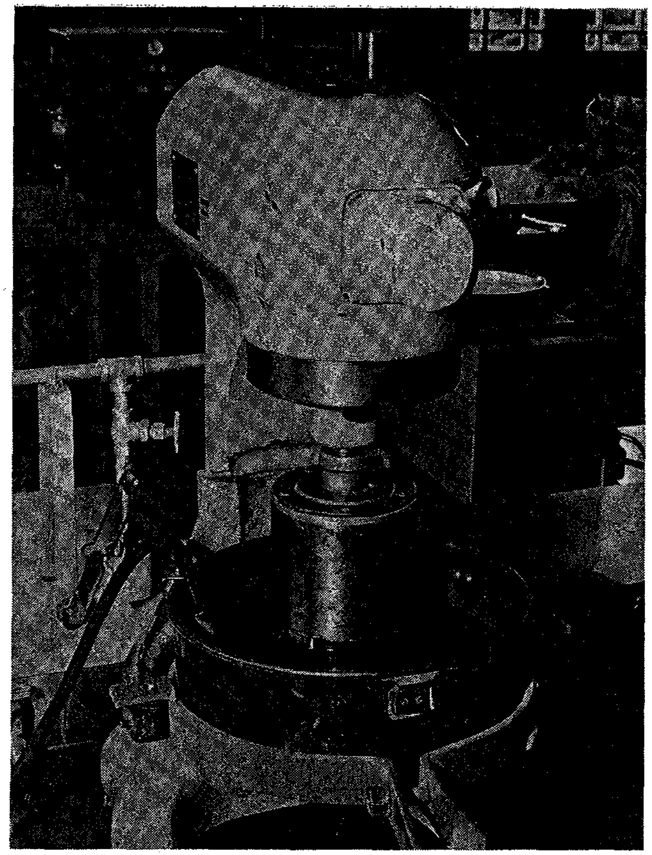


Figure 14. Hobart mixer modified for abrasion testing.

Ten-hour period	Normal Force on Friction Plane (psi)	Surface Wear (in inches)	Total Wear (in inches)
1	0.25	0.002	0.002
2	0.47	0.007	0.009
3	0.60	0.006	0.015

The normal force on the friction plane was multiplied by 10 hours for abrasive action in pounds per square inch per hour. These data were then used for the preparation of an approximate curve of surface wear in inches versus abrasive action in pounds per square

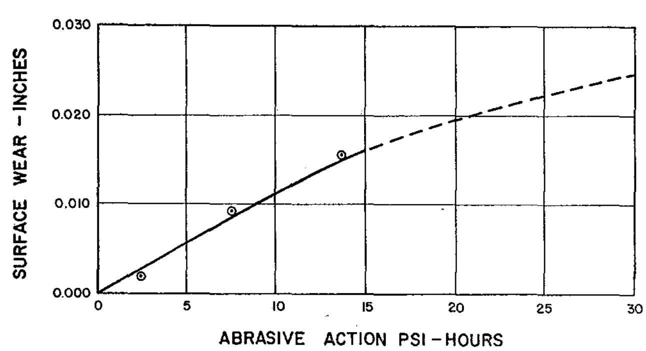


Figure 15. Surface wear of synthetic aggregate mixes.

inch per hour as shown in Figure 15. This curve was then extended for an extrapolation of surface wear after 30 psi hours. From this curve, the estimated surface wear of this mix amounts approximately 0.025 inches of wear due to 30 psi hours of abrasive action. This rate of wear is not considered excessive in view of the surface material that is normally lost due to oxidation, weathering, and stripping.

It is now recognized that a high level of surface wear is desirable to prevent the development of slick surfaces. Aggregates with a low wear coefficient normally develop a low coefficient of friction due to the polished surface texture that develops during service. The bleb structure within the synthetic aggregate particles preclude the development of a polished surface and the associated decrease in the coefficient of friction.

Use of Synthetic Aggregates for the Construction of Bituminous Surfaces

The Texas Highway Department has been seriously considering the use of lightweight aggregates for bituminous pavement construction during the past decade. The use of this material was restricted primarily to seal coat construction during the early stages of field testing. This new type of aggregate demonstrated high quality performance for seal coat construction. In addition to high quality structural performance, the synthetic aggregate yielded a surface texture with superior skid resistant characteristics. Figure 16 shows the surface texture and condition of a lightweight aggregate seal coat constructed during 1962 on U.S. 80 near Abilene, Texas.

The favorable performance obtained from the use of lightweight aggregates for seal coat construction led to the consideration of the use of such aggregates for friction textured hot mixes. The significance of the use of friction textured aggregates for the construction of highway surfaces was further emphasized by the national goals for upgrading the safety of our highway system. This interest led to the location of the three field tests of friction textured hot mixes on primary highways. The surface types and field test locations are described as follows:

(a) A field study of a dense graded mix produced from calcined clay constructed in 1963 near Houston, Texas.

(b) A field study of four dense graded mixes (4 synthetic aggregates and 4 test sections) on I 20 east of Dallas, Texas. Constructed during September of 1966.

(c) A field study of a dense graded mix on I 35 in Austin, Texas. Constructed during August of 1968 as a contract job and consisted of about 20 lane miles.

The above described test sections have demonstrated high quality structural performance during the respective periods of study and observation. In general, the synthetic aggregate pavements yield increases in the coefficient of friction during the initial stages of surface wear. This increase in the coefficient of friction is attributed to the exposure of the bleb structure during surface wear or abrasion. The change takes place during the period of wear required to remove the asphalt film and hardened shell encapsulating the synthetic aggregate particles. After the exposure of the bleb structure by surface wear, the coefficient of friction stabilizes and remains relatively constant during the remaining stages of surface wear.

Figure 16. Surface texture of a synthetic aggregate seal coat after six years of service (U.S. 80—Abilene).

Investigation of Cold Mixes Containing Synthetic Aggregates

The synthetic aggregates under study were also considered for the production of economical and high quality cold mixes. The use of synthetic aggregates in cold mixes hold promise of reducing transportation and handling costs, increasing the stability, and improving the skid resistance. The investigation consisted of a combination of laboratory and field testing of economical blends of the synthetic aggregates and natural aggregates. This plan of study was designed as a preliminary investigation of material properties and performance characteristics of cold mixes containing the three synthetic aggregates under study.

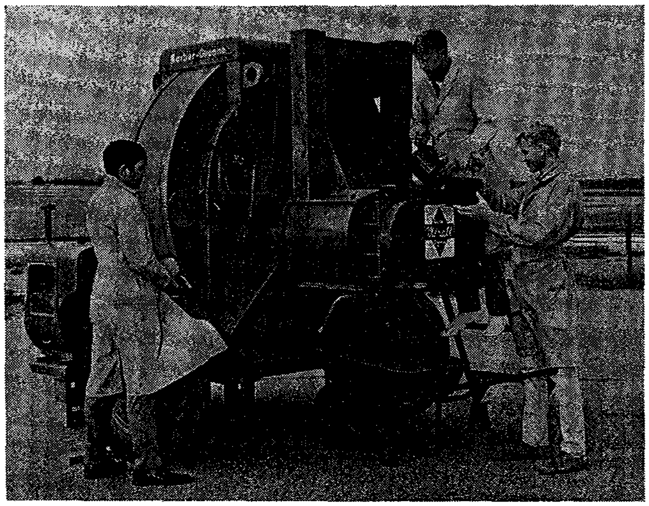


Figure 17. Barber-Greene Mixall used for mixing test batches.

The variables introduced in the investigation of cold mixes consisted of three synthetic aggregates, two sources of natural aggregate, two blend ratios, and three water-primer combinations. The study of these variables necessitated the preparation of 36 designs of cold mixes. Table 19 shows the basic schedule for preparation of a 12 batch series (variables in constituents for one synthetic aggregate). The actual design combinations were not prepared in strict conformance with this schedule due to limited control over the accuracy of the batching operation. The actual batch combinations are reported with the test data.

The gradations of the synthetic aggregates and natural aggregates were the same gradations that were used for hot mix preparation. These data are presented in Tables 1 and 6. Test data describing the properties of asphalt cement and primer are as follows:

a) Asphalt Cement AC-10 - Texaco

Specific gravity @ 77°F	— 1.004
Melting point—ring and ball	— 116°F
Penetration @ 77°F	— 106°F
Ductility @ 77°F	— 200 cm.
Solubility in CCL_4	— 99.92
Flask point (Cleveland open cup)	— 565°F
Olinis spot test	— negative

b) Primer—American Petrofina @ Mt. Pleasant

Pounds per gallon @ 60°F	— 7.86
Specific Gravity @ 60/60°F	— 0.944
Viscosity @ 77°F—furol	— 25 sec
Percent water	— 4
Distillation ASTM D-402	
Residue (% by vol.)	— 41
Float test on Residue @ 122°F	— 88 sec
Spot test	— negative

The principal phases of the investigation of cold mixes containing synthetic aggregates are described by the following work operations:

a) Cold mix preparation.

b) Laboratory testing for workability-stability relations,

c) Field testing of actual performance,

d) Visual inspections of workability and weathering characteristics under field conditions.

The following subsections contain additional information regarding these four phases of the program of investigation.

Cold Mix Preparation. The cold mixes for this investigation were prepared by mixing the batched quantities of aggregates, asphalt, water, and primer in the Barber-Green Mixall as shown in Figure 17. The test batched consisted of approximately two cubic feet of cold mix. The mix constituents were added to the pugmill mixer in the following order: aggregate combination, asphalt, water, and primer. These materials were heated to temperatures within the ranges described below:

Aggregates	235°F ∓ 15°F
Asphalt	235°F ∓ 15°F
Primer	125°F ∓ 10°F
Water	150°F ∓ 10°F

The total mixing time amounted to approximately 1 minute and 45 seconds. This was accomplished by sequence mixing phases as described below:

Constituents	Mixing Time
Aggregate combination	15 sec
Aggregates and asphalt	30 sec
Aggregates, asphalt, and water	30 sec
Aggregates, asphalt, water, and primer	30 sec

TABLE 19. VARIABLES IN COLD MIX CONSTITUENTS

Cold Mixes for Synthetic Aggregates 1 - 3		Synthetic Aggregate Percent by Volume	Limestone Screenings Percent by Volume	Sand Percent by Volume	Asphalt Percent Based On Wt. of Agg.	Primer Percent Based On Wt. of Agg.	Water Percent Based On Wt. of Agg.
1	I	35	65		7	2.5	2.0
2	II	35	65		7	1.9	2.0
3	III	35	65		7	1.3	3.3
4	I	35		65	7	2.5	2.0
5	II	35		65	7	1.9	2.6
6	III	35		65	7	1.3	3.3
7	I	55	45		7	2.5	2.0
8	II	55	45		7	1.9	2.6
9	III	55	45		7	1.3	3.3
10	I	55		45	7	2.5	2.0
11	II	55		45	7	1.9	2.6
12	III	55		45	7	1.3	3.3

Representative samples of the batches of cold mix were placed in plastic containers (1/2 gallon ice cream containers with lids) for laboratory testing. The remaining portions of the batches were marked and exposed to normal weathering conditions as shown in Figure 18.

Laboratory Testing for Workability-Stability Relations. The program of laboratory testing consisted of a visual inspection of workability at 50°F and laboratory tests (unconfined compression tests) for stability at 73°F. A visual inspection and manual probing of each test mix at 50°F provided a relative measure of workability. A relative measure of stability was obtained from an unconfined compression test procedure developed by Hargett.

The unconfined compression test specimens were prepared by compacting the cold mix (heated for 2 hours at 140°F) in a split mold as shown in Figure 19. A sufficient quantity of material was used to produce test specimens with a height-diameter ratio of 2-1 or greater. The compaction consisted of the development of a total load (static) equivalent to 1000 psi during a time interval of approximately three minutes.

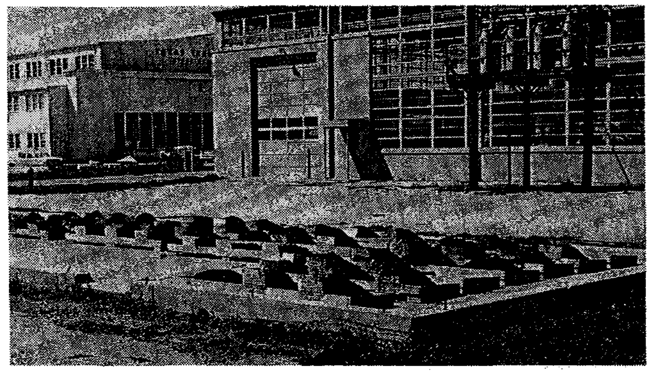


Figure 18. Cold mixes exposed to normal weathering conditions.

The test specimens were subjected to a controlled temperature of 73°F for at least 24 hours prior to testing. Laboratory tests were conducted at room temperature (approximately 73°F) at a slow rate of deformation (0.06 in. per min.). The unconfined compression test data and relative ratings of workability are included in Table 20. These test data reflect workability-stability

TABLE 20. MIX CONSTITUENTS AND WORKABILITY - STABILITY RELATIONS

Mix Constituents and Identification	Workability-Stability at The time of Preparation		Workability-Stability after 6 months of weathering	
	Workability @ 50°F	Unconfined compressive strength-psi @ 73°F	Workability @ 50°F	Unconfined compressive strength-psi @ 73°F
1/L::35/65, 6.7A, 2.0W, 2.6P	acceptable	16	Not available at the time of reporting	
1/L::35/65, 6.9A, 2.6W, 1.9P	acceptable	23	Not available at the time of reporting	
1/L::35/65, 6.9A, 3.3W, 2.6P	acceptable	30	Not available at the time of reporting	
1/S::35/65, 7.5A, 1.6W, 2.0P	good	3	Not available at the time of reporting	
1/S::35/65, 5.9A, 1.6W, 3.1P	good	unstable	Not available at the time of reporting	
1/S::35/65, 6.1A, 2.5W, 2.5P	acceptable	3	Not available at the time of reporting	
1/L::55/45, 7.1A, 2.0W, 2.6P	not workable	21	Not available at the time of reporting	
1/L::55/45, 6.6A, 2.6W, 1.9P	poor	27	Not available at the time of reporting	
1/L::55/45, 6.1A, 3.3W, 1.3P	poor	30	Not available at the time of reporting	
1/S::55/45, 7.0A, 2.0W, 2.6P	acceptable	5	Not available at the time of reporting	
1/S::55/45, 7.0A, 2.6W, 1.9P	acceptable	5	Not available at the time of reporting	
1/S::55/45, 6.9A, 3.3W, 1.3P	not workable	6	Not available at the time of reporting	
2/L::35/65, 7.1A, 2.0W, 2.6P*	good	18	poor	32
2/L::35/65, 7.0A, 2.7W, 1.9P	acceptable	30	used for field test	used for field test
2/L::35/65, 7.0A, 3.3W, 1.3P	acceptable	30	poor	63
2/S::35/65, 7.3A, 2.0W, 2.6P	good	unstable	acceptable	5
2/S::35/65, 7.3A, 2.7W, 1.9P	good	3	acceptable	unstable
2/S::35/65, 7.3A, 3.3W, 1.3P	acceptable	4	poor	10
2/L::55/45, 7.3A, 2.0W, 2.6P	acceptable	11	not workable	33
2/L::55/45, 7.3A, 2.7W, 1.9P	acceptable	17	used for field test	used for field test
2/L::55/45, 7.3A, 3.3W, 1.3P	poor	27	poor	70
2/S::55/45, 7.2A, 2.0W, 2.6P	good	4	not workable	6
2/S::55/45, 7.2A, 2.7W, 1.9P	acceptable	5	poor	unstable
2/S::55/45, 7.2A, 3.3W, 1.3P	acceptable	5	not workable	15
*7.1% asphalt (A), 2.0% water (w), 2.6% primer (P).				
3/L::35/65, 6.8A, 2.0W, 2.6P*	acceptable	17	acceptable	16
3/L::35/65, 7.4A, 2.7W, 1.9P	acceptable	23	used for field test	used for field test
3/L::35/65, 7.4A, 3.3W, 1.3P	acceptable	39	acceptable	76
3/S::35/65, 7.6A, 2.0W, 2.6P	acceptable	unstable	acceptable	unstable
3/S::35/65, 7.6A, 2.7W, 1.9P	acceptable	unstable	acceptable	unstable
3/S::35/65, 7.0A, 3.3W, 1.3P	acceptable	unstable	acceptable	5
3/L::55/45, 7.3A, 2.0W, 2.6P	acceptable	21	acceptable	34
3/L::55/45, 7.3A, 2.7W, 1.9P	acceptable	18	used for field test	used for field test
3/L::55/45, 7.0A, 3.3W, 1.3P	acceptable	31	acceptable	78
3/S::55/45, 7.6A, 2.0W, 2.6P	good	2	good	5
3/S::55/45, 6.8A, 2.7W, 1.9P	acceptable	3	acceptable	8
3/S::55/45, 7.5A, 3.3W, 1.3P	poor	5	poor	16

*6.8% asphalt (A), 2.0% water (W), 2.6% primer (P).

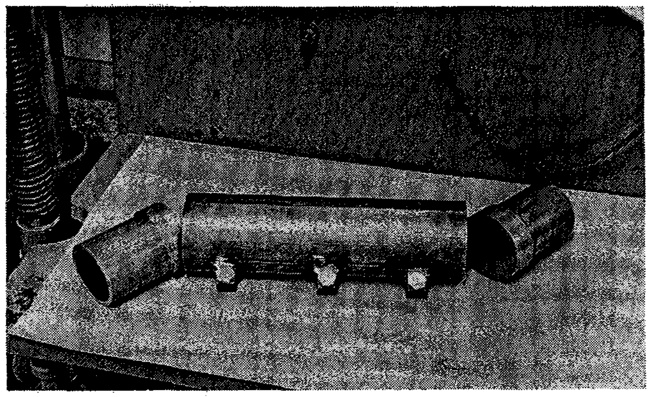


Figure 19. Split mold for static compaction of cold mixes.

Figure 20. Field test plots of cold mix.

relations for all of the different designs (total of 36) at the time of preparation as well as a measure of the workability-stability relations of 24 test batches that had been subjected to approximately six months of weathering (see Figure 18 for weathering conditions). Test data regarding the workability-stability relations of the weathered designs of cold mix containing synthetic aggregate number one are not included in view of the limited weathering period.

These test data reflect an increase in unconfined compression strength of the cold mixes during the six-month weathering period. This increase in strength is attributed to an increase in the cohesive strength of the asphalt resulting from the loss of moisture and volatiles (water and primer). In the meantime the workability of the mix is reduced by the increase in cohesive strength (loss of moisture and volatiles).

TABLE 21. COLD MIXES FOR FIELD TESTING

Test Plot No.	Constituents and Mix Identification	Weathering Period
1	3/L::35/65 + 7A + 2.6W + 1.9P*	3 months
2	3/L::35/65 + 7A + 2.6W + 1.9P	3 months
3	3/L::55/45 + 7A + 2.6W + 1.9P	3 months
4	3/L::55/45 + 7A + 2.6W + 1.9P	3 months
5	2/L::35/65 + 7A + 2.6W + 1.9P	4 months
6	2/L::35/65 + 7A + 2.6W + 1.9P	4 months
7	2/L::55/45 + 7A + 2.6W + 1.9P	4 months
8	2/L::55/45 + 7A + 2.6W + 1.9P	4 months
9	1/L::35/65 + 7A + 1.6W + 2.0P	6 months
10	1/L::35/65 + 7A + 1.6W + 2.0P	6 months
11	1/S::55/45 + 6.8A + 3.1W + 1.7P	13 months
12	1/S::55/45 + 6.8A + 3.1W + 1.7P	13 months
13	1/S::55/45 + 6.8A + 3.1W + 1.7P	13 months
14	Pelletized cold mix—Proj. 6129	5 months
15	Pelletized cold mix—Proj. 6129	5 months
16	Limerock asphalt type C	From Commercial Stock

*7% asphalt (A) + 2.6% water (W) + 1.9% Primer (P). Percentages by total weight of mix.

Field Testing of Actual Performance. Five out of the 36 designs of cold mix were selected for field testing along with three other cold mixes. The selection of the five cold mixes (5 out of 36) was based on workability-stability relations obtained from the program of laboratory testing. The three other cold mixes were included in the field test in view of promising characteristics or established performance. These three mixes are described as follows:

a) A coarse graded mix prepared with sand and aggregate No. 1 that had demonstrated good workability characteristics during 13 months of weathering (exposed to natural weathering conditions).

b) A pelletized mix prepared as a part of research project 6129 (winter maintenance).

c) Type C limerock asphalt mix.

Table 21 shows the test plot numbers, mix constituents (identification), and weathering period prior to placement. All of the mixes demonstrated good workability characteristics at the time of placement.

The field test plots were located on FM2818 west of College Station. The field test plots were located in the outside wheel path where there were no symptoms of base or surface failures. Squares (1-½ ft. squares) were cut out of the old pavement surface with a clipper saw for the cold mix test plots. The holes were tacked with RC-2 asphalt. A ¾" template was placed over the holes for confinement and depth control of the loose cold mix (during placement). The cold mixes were compacted with a small vibratory roller. Figure 20 shows the placement of cold mix in the small test plots and the vibratory roller used for compaction.

At the end of a three-month period of service all of the mixes in the test plots were displaying excellent stability and waterproofing characteristics. The two test plots of pelletized cold mix were showing some evidence of flushing (surface glazing).

Use of Synthetic Aggregates in Open Graded Plant Mix Seals—Field Investigation

This phase of the study was conducted in response to the increasing demand for friction textured overlays that can be used to reduce the threat of hydroplaning. This portion of the study was directed toward a further investigation of construction peculiarities, skid resistance, and field performance of plant mixed seal coats prepared with the three lightweight aggregates under consideration in this study. Primary consideration was given to the design and investigation of an open graded mix with a coarse texture and sufficient interconnected voids to facilitate surface drainage. Figure 21 shows the principal features associated with the friction textured seal coat under consideration.

The aggregate combinations were prepared by blending coarse graded lightweight aggregate with a fine graded aggregate (wet bottom boiler slag). This aggregate blend consisted of 65 percent of lightweight aggregate and 35 percent slag (volume percentages). Preliminary laboratory investigations, pilot tests under parking lot traffic, and the guidelines for plant mixed seals reported by McKenna[9] were used to establish the above described aggregate blend ratios. The blended combinations of the three lightweight aggregates and wet bottom boiler slag yielded gradation curves that were within the gradation band for gap-graded mixes shown in Figure 22. The principal variables introduced in the study were the three lightweight aggregates and variations in asphalt content (approximately 70 penetration). The asphalt content was varied in weight percentage points of 0.5 percent between 7.0 and 8.5 percent.

The field test sections were located on a secondary highway (FM 1687) west of Bryan, Texas. Figure 23 shows a plan view of the test sections. These test sections show type of aggregate and asphalt content included in the open graded mixes. The structure of flexible pavement is described as follows:

Surface—seal coat (approx. ½″)
Base—clayey gravel—6″
Base—iron ore gravel—6″
Sub-base—sand—clay
Subgrade—sandy clay

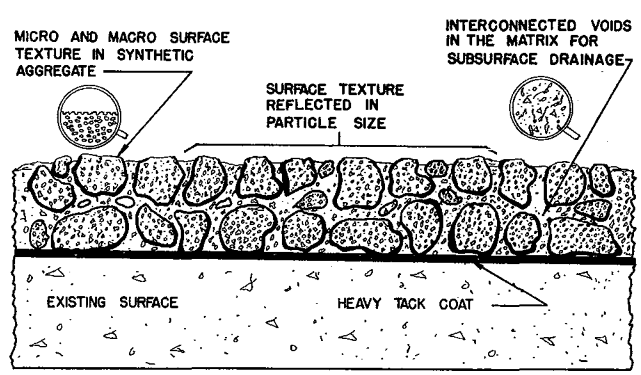


Figure 21. Principal features associated with open graded plant mix seal coats prepared with synthetic aggregate.

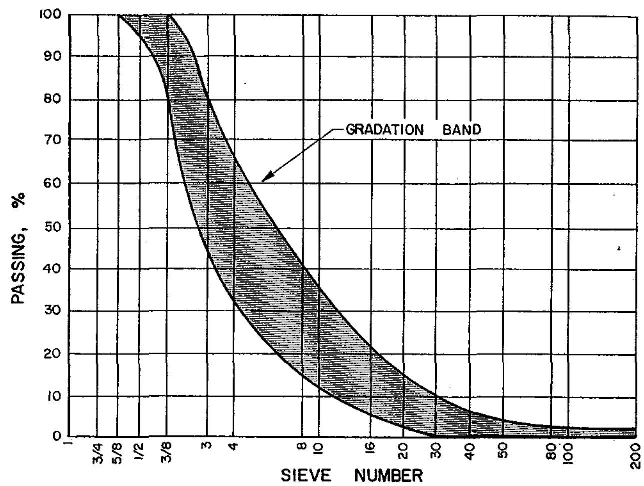


Figure 22. Gradation band for open-graded plant mix seal coats.

The traffic traversing the test sections consists of cable dump trucks and typical farm-to-market traffic. The volume of traffic is estimated to be between 750 and 1000 vehicles per day. Approximately fifty percent of the traffic (ADT) is truck traffic.

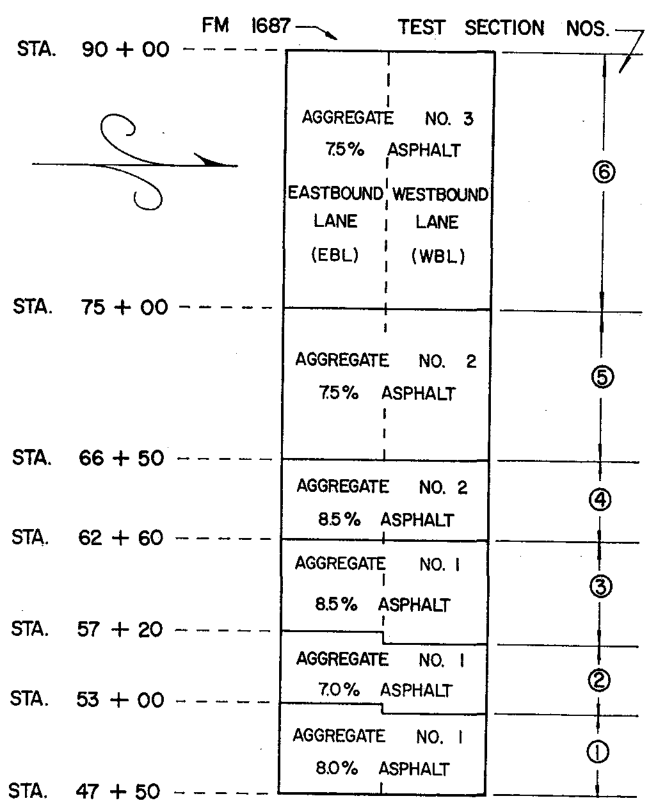


Figure 23. Field test sections of an open graded plant mix seal (FM 1687).

TABLE 22. SPECIFIC GRAVITIES AND PERCENT VOIDS OF FIELD SAMPLES

Test Section	Specific Gravity after 14 days	Percent Voids after 14 days	Specific Gravity after 82 days	Percent Voids after 82 days
1 WBL	1.54	18.7	1.53	19.5
2 WBL	1.53	20.1	1.56	18.7
3 WBL	1.25	20.6	1.28	18.7
4 WBL	1.36	22.1	1.41	19.4
5 WBL	1.35	23.6	1.38	21.4
6 WBL	1.44	18.9	1.49	17.1
6 EBL	1.53	20.1	1.54	19.7
5 EBL	1.27	21.4	1.27	20.7
4 EBL	1.31	17.4	1.31	17.1
3 EBL	1.32	23.0	1.34	22.1
2 EBL	1.45	22.7	1.50	20.2
1 EBL	1.45	20.5	1.49	17.8

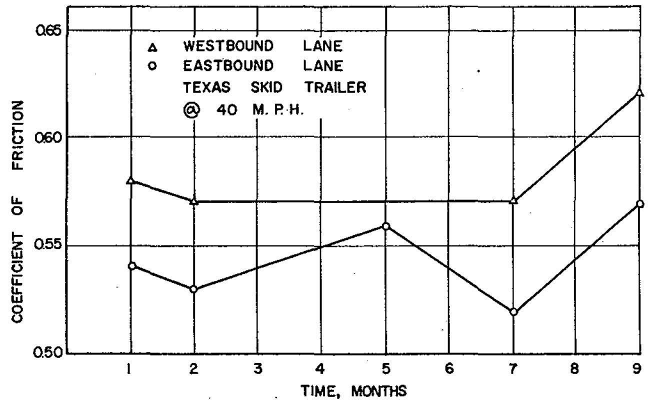


Figure 24. Skid resistance of open graded mixes.

The open graded plant mix seals were prepared in a hot mix plant and placed with a conventional paver. The plant operation was directed toward the production of a hot mix with a temperature of approximately 300°F. However, due to lack of continuity in the operation, the actual batch temperature varied between 275°F and 350°F. The plant operation reflected no peculiar problems resulting from the use of the lightweight aggregates blended with a fine aggregate having a normal or high unit weight. The plant operation did emphasize the need for a better understanding of weight-volume relations of mix constituents having different specific gravities. For plant regulation purposes it is convenient to have a grading plot based on weight percentages of known blends of the aggregates being used. The plant operator with the aid of the field laboratory personnel may then make the necessary adjustments to meet the grading requirements of specifications by running regular weight based sieve analyses on hot bin aggregates. Spot checks on the volumes of materials entering the cold feed will also serve to assure that essentially correct quantities of materials are entering the mix. The problem of overlapping sizes of aggregates of different specific gravities then becomes a minor one.

The surface of the existing pavement was tacked with a rapid set high viscosity emulsified asphalt at the rate of about 0.12 gallons per square yard prior to the placement of the plant mixed seal coat. A conventional paver was used for field placement of "laydown" of the seal coat. The compacted thickness of the seal coat was approximately 5/8 of an inch. The initial rolling was accomplished with a tandem roller (approximately 8.4 tons); whereas, a pneumatic roller (15-ton, 50 psi, tire pressure) was used for the second rolling. Field density tests were conducted after 14 and 82 days for a determination of the specific gravities and percent voids. The specific gravities and percent voids are reported in Table 22.

There were no peculiar construction problems encountered during the placement of the open-graded plant mixed seal coats. The cost of the construction of the test sections amounted to $0.39 per square yard. This unit cost does not reflect the cost of the lightweight aggregates which were furnished for freight costs by the respective producers. If the lightweight aggregate were assumed to cost eight dollars per ton fob point of production and it is further assumed that this coat is added to the unit price listed above, the average cost of the surface would be $0.50 per square yard or about double the cost of a seal coat. However, one should not be misled in considering the over-all relative economies of these two approaches. The plant mixed seal would quite likely be less expensive due to an expected longer life. Machine laid hot mixes offer other well known advantages.

The field evaluation procedure consisted primarily of visual inspections of structural performance and field measurements of skid resistance and density changes. During the period of observation the test sections have demonstrated good structural performance with the exception of the eastbound lane in test Section No. 2. This test section reflected some surface break-up which was attributed primarily to weak subgrade support caused by poor drainage in the side ditch (water standing in the side ditch). The coefficients of skid resistance were measured with the British portable tester and the Texas skid trailer.

The average coefficients measured by the British portable tester and the Texas skid trailer are reported in Tables 23 and 24. Figure 24 shows a graphical representation of skid resistance as measured with the skid trailer during the nine-month study period.

TABLE 23. COEFFICIENTS MEASURED WITH THE BRITISH PORTABLE TESTER

Test Sections	Coefficient @ 1 month	Coefficient @ 3 months	Coefficient @ 6 months	Coefficient @ 7 months
1 WBL	0.42	0.53	0.62	0.65
2 WBL	0.41	0.55	0.61	0.62
3 WBL	0.38	0.51	0.60	0.61
4 WBL	0.33	0.50	0.56	0.59
5 WBL	0.43	0.53	0.64	0.60
6 WBL	0.28	0.50	0.59	0.55
Average	0.38	0.52	0.60	0.60
6 EBL	0.42	0.51	0.60	0.55
5 EBL	0.44	0.57	0.63	0.57
4 EBL	0.45	0.54	0.59	0.54
3 EBL	0.45	0.57	0.66	0.50
2 EBL	0.44	0.59	0.64	0.53
1 EBL	0.46	0.59	0.62	0.56
Average	0.44	0.56	0.62	0.54

TABLE 24. COEFFICIENTS MEASURED WITH THE TEXAS SKID TRAILER (40 mph)

Test Sections	Coefficient @ 1 month	Coefficient @ 2 months	Coefficient @ 5 months	Coefficient @ 7 months	Coefficient @ 9 months*
1 WBL	0.58	0.61	0.58	0.58	0.51
2 WBL	0.60	0.62	0.61	0.59	0.63
3 WBL	0.56	0.54	0.58	0.56	0.63
4 WBL	0.57	0.55	0.55	0.57	0.60
5 WBL	0.59	0.56	0.59	0.57	0.67
6 WBL	0.55	0.55	0.53	0.54	0.70
Average	0.58	0.57	0.57	0.57	0.62
6 EBL	0.51	0.51	0.53	0.44	0.45
5 EBL	0.56	0.54	0.54	0.48	0.54
4 EBL	0.52	0.49	0.53	0.53	0.58
3 EBL	0.54	0.52	0.58	0.54	0.62
2 EBL	0.57	0.55	0.58	0.54	0.64
1 EBL	0.56	0.54	0.57	0.57	0.60
Average	0.54	0.53	0.56	0.52	0.57

*Measured with skid trailer from Tyler.

The Texas Highway Department has four two-wheel skid trailers. One of these is considered research equipment while the other three are stationed across the state for routine evaluation of pavement surfaces. With the exception of the data in column five of Table 24, measurements on the subject test sections were made with the research trailer. This trailer is designed for locking either or both of its wheels and also incorporates a feature that makes possible an adjustment in the amount of water that may be applied to the pavement surface.

It may also be noted in Table 24 that at age 7 months sections 5EBL and 6EBL show a definite decrease in friction values. Contamination from a clay gravel side road is considered the cause. This is also evident in section 6EBL at age 9 months.

Early in the life of these test sections a series of tests were performed using the research trailer with variables of speeds and amount of water on the pavement. These data are shown in Table 25. It is evident that there is only minor decay in the friction values with increase in speed and amounts of water. Apparently drainage at the time of the tests was adequate. Later tests are planned. Such tests will be made after a summer of traffic. It is anticipated that the voids which ranged from about 12 to about 23 percent will have decreased measurably.

The scope of the study also included an investigation of the coefficients under a surface condition normally associated with a high intensity rain storm. A water truck was used for prewetting the surface and for the application of water prior to the skid tests. The water discharged from the water truck and the water discharged from the skid trailer (large water orifice) provided a surface coating of water that represented severe weather conditions. The test data obtained from this phase of the field investigation are reported in Table 25. These test data show the effectiveness of the open graded seal coat for preventing a significant decrease in the coefficient of friction with increases in speed (hydroplaning).

TABLE 25. EFFECTS OF SPEED AND HEAVY COATINGS OF WATER ON COEFFICIENT OF FRICTION

Test Section	With large water orifice and speed of 20 MPH	With large water orifice and speed of 40 MPH	With large water orifice and speed of 60 MPH	Pre watered surface with large water orifice and speed of 60 MPH
1 WBL	0.66	0.61	0.53	0.53
2 WBL	0.60	0.62	0.57	0.56
3 WBL	0.63	0.54	0.51	0.52
4 WBL	0.63	0.55	0.59	0.60
5 WBL	0.68	0.56	0.56	0.55
6 WBL	0.62	0.50	0.53	0.49
6 EBL	0.59	0.51	0.49	0.50
5 EBL	0.68	0.54	0.49	0.51
4 EBL	0.64	0.49	0.43	0.50
3 EBL	0.66	0.52	0.49	0.52
2 EBL	0.63	0.55	0.50	0.55
1 EBL	0.63	0.54	0.49	0.52

APPENDIX A

Volumetric Blending to Satisfy Gradation Specifications

The blending procedure described herein was prepared for the blending of aggregates having different specific gravities. In brief, the procedure consists of a paper analysis of the grade fractions resulting from a trial or assumed paper blend of the aggregates under consideration. The trial blend ratios reflect units of volume. The procedure for blending lightweight aggregates with natural aggregates is outlined as follows:

1. Examine the grade fractions reflected in the available aggregate sources. Materials or material combinations that reflect the desired grade fractions are selected for trial blending analyses.
2. Tabulate gradation data for the aggregates selected on an analysis sheet (analysis sheet must reflect percentages passing a specified sieve size and retained on the next smaller sieve size).
3. Select trial blend ratios after making a careful study of gradation specifications and the grade fractions available in the materials selected for blending. (Computations are simplified by the use of a total of 10 blend parts.)
4. Multiply the grade fraction percentages by the blend ratios selected.
5. Total the grade fraction percentages in each column and divide by the total number of blend parts.
6. Compare the gradation of the blended aggregate combination with specifications.
7. Repeat Steps 3, 4, and 5 until a material combination is obtained to meet specifications. Materials reflecting other grade fractions may be included if necessary.

An example of volumetric blending by trial and error is included for a further explanation of this procedure.

Problem: Determine the blend ratios to satisfy the Asphalt Institute's specifications for a Type IVa mix. Volume measurements are required for an accurate analysis of the specified grade fractions, whereas weight measurements are required for accurate batching procedures.

Given:

(a) Gradation specifications (limits for the Asphalt Institute's Type IVa mix).

(b) Grade fractions for one synthetic aggregate and two natural aggregates.

(c) Specific gravities for the three aggregates are as follows:

Aggregate A (lightweight)
Specific Gravity = 1.05

Aggregate B (limestone chips)
Specific Gravity = 2.71

Aggregate C (field sand)
Specific Gravity = 2.63

The following two tabular sheets show an example of trial analyses and the aggregate blending in order to satisfy gradation specifications. The procedure outlined above was used for the solution of the problem (Steps 2 through 6).

TABULAR SHEET FOR AGGREGATE BLENDING

SPECIFICATIONS AND MATERIALS	BLEND PARTS	GRADE FRACTIONS 1/2"*–3/8"	3/8"–4	4–8	8–30	30–50	50–100	100–200	200–PAN		
ASPHALT INSTITUTE TYPE IVa MIX		20–0	25	20–25	17–21	5–6	5–7	4–6	4–10	TOTAL	
SYNTHETIC AGGREGATE MATERIAL – A		10	40	40	7	3	–	–	–	100	
LIMESTONE CHIPS MATERIAL – B		10	15	15	50	5	5	–	–	100	
FIELD SAND MATERIAL – C		–	–	–	–	15	25	35	25	100	
TRIAL NO. 1	TRY 3 PARTS OF A, 1 PART OF B, AND 1 PART OF C										
A	3	30	120	120	21	9	–	–	–	300	
B	1	10	15	15	50	5	5	–	–	100	
C	1	–	–	–	–	15	25	35	25	100	
TOTALS	5	40	135	135	71	29	30	35	25	500	
DIVIDE BY 5	1	8	27	27	14	6	6	7	5	100	
NOTE THE DIFFERENCES BETWEEN ABOVE PERCENTAGES AND SPECIFIED PERCENTAGES											

*PERCENT PASSING 1/2" AND RETAINED ON 3/8."

TABULAR SHEET FOR AGGREGATE BLENDING

SPECIFICATIONS AND MATERIALS	BLEND PARTS	GRADE FRACTIONS 1/2"–3/8"	3/8"–4	4–8	8–30	30–50	50–100	100–200	200–PAN		
TRIAL NO. 2	TRY 3 PARTS OF A, 2 PARTS OF B, AND 1 PART OF C										
A	3	30	120	120	21	9	–	–	–	300	
B	2	20	30	30	100	10	10	–	–	200	
C	1	–	–	–	–	15	25	35	25	100	
TOTALS	6	50	150	150	121	34	35	35	25	600	
DIVIDE BY 6	1	8	25	25	20	6	6	6	4	100	
NOTE THE ABOVE PERCENTAGES SATISFY ASPHALT INSTITUTE SPECIFICATIONS FOR A TYPE IVa MIX.											

The theoretical blending of 3 parts of lightweight aggregate with 2 parts of limestone chips and 1 part of field sand satisfied the gradation specifications for a Type IVa mix. The blend ratios for volume blending are as follows:

A—Lightweight Aggregate	50%
B—Limestone Chips	33%
C—Field Sand	17%

Since the aggregates for bituminous mixes are frequently batched by weight, the ratios for weight blending are determined as follows:

A—Lightweight Aggregate	.50 x 62.4 x 1.05 =	32.8 lbs.
B—Limestone Chips	.33 x 62.4 x 2.71 =	55.6 lbs.
C—Field Sand	.17 x 62.4 x 2.63 =	27.9 lbs.
	TOTAL	116.3 lbs.

A—Lightweight Aggregate	32.8 ÷ 116.3 = 28%
B—Limestone Chips	55.6 ÷ 116.3 = 48%
C—Field Sand	27.9 ÷ 116.3 = 24%

Typical sieve analyses of actual blends of lightweight aggregates and natural aggregates are not suitable for field tests and control of the specified grade fractions. Typical gradation analyses are distorted by the weight measurements of the grade fractions of materials having different specific gravities. A volumetric analysis of the various grade fractions may be used for an approximate control test.

Asphalt Content. The blending of lightweight aggregates with natural aggregates will reflect a significant reduction in the total weight of the aggregate combination. Therefore, the established guidelines for asphalt (asphalt content based on weight of aggregate combination) are distorted by the use of lightweight aggregates. In view of this distorted relationship, asphalt content for mixes containing lightweight aggregates should be based on aggregate volume instead of aggregate weight. When lightweight aggregates are used, the relationship of the volume of voids to the total volume of mix is recognized as the only consistent index of the needs for asphalt binder.

SUMMARY

This program of laboratory and field testing provides a documentary of the material properties and performance characteristics of synthetic aggregates used for bituminous mixes. The findings resulting from this program of investigation furnish the construction industry with basic design criteria and a reliable base for professional practice. The significant findings are briefly summarized as follows:

1. The durability and material properties of synthetic aggregates may be utilized for the production of high quality bituminous mix.
2. The use of lightweight aggregates in open graded (free draining) mix designs offers an excellent approach to the solution of the "slick when wet" problem in areas of high annual rainfall.
3. The bituminous mixes containing lightweight aggregates yield a high level of internal friction and stability.
4. The high coefficient of friction and the non-polishing characteristics possessed by the lightweight aggregate offers a reliable solution to the problem of providing a dependable level of skid resistant highway system.
5. The low unit weight of hot mix and hot mixed cold lay mixes prepared with lightweight aggregates offers definite promise for significant savings on freight and transportation costs. Construction equipment maintenance costs will also be reduced.
6. The physical properties of lightweight aggregates offer definite promise for the incorporation of varying amounts of water and volatiles (primer) needed to produce cold mixes with levels of workability that are commensurate with the current needs for winter maintenance operations.
7. The high level of stability and the high coefficient of friction possessed by asphaltic concrete mixes containing lightweight aggregates provides the highway construction industry with the basic requisites for friction textured overlays in maintenance operations.

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