INTERIM REPORT ON THE LABORATORY CONSIDERATIONS FOR THE USE OF SYNTHETIC AGGREGATES FOR HOT-MIX ASPHALT PAVEMENTS

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TABLE OF CONTENTS

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

LIST OF TABLES

LIST OF FIGURES

FIGURES

INTRODUCTION

Since the introduction of lightweight synthetic aggregate as coverstone for seal coats and surface treatments on Texas highways in 1961, aggregate producers, contractors, highway personnel and even the driving public have watched the performance of this material with a critical eye. Service records for the past five years are now available and these records show conclusively that synthetic aggregate of the proper quality produces a high performance coverstone provided proper procedures are observed in the design and construction of such surfaces.

Records are available on some 2000 miles of primary and secondary Texas highways with traffic volumes from 100 to 8000 vehicles per day to show that this material is serving the driving public safely and economically.

It seems reasonable to expect that this same type of material would serve equally well in hot-mix asphalt paving materials; therefore, the exploratory research reported in this paper was undertaken to verify this hypothesis.

The basic physical characteristics of synthetic aggregates that have a definite influence on the use of these materials in asphaltic concrete are: asphalt affinity, abrasion or wear characteristics, and aggregate durability as determined by freezing and thawing or sodium sulfate soundness. Data on these properties are given in papers by Gallaway and Harper[1*] and by Ledbetter.[2]

The research approach for verification of this hypothesis was a complete factoral design including the necessary basic research, laboratory evaluations and field service trials. The subject study, however, covers only a limited segment of the overall research plan and is therefore incomplete and the conclusions are tentative. It is, nevertheless, clearly evident that synthetic aggregate has a definite potential as a major portion of the aggregate system in flexible pavement structures.

All of the synthetic aggregate used in this study can be classified as Class I Group A, or Class I Group B, according to the proposed Synthetic Aggregate Classification System.[3]

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*Superscript numbers refer to the Reference List.

SUMMARY

1. A literature search revealed only limited material published on the use of synthetic aggregate in plant mixed asphalt pavements. Data from eight different trial sections indicate that such materials produce paving mixtures of acceptable quality.

2. Class I synthetic aggregates from seven sources were used with two different field sands, gradings of which are shown in Table II, to produce laboratory designs that were tested by several methods to determine their suitability for hot-mix asphalt pavements.

3. Limited laboratory studies of the following parameters were included for specific mixtures of synthetic aggregate, field sand and paving grade asphalt cement.

a) Laboratory compaction degradation.

b) Hveem stability and cohesion.

c) Asphalt demand.

d) Water susceptibility.

e) Swell characteristics and expansion pressure.

f) Air permeability.

4. Compaction degradation was measured on one material for a 100 percent synthetic aggregate design by examining the change in the particle size distribution after laboratory compaction at three energy levels and four asphalt contents. An analysis was also made on synthetic aggregate from all sources for designs containing field sand. Asphalt content was varied and change in the surface area of the aggregate in each design was measured.

5. Hveem stability and cohesiometer measurements were made on designs involving synthetic aggregate from all sources. Asphalt content was varied from 6.0 to 10.0 percent for all designs.

6. The study included laboratory measurements of asphalt absorption as determined by examining typical mix designs and by complete immersion of the synthetic aggregate in hot asphalt cement. Comparisons of asphalt and

water absorption were made. Data on total asphalt demand are included.

7. Water susceptibility of selected hot-mix designs was determined by the Immersion-Compression Test (ASTM 1074-75).

8. Swell characteristics of typical laboratory designs were measured by the Texas Highway Department Method (Test Method Tex-209-F). Expansion pressure was measured after the method of the California Department of Highways.

9. Air permeability was measured on designs made from aggregates of the different sources. A range of asphalt contents and air voids was included.

SUMMARY OF RESULTS

The following summarized results and conclusions are tentative since they are based on incomplete laboratory data and limited field trials.

1. Research findings reveal that economical hot-mix designs can be produced by blending synthetic coarse aggregate (1/2-inch to No. 10) with locally available fine aggregates such as crusher fines and field sand, or both. Where field sand alone is used as the fine material, the coarser gradings produce more economical mixes.

Designs meeting the specification requirements of the Texas Highway Department's Item 340, Hot-mix Asphaltic Concrete Pavement, Class A Type D, were easily obtained with the materials under study. Proof of service performance for the various producers products has not been obtained.

2. Laboratory compaction degradation was found to be a minor problem even for designs containing 100 percent synthetic aggregate. The Texas gyratory shear compactor was used in the study; so, it is not known what results would be obtained with, say, the Marshall impact hammer or the California kneading compactor. A high Hveem stability is a common characteristic of designs containing aggregate with a rough surface texture and it is probably for this reason that the hot-mix designs that were investigated produced stabilities in the range of 40 to 50. Large changes in asphalt content had little effect on measured stabilities. This characteristic has economic potential.

3. Asphalt absorption of the synthetic aggregate under study was essentially constant at 2 to 3 percent for the various producers' products when the available asphalt was limited; however, when an unlimited supply of hot asphalt cement was made available to the different materials under study, considerable difference was noted in the absorption capacity. Depending on particle size distribution and source of material, the absorption varied from 2.0 to 15.4 percent by weight. Under plant and field construction conditions, asphalt absorption of the synthetic aggregate fraction would normally be in the range of 2 to 3 percent by weight. Microscopic examinations indicate this absorption to be non-selective. Design asphalt contents of 7 to 10 percent by weight of mix are common. Corrected to a volume or film thickness basis, these compare favorably with THD Class A type D hot-mix dense aggregate designs in use today.

4. Hot-mix designs examined for water susceptibility included field sands so the results obtained are not clear, and the method used to make the evaluations is not absolute. However, at reasonable asphalt contents most of the designs were acceptable from the viewpoint of water susceptibility.

5. The synthetic aggregates included in this study exhibited negligible expansion pressure and the swell as measured by Test Method Tex-209-F was in the range of 0.004 inch or less, compared to an allowable of 0.03 inch. It is therefore apparent that the qualities measured by these tests are quite high.

6. Air permeability measurements were made on a single design using aggregates from all seven sources. As has been found in the past, a general decrease in air permeability is associated with an increase in asphalt content; however a coefficient of determination of 0.43 was obtained when air permeability was related to air voids in the compacted laboratory specimens. Results in the field are likely to be even more variable. Permeability to water instead of air should be measured.

OBJECTIVES AND PLAN OF RESEARCH

(Phase II)

Objectives

The second phase of this research (2-14-63-51) which is reported herein was to determine and relate the basic physical characteristics of synthetic (lightweight) aggregates to their uses in hot-mix, hot-laid asphalt pavement surfaces. The secondary objectives were an outgrowth of the primary study of lightweight aggregates as coverstone for seals and surface treatments.

The objective of the second phase of the study was to determine the physical characteristics of synthetic aggregates that affect their use as aggregate in plant mixed asphaltic concrete for thin overlays and anti-skid pavements. With this objective in mind, and in view of the basic physical characteristics of the aggregate, it is anticipated that guide lines for the design and specification of asphaltic concrete utilizing these aggregates can be produced.

Plan of Research

The basic plan of the research was to examine mixtures containing lightweight aggregate in consideration of the following:

1. Laboratory compaction degradation.
2. Hveem stability and cohesion.
3. Asphalt demand by film thickness.
4. Water susceptibility.
5. Swell characteristics and expansion pressure.
6. Permeability to air.

A very limited study of these items was conducted in the laboratory in an effort to examine certain design parameters. To date, there has been no correlation of these data to the field performance of asphaltic concrete mixtures made from synthetic aggregate blends.

BACKGROUND INFORMATION

In 1955, the State of Louisiana placed a field test section of asphalt pavement made from lightweight aggregate hot-mix. This experimental section of roadway was two hundred feet in length and four traffic lanes wide. The compacted layer was approximately two inches in thickness.[4] The lightweight aggregate used in that study was an expanded clay from the same source as one of the materials studied in this investigation.

The Louisiana study incorporated the lightweight aggregate as the material coarser than a No. 40 sieve. The mixture design (Marshall method) included fine river sand for the aggregate passing the No. 40 sieve, and the asphalt content was twelve percent by weight on an 85-100 penetration grade asphalt.[4] The road was in good condition at the time of reporting (1959), with a daily traffic volume of 7300 vehicles.

Also in 1955, the Southern Lightweight Aggregate Corporation became interested in the potential use of lightweight aggregate for asphaltic concrete surfaces. This work reported by Wycott,[5] included a design by the Hubbard-Field method and strength testing by the American Society for Testing and Materials (ASTM) methods D1074-58 and D1075-54. The aggregate used in that study was 100 percent lightweight aggregate, and the grading was the same as that for concrete masonry units (ASTM C331-53T). The bitumen contents ranged from nine to twelve percent by weight for the laboratory test. In 1957, a field trial of the optimum laboratory design was made in the City of Richmond, Virginia. This test section, like the Louisiana trial, was 200 feet in length and four traffic lanes wide. The gradation of the lightweight aggregate in the field trial was changed slightly from the laboratory design and the asphalt content was 11.2 percent by weight. The pavement, which had an average daily traffic of 12,700 vehicles, was in excellent condition two years later.[5]

The State of Texas, which has been a leader in the use of lightweight aggregates for seal coats and surface treatments,[1] has also placed some experimental pavement surfaces utilizing synthetic aggregates.

The first experimental section of synthetic aggregate to be placed in Texas was constructed on SH-6 in Fort Bend County during August, 1963. The aggregate blend was approximately 68 percent calcined clay and 32 percent field sand. The asphalt content was 6.2 percent by weight of the mixture. The laboratory compacted specimens made from samples of loose mix secured from the field had an average Hveem stability of 41 percent and 3.4 percent air voids.[6]

Since 1963, several districts (12, 14, 15, and 18) of the Texas Highway Department have made laboratory and field trials using synthetic aggregates in hot-mix asphaltic concrete surfaces and bases, but detailed reports have not been published on these trials. The most recent of these field trials was one placed on IH-20 near Mesquite, Texas. The test section was placed on the inside lane of the Dallas-bound roadway. The average daily traffic in 1965 was approximately 33,000 vehicles. Two different sources of lightweight aggregate were used in this experimental section, and both of these materials were evaluated to a limited extent in the current research study. The mixture designs were made using the Texas Highway Department modification of the Hveem method. The laboratory designs yielded stabilities in the order of 45 to 50 percent and cohesiometer values of 100 to 150 grams per inch of width. The air voids of the laboratory specimens were approximately two to five percent.[7] The field test included two designs for each aggregate, however, both designs used 50 percent by weight lightweight aggregate and 50 percent sand. The basic difference in each design was the type of sand used. The asphalt content in all four sections was 6.5 to 7.0 percent by weight of mixture.

These pavements have been in service about six months at the time of this writing, and they are performing very satisfactorily. The Texas Highway Department measured the skid properties or coefficient of friction of these surfaces after about three months of service. The coefficient of friction of the lightweight sections averaged about 0.48 at 50 miles per hour, while the coefficient of the adjacent lane which was placed at the same time utilizing normal aggregates was 0.36.[8]

MATERIALS

Lightweight Synthetic Aggregate

The aggregates for this study were secured from the six producers of lightweight aggregate in Texas and one producer in Louisiana. These include both expanded clay and expanded shale products and fall into Class I of the proposed THD Classification System for synthetic aggregates. The materials from all of the potentially available suppliers were used in this study because each supplier uses different raw material and different methods of burning and crushing, or both. Hence, these aggregates represent the entire range of such materials currently produced in Texas.

The major interest of each of these producers is the production of aggregate suitable for use in the concrete block industry; therefore, the materials supplied did not conform to the grading requirements of Texas Highway Department Specifications (1962) for asphaltic concrete. The producer should, however, have no problem altering his procedures to meet grading requirements.

The aggregates used in this study were the same as those in Phase I of the study. These aggregates generally were Type F, Grade 3 or 4, conforming to Texas Highway Department Special Specification, Item 1269, Aggregates for Surface Treatments (Lightweight). See Appendix B. Typical physical properties for these aggregates are shown in Table I.

Table I

Physical Properties of Synthetic Aggregate

Aggregate	Raw Material	Vacuum Sat. Density 3/8"—#4, g/cc	Dry Loose Unit Wt.* lb/ft^3	Los Angeles Abrasion[10] (C Grading), % Loss	
				ASTM	THD Item 1269
A	shale	1.84	45.7	23.8	17.8
B	shale	1.42	40.6	25.0	15.3
C	clay	1.35	41.3	24.4	13.9
D	shale	1.68	48.9	22.0	14.8
E	clay	1.62	38.6	34.9	40.7
F	clay	2.01	43.7	28.6	20.0
G	shale	1.77	45.5**	25.4	21.2

*THD Item 1269, Grade 4.
**THD Item 1296, Grade 3.

Since these aggregates are generally produced for concrete block and seal coat work, it was necessary to screen and grade them to meet the mixture design requirements.

The lightweight aggregate was used as the coarse fraction (plus No. 10 sieve) of the asphaltic concrete surface course to provide better skid resistant properties in the pavement. Lightweight aggregates used in this manner do not "polish" or become slick because of the aggregates wear, a textured surface will remain. Also, the low unit weight property of the material was used to maximum advantage, thus effecting greater economy in the design.

Field Sands

Since asphaltic concrete mixtures containing lightweight aggregate utilize the lightweight material as the coarse fraction, the fine fraction should consist of some locally available filler material. This filler would normally consist of field sand, crusher screenings, shell, or possible lightweight fines; however, the use of a lightweight fine fraction would increase the asphalt demand. This increase in asphalt content would arise from the increased volume for a given unit of weight for the lightweight fines. In addition, the lightweight fine aggregate is more absorptive than most stone screenings.

For the purpose of this study, field sand was chosen because of its economy and wide availability. The field sand is normally expected to provide the particle sizes smaller than the No. 8 sieve. In some instances, as was the case in this study, a blend of a coarse and fine sand may be necessary to obtain an improved particle size distribution. The sieve analysis data for the field sands used in this study are shown in Table II. These sands, typical of many sands found in Texas, will be designated FS 1 and FS 2 for the purpose of this report.

Asphalt

The asphalt used as a binder for this study was an 85-100 penetration grade with a history of an intermediate susceptibility to hardening. This asphalt would be classified, viscosity-wise, between an AC-10 and an AC-20, according to the present Texas Highway Department Specifications. The pertinent information for this material is shown in Table III.

This asphalt was used throughout the study so that the type and grade of binder would be constant. This particular material was chosen as it is representative of the asphalts commonly used for surface coarses of asphaltic concrete in Texas.

Table II

Gradation of Field Sands

U. S. Sieve No.	Percent Passing	
	FS 1	FS 2
16	100.0	100.0
30	99.4	100.0
50	67.8	98.7
100	17.4	75.9
200	8.4	28.5

Table III

Asphalt Cement Characteristics

Viscosity	
@ 25°C (77°F) and Sr + 5 x 10^{-2} sec^{-1}, megapoise	1.02
@ 60°C (140°F), poise	1760.
2 135°C (275°F), poise	2.74
Penetration, 100g, 5 sec, 25°C (77°F)	91.
Specific Gravity, 25°C/25°C (77°F/77°F)	1.014
Ductility, 5cm/min, 25°C (77°F)	150+

DESIGN DATA

Gradation

Hot-mix asphaltic concrete paving has become one of the most popular paving materials in the highway construction industry. The importance of the proper design of such paving mixtures cannot be over-emphasized. There are many design methods for determining the optimum usage of materials; however, the three most widely used are the (1) Marshall, (2) Hubbard-Field, and (3) Hveem methods. The selection and use of any mixture design method is principally a matter of engineering preference.

The Marshall method is applicable to hot-mix asphaltic paving mixtures using asphalt cement and containing aggregates of one inch maximum size. The Marshall molding and testing procedures can also be used for field control on hot-mix jobs. Since the equipment required for the test is simple and inexpensive, it has been widely adopted. On the other hand, the Hubbard-Field method is more suited to laboratory designs. This method was primarily used for the design of sheet asphaltic mixtures (100 percent passing No. 4 sieve), but later modifications allow it to be used for coarser mixtures.

The Hveem method is the same as that currently used by the California Division of Highways, and it is also an approved ASTM standard. This method is applicable to paving mixtures using asphalt cements and liquid asphalt. The method is used by many agencies for both laboratory design and field control. The Texas Highway Department uses a modification of the Hveem procedure for its design and control work. The Texas modifications are essentially in the area of predicting an optimum asphalt content and in molding of the test specimens. The Texas procedure involves the use of a gyratory shear type molding press for forming both the laboratory and quality control specimens.

One of the primary considerations in the design of an asphaltic concrete mixture is the gradation requirements. The aggregate blend may vary from a dense combination of materials to a gap or skip gradation. The Texas Highway Department specifications for asphaltic concrete lend themselves to the latter type of grading. This also proves to be advantageous in the design of mixtures utilizing lightweight aggregate because the lightweight material is generally used as the coarse fraction (plus No. 10 sieve) and is shipped to the job site; whereas, the fine fraction may be a locally available field sand which would introduce a gap in the gradation. The use of gap graded blends containing lightweight aggregate is generally satisfactory since the stability of these blends will nearly always meet specified requirements and will probably be workable in the field.

Another major factor in blending or combining lightweight aggregates is that of unit weight. Normally, lightweight aggregate will have a dry loose unit weight in the range of 35 to 55 pcf; whereas, the sand or normal weight aggregate will have a dry loose unit weight of 90 to 100 pcf. This difference in unit weight or specific gravity can result in serious difficulty if it is not considered when making the aggregate combination. This fact is illustrated in Figure 1. In order to achieve a more accurate picture, it is necessary to combine the materials on a volume basis and convert the resultant combination to weight measurements for field batching purposes. Weight measurements are more accurate and are easily controlled in both the laboratory and the field.

A number of aggregate blends were considered before a selection was finally made. Some of these combinations are shown in Figure 2. Combination No. 2 is a dense graded blend containing approximately 70 percent lightweight aggregate by volume. This particular blend was strongly considered, but it was not used in the study because it was felt that the asphalt demand would be excessive since approximately 20 percent by volume of the lightweight fraction was between the No. 10 and the No. 30 sieve. Also a grading of this type utilizing the lightweight fines might not be as economical as blends containing local materials. Combination No. 4 and Combination No. 6 were then considered as being the logical choices from an economical point of view. Combination No. 4 containing 50 percent lightweight coarse aggregate (by volume) would be the most adaptable for field uses because of improved workability; however, Combination No. 6, containing 70 percent (by volume) lightweight aggregate was chosen for this study. This particular blend was selected as it represented the maximum probable amount of lightweight material that could be incorporated in a bituminous mixture. It was considered that this maximum lightweight aggregate blend would describe the most unfavorable conditions if the synthetic aggregate were not suitable for asphaltic concrete. Again, it is recognized that this particular combination would probably have poor workability in the field.

Laboratory Compaction Degradation

One of the more important problems of the study was that concerned with laboratory compaction-degradation. Hence, such a study was undertaken. For this study, a dense-graded combination containing 100 percent lightweight aggregate was selected. This selection was made for two reasons. First, an all-lightweight design would be most susceptible to particle breakdown and second, any added fine material such as field sand would cloud any analyses made with sieves. To determine the degrading effect by some other method would be more expensive. The original grading curve for this combination is shown in Figure 3.

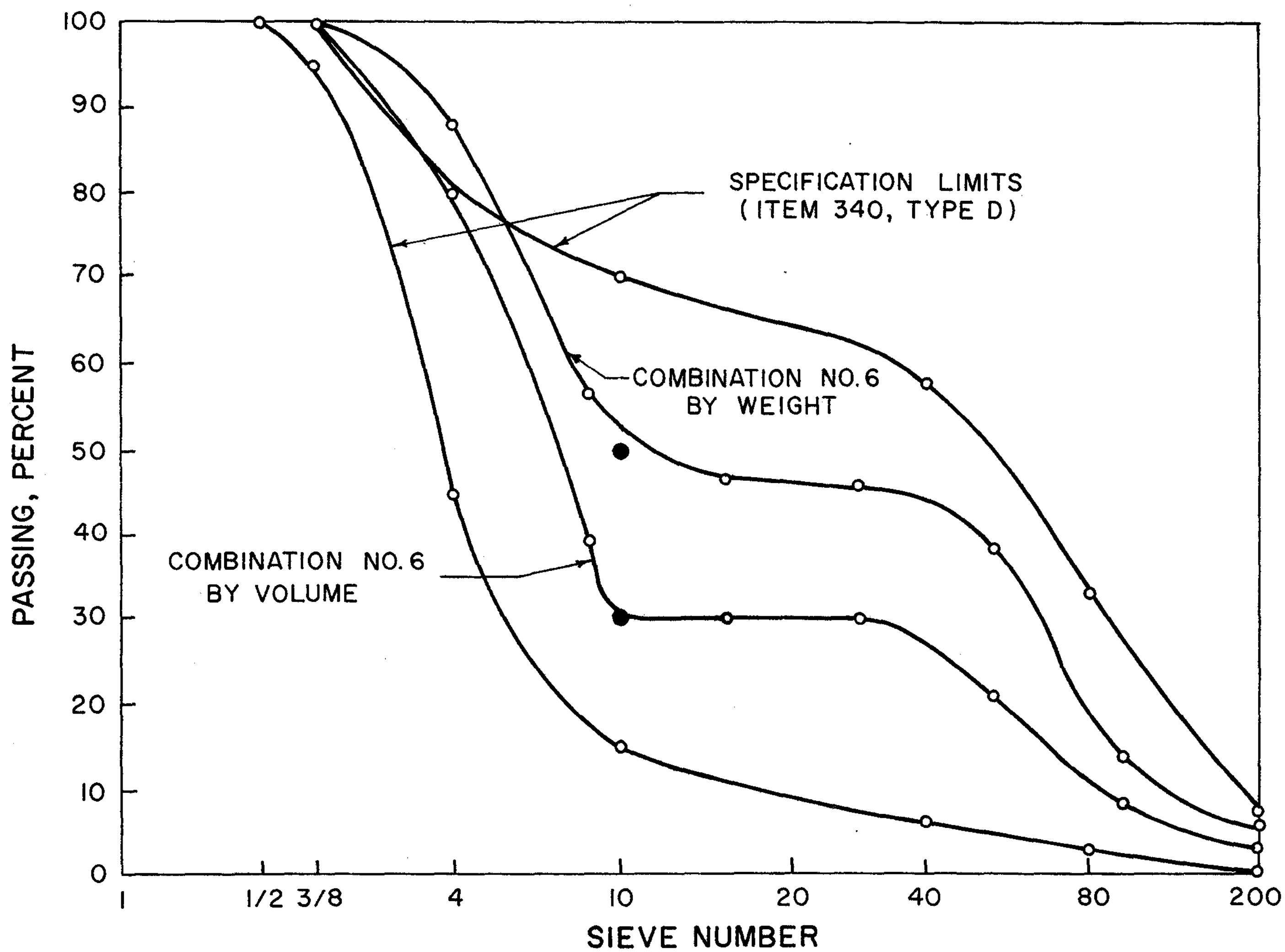

FIGURE I. AGGREGATE BLENDS BY WEIGHT AND VOLUME METHODS

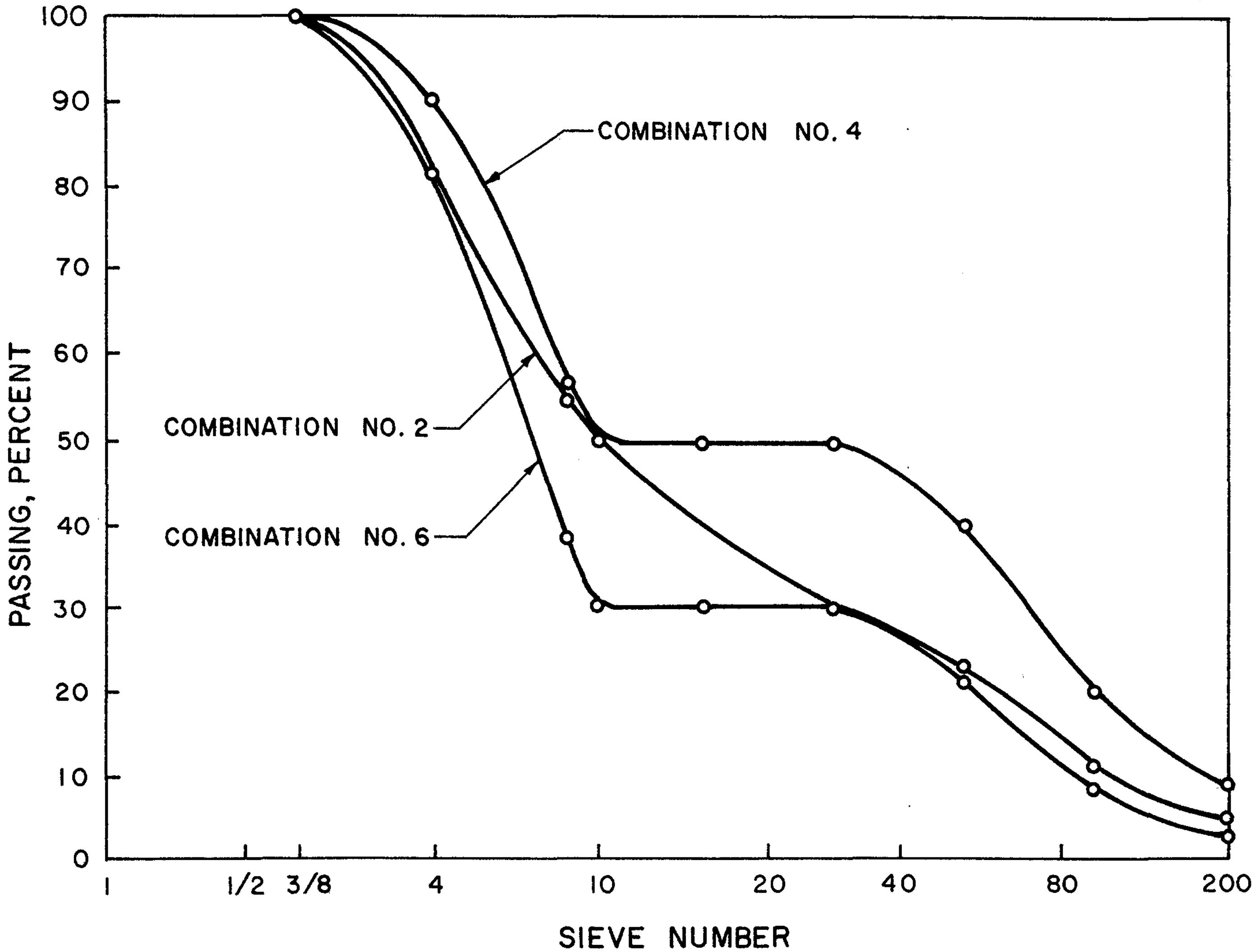

FIGURE 2. GRADATION CHART FOR VARIOUS AGGREGATE BLENDS (VOLUME COMBINATIONS)

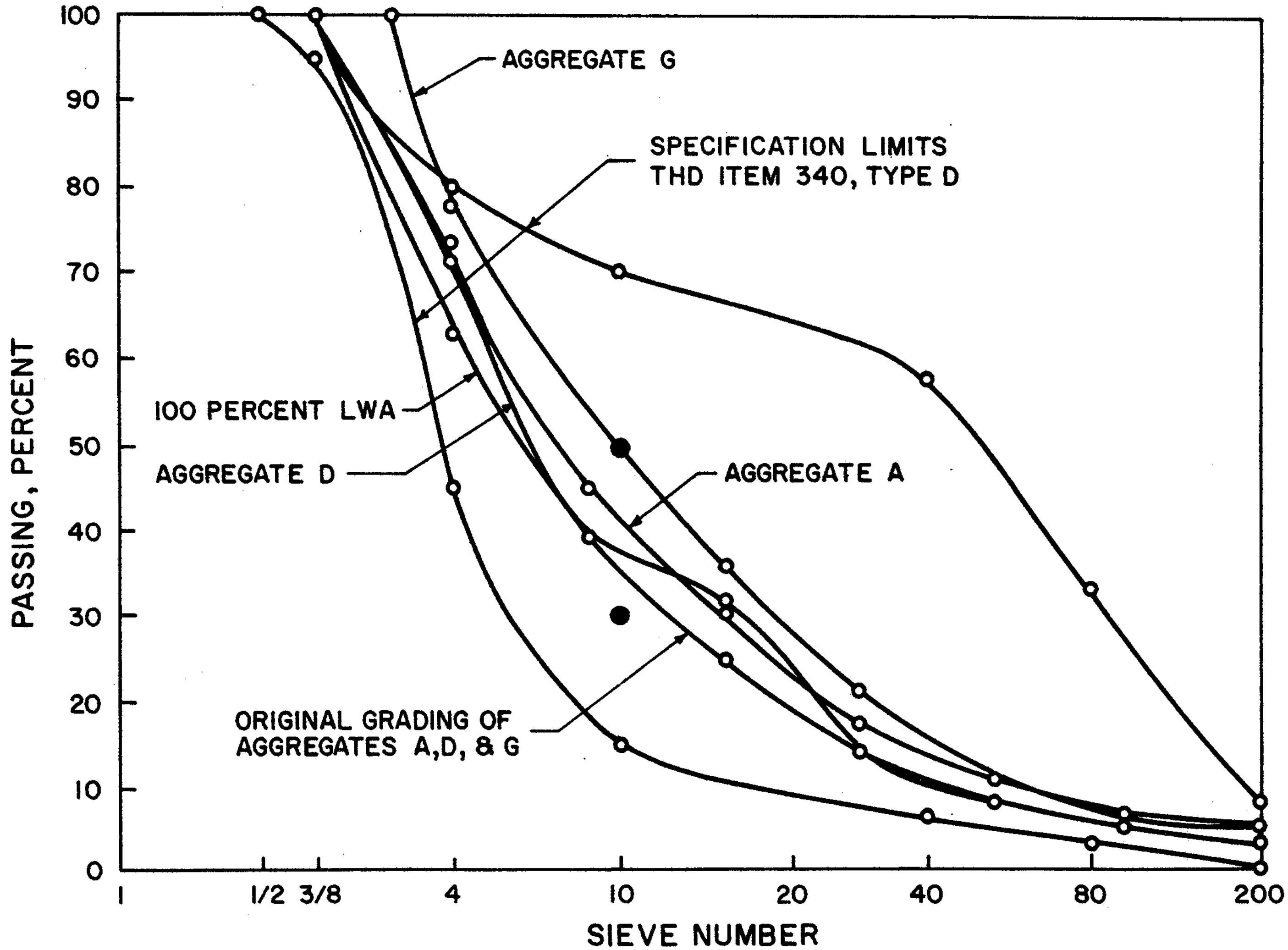

FIGURE 3. ORIGINAL AND RECOVERED AGGREGATE FROM A DEGRADATION STUDY OF 100 PERCENT LWA MIXTURES

The mixtures were prepared at three asphalt contents with the estimated optimum value being that determined by the California Centrifuge Kerosene Equivalent Method.[9] Design details are given in Table IV. These mixtures were prepared by the Texas Gyratory Shear method in accordance with standard procedure.[10] Various laboratory tests outlined in the Plan of Research were performed on the test specimens and the asphalt was extracted from the aggregate by reflux extraction (AASHO T184 60). A sieve analysis was made on the recovered aggregate to determine the change in particle size distribution. The surface area[9] was also computed and these data are tabulated in Appendix A. Typical data are presented in Figure 3.

Table IV

Typical Mixture Design Data

for Laboratory Compaction Degradation

(100 percent Lightweight Aggregate A)

Asphalt Content	Density g/cc	Voids %	Stability %	Cohesion g/in. Width
8.0	1.50	10.7	46	61
9.0	1.51	9.3	47	94
10.0	1.54	6.3	48	132

There was no pattern of behavior or relation between the effects of asphalt content and the change in surface area tabulated. Data for these aggregates are shown in Table V.

The differences in the original and final surface areas as listed below do not reflect which original particles received the most damage during compaction. For example, in Figure 3, aggregate G has a smaller change in surface area, but the particles between the 3/8 inch and 1/4 inch sieves have disappeared. The possible relationship between the Los Angeles Abrasion Test and the change in surface area was examined and no positive correlation was found to exist.

Table V

Effect of Asphalt Content on

Change in Surface Area

Aggregate Source	Asphalt Content % by Weight	Change in Surface Area % of Original
A	8.0	33.1
	9.0	34.6
	10.0	42.8
B	5.0	24.4
	6.0	4.5
	7.0	4.0
C	8.0	15.2
	9.0	28.9
	10.0	25.1

In addition to the above study, sieve analyses were also made on the recovered aggregate from hot-mix designs containing lightweight aggregate and field sand. This determination was made fully aware of the errors that exist due to differences in the unit weight of particles on a given sieve; however, it was felt that these data could still have some value. Since the aggregate blend used in this study (Combination No. 6) was a volume combination, it was converted to a weight basis for a better comparison with the data on the recovered aggregate. Typical results are shown graphically in Figure 4. This figure includes the original gradation of Combination No. 6 computed on both a volume and a weight basis and the gradation of the aggregates recovered from hot-mix designs made from field sand and aggregates E and D. Aggregate E had the most laboratory degradation, while the best aggregate, D, showed no appreciable breakdown in this respect. Figure 5 is a bar chart showing aggregate B broken down into the percent retained between individual sieves. It appears from this chart that the course aggregate is breaking into smaller pieces with only minor changes taking place in the finer material.

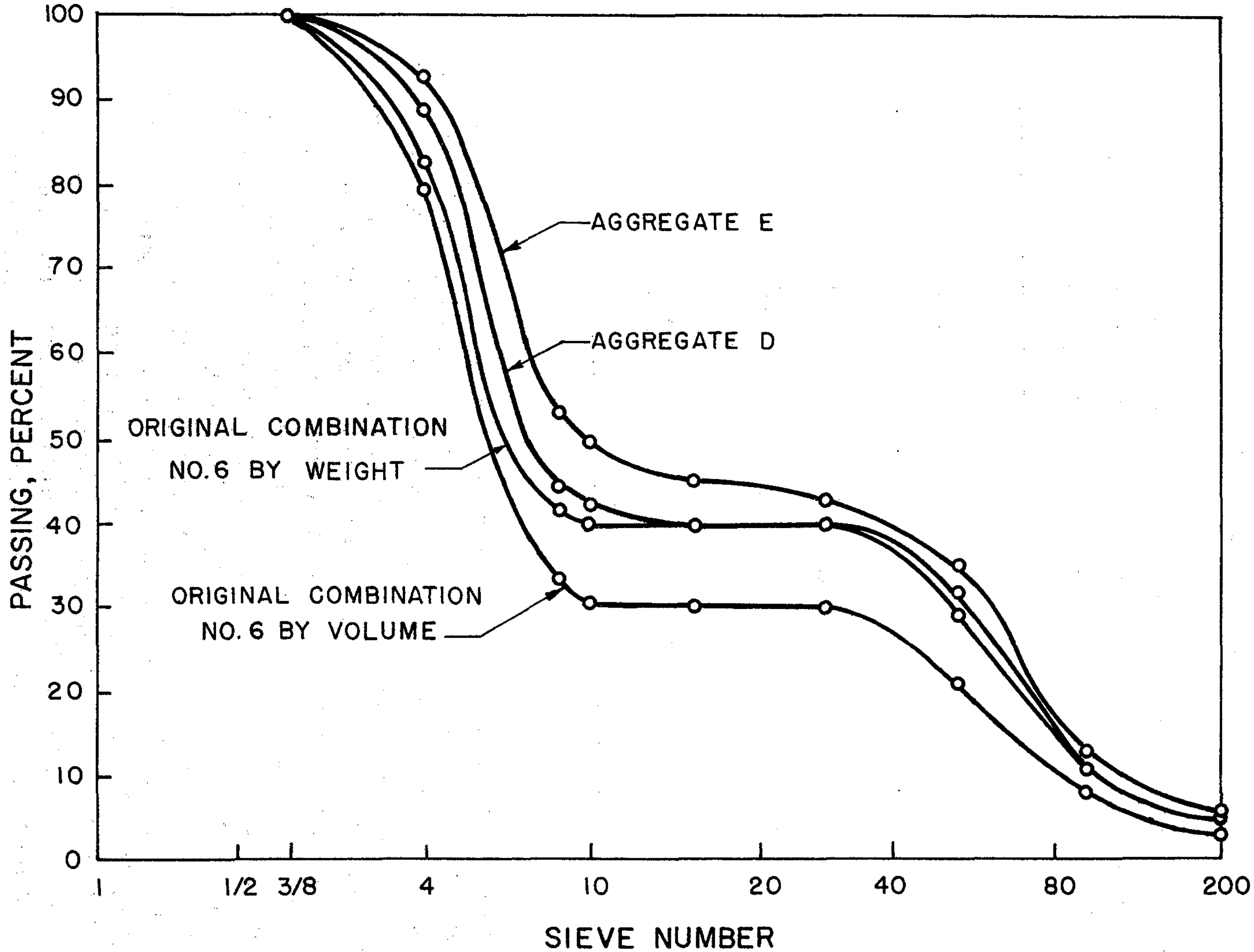

FIGURE 4. ORIGINAL AND RECOVERED AGGREGATE FROM A DEGRADATION STUDY OF LWA AND FIELD SAND MIXTURE.

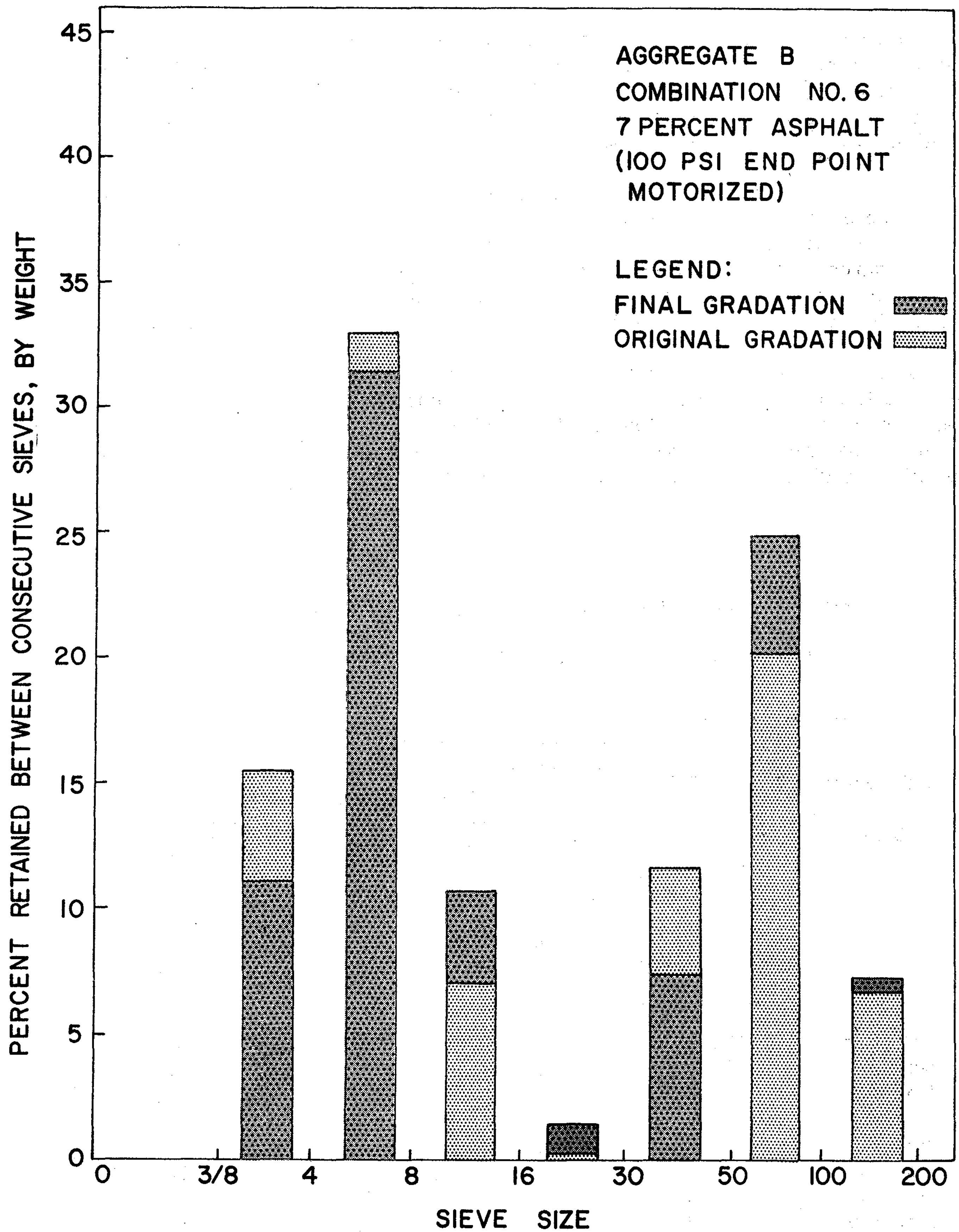

FIGURE 5. AGGREGATE DEGRADATION FOR INDIVIDUAL SIEVES

The coarse material retained on the No. 4 sieve was reduced approximately six percent by weight and the total weight on the Nos. 8, 16, and 30 sieve sizes increased by about the same amount. This indicates the lightweight is degrading. Further examination of the material retained on the No. 50 sieve reveals the field sand may also be degrading.

Another interesting facet to the laboratory degradation problem was that there may have been differences in degradation characteristics due to different compactive efforts; so, a series of laboratory compaction tests was conducted using aggregate A. These tests were made using the Texas Highway Department manual molding press and the Texas Highway Department motorized press at two energy levels. The results in the form of a sieve analysis is shown in Table VI.

These limited data indicate that there is no significant difference in degradation due to compaction in the manual press and the motorized press, or between the various energy levels of the different presses for aggregate A. It cannot, however, be assumed that this resistance to degradation would prevail for other synthetic aggregates produced in Texas.

Table VI

Effect of Compactive Effort on Compaction Degradation

(Aggregate A, Combination No. 6, 6.5% Asphalt)

U. S. Sieve Size	Aggregate Gradation Percent Passing (by Weight)			
	Before Compaction	After Compaction		
		THD Manual Press	THD Motorized Press	
		100 psi End Point	50 psi End Point	150 psi End Point
3/8 inch	100.0	100.0	100.0	100.0
No. 4	83.6	83.7	83.3	82.8
No. 8	43.9	50.4	50.2	48.9
No. 16	36.3	37.8	37.3	37.4
No. 30	36.1	36.7	36.0	36.1
No. 50	26.5	30.1	30.1	29.4
No. 100	9.9	10.6	10.5	10.5
No. 200	4.2	4.2	4.6	4.2

Strength Measurements

Texas, as well as other states, uses a modification of the California design procedure for establishing compliance to hot-mix specifications. The current Texas specifications[11] generally require certain density and stability values and in some cases, cohesiometer values. The aggregates are also required to meet certain grading limits, these requirements for Texas Highway Department Item 340, Type D, have been shown in Figure 1.

Stability

The Texas Highway Department modified Hveem stability requirements for most surface course designs is a minimum of 30 percent, and surfaces designed in the normal manner using lightweight aggregate as the coarse fraction will easily meet this minimum requirement. In fact, stabilities of 40 to 50 percent are common. The stability of asphaltic surface mixtures containing lightweight aggregate as the coarse fraction is generally not very susceptible to change in asphalt content, say in the range of one or two percentage points. This is particularly advantageous because larger amounts of asphalt cement may be incorporated into the mixture for expected greater durability. Job control is not as critical for mixtures containing lightweight aggregate as it is for some mixtures because small variations in asphalt content will not produce unstable mixes; whereas, a variation of 0.2 percent asphalt in a slick pea gravel-sand mixture may lead to drastic changes in stability. Some typical data for stability are presented in Table VII. In general, the stability will increase with increasing asphalt to an optimum amount and then decrease. This is the expected and normal behavior for non-lightweight mixtures. However, for the variations in asphalt content indicated above, the stability is nearly constant, i.e., within the repeatability of the test. The data for all of the mixtures are tabulated in Appendix A.

Cohesion

The cohesion of mixtures containing lightweight as the coarse fraction generally increases with increasing asphalt content; however, the cohesion is highly influenced, and this is commonly known, by the type, grade and amount of asphalt cement used. The Texas Highway Department currently requires a cohesiometer value of 100 grams per inch of width when specification Item 346 is used, but this item is not the one in general use. Typical cohesiometer values are shown in Table VII and in Appendix A.

Density

The specimen density and air voids for these mixtures are generally within the ranges specified by the Texas Highway Department. The specimen density increases with increasing asphalt content, e.g., to the point of flushing or zero voids. In this sense, lightweight aggregate mixtures behave as ordinary "dense rock" mixtures. When the air voids in the lightweight aggregate mixtures are computed in the manner described in the Texas Highway Construction Bulletin C-14,[12] they may exceed the allowable specified values. It is planned that this problem will be studied by the Texas Transportation Institute in a proposed new program, and it may be that new design criteria are in order. The specimen density and air voids are the most repeatable characteristics thus far encountered in the design of mixtures containing lightweight aggregate as the coarse fraction.

Table VII

Typical Strength and Density Measurements

Aggregate Source	Asphalt Content	Laboratory Density	Specimen Voids*	Stability	Cohesiometer Value
	% by Wt.	g/cc	%	%	g/in. Width
B	6	1.372	8.3	44	104
	7	1.376	6.3	42	88
	8	1.383	6.1	42	76
	9	1.405	4.4	43	106
D	6	1.681	6.1	42	67
	7	1.696	5.6	40	86
	8	1.717	5.2	40	87
	9	1.741	1.7	37	233

*Based on Rice's Method for Maximum Specific Gravity.[13]

It will be noted from Table VII, that the relative density and air voids computations are based upon the specific gravity of the loose mixture after Rice[13] instead of the formula considerations of the Texas Highway Department Bulletin C-14. The reason for using different procedures than those now employed by the Texas Highway Department is that the vacuum-saturation procedure takes into account the absorption characteristics of the aggregates; whereas, the formula method does not. Hence, due to the absorptive nature of the lightweight aggregate, it was felt that the vacuum-saturation method of determining the maximum specific gravity of the loose mixture would give superior results. The relative density and air voids computed in this manner will produce values lower than those by methods currently specified by the Texas Highway Department, but the relative density will never exceed 100 percent. The methods currently used by the Texas Highway Department which do not account for asphalt absorption by the aggregate, may lead to unrealistic values of 103 to 104 percent relative density.[14] Differences for highly absorptive materials such as synthetic aggregate may be expected to be even greater.

Asphalt Demand

The asphalt demand for lightweight aggregate hot-mixed asphalt paving mixtures may be predicted by film thickness and surface area methods together with a knowledge of the aggregate absorption requirements.

Film Thickness and Surface Area

It has been previously shown that the effective asphalt film thickness for hot-mixed asphalt pavements in Texas is in the range of 5 to 11 microns.[14] The asphalt cement required to coat the aggregate to a given film thickness may be computed by a method outlined by Harper, Jimenez, and Gallaway.[15] This method is based on the surface area concepts of Hveem and the California Highway Department.[9] When computed in this manner and assuming effective film thickness of 8 microns, aggregate A, for example, requires approximately 5.6 percent (by weight of the aggregate) asphalt cement. It logically follows that greater film thicknesses for a given aggregate gradation will require more asphalt. For instance, if the film thickness for the above example is increased to 10 microns, about 6.9 percent asphalt cement is required. The reader should bear in mind that these asphalt contents are influenced only by the gradation and density of the aggregates involved and not by the "nature" of the stone. The total asphalt content must take into consideration the absorptive characteristics and surface texture of the aggregates as well as the film thickness requirements.

Asphalt Absorption

Since lightweight aggregates have a very porous structure and the water absorption values may range up to 30 percent for an aggregate such as B[2], the asphalt absorption for these aggregates may be a major factor in mix design considerations; hence, a laboratory study was performed to determine the asphalt absorption characteristics of these aggregates. This study incorporated two methods for determining the asphalt absorption. One was to immerse the aggregate in hot asphalt[16] and determine the absorption when an unlimited supply of hot asphalt was available. The other method was to determine the asphalt absorption from a regular mixture of asphalt and aggregate. The latter approach will limit the asphalt available for absorption and; thus, it will decrease the total absorption. These laboratory studies have shown that very good mixtures can be made with lightweight aggregates used as the coarse fraction in spite of the relatively high absorption that takes place.

The method involving the total immersion of aggregate particles into hot liquid asphalt cement is a modification of that reported by Goshorn and Williams.[16] To carry out these tests, the coarse fraction was divided into two sizes in keeping with the earlier work in lightweight aggregate seal coats,[1] and these fractions were tested by procedures outlined by Goshorn and Williams. The absorption, so determined for each aggregate, is shown in Table VIII.

Table VIII

Asphalt Absorption for Lightweight Aggregate (Immersion Method)[15]

Aggregate Source	Absorption, % by Weight of Dry Aggregate	
	5/8" - 3/8"	3/8" - No. 10
A	5.4	5.8
B	7.7	5.1
C	7.4	7.5
D	2.0	3.6
E	9.5	7.6
F	13.4	15.4
G	10.1	12.6

In the computation of the asphalt absorption, it was necessary to compute the bulk specific gravity of the stone in both the dry and saturated surface dry condition; hence, the water absorption (three days soaking) was also determined. When the water absorption and asphalt absorption data were plotted in Figure 6, it was found that a definite correlation (coefficient of determination, $r^2 = 0.912$)

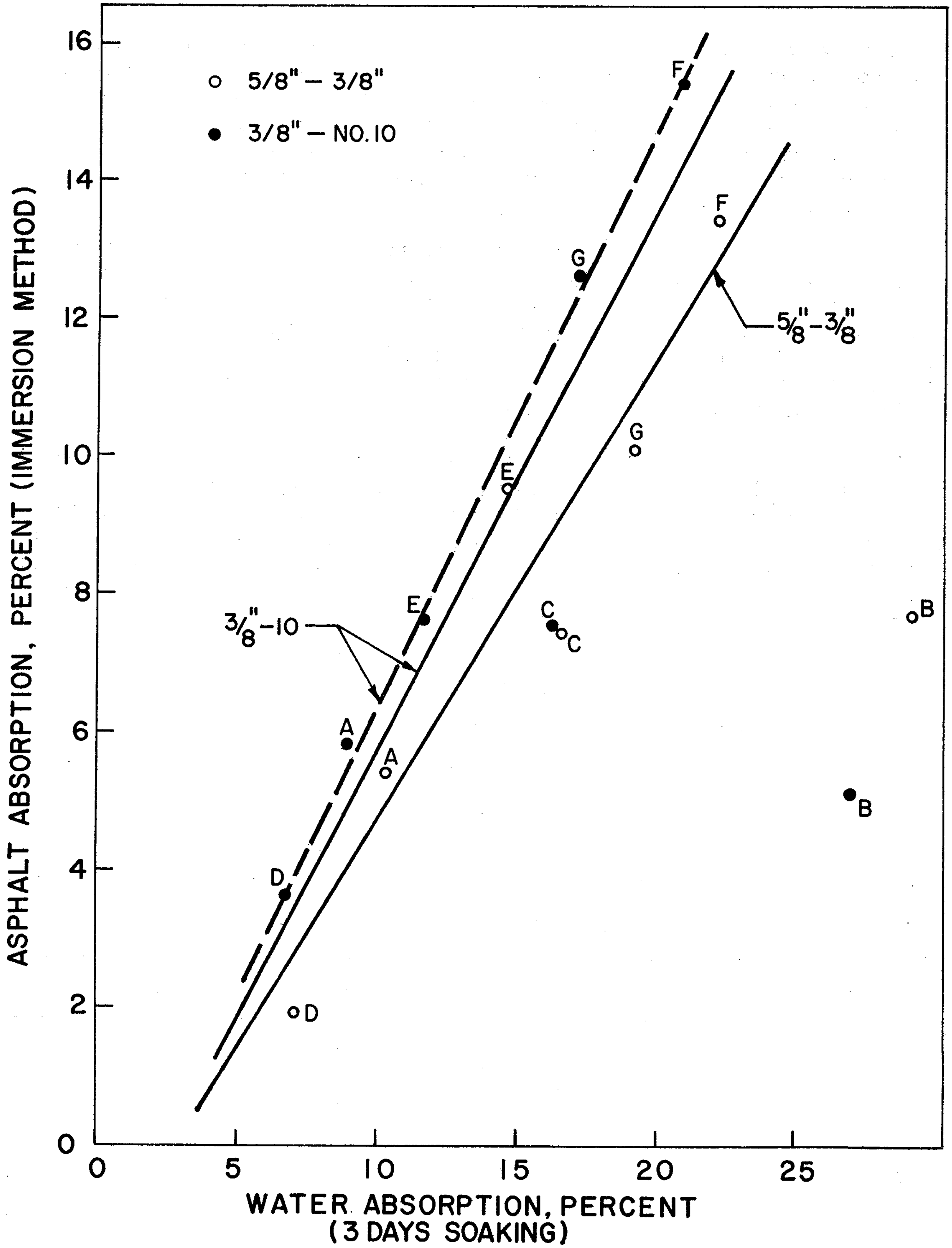

FIGURE 6: CORRELATION OF ASPHALT AND WATER ABSORPTION

existed between the two parameters for the 5/8 inch to 3/8 inch size aggregate. A good correlation, $r^2 - 0.86$, was found to exist for the smaller stone; however, there is one outlying data point. If this point were not considered, the line fit would be excellent as is indicated by the dashed line on the graph. The data for aggregate B was excluded from the regression analysis because subsequent to these tests, the production methods have been changed to reduce the water absorption.

The second and probably the most realistic method for obtaining the asphalt absorption was that outlined by Rice.[13] This method is preferred since the absorption is calculated from the data on actual mixtures. The data presented in Table IX are based on the assumption that the absorption in the sand is negligible and the primary absorption is by the lightweight aggregate. Table IX also includes data from mixtures cured by different methods to determine the effects of time and temperature upon absorption.

The mixtures represented in Table IX were made at 9.0 percent asphalt (by weight of mixture) which allows a reasonable amount of asphalt cement available for absorption. The curing times were chosen to represent the maximum time and temperature conditions (curing No. 1) of field mixtures and those which are more representative of a newly constructed pavement (curing No. 2). The data show that regardless of the curing conditions, the asphalt absorption is almost constant, i.e., approximately 2.0 to 3.0 percent by weight of aggregate.

Table IX

Asphalt Absorption for Lightweight Aggregate

(Rice's Method)[5]

Aggregate Source	Absorption, % by Weight of Lightweight Aggregate in Mix	
	3/8 inch -- No. 10	
	Curing No. 1*	Curing No. 2**
A	3.1	2.4
B	0.8	2.2
C	2.6	2.2
D	0.4	0.1
E	2.8	2.6
F	2.8	2.0
G	2.8	3.2

*Curing No. 1 -- 3 hours at 250°F.
**Curing No. 2 -- 1 hour at 250°F. and 20 hours at 140°F.

Total Asphalt Demand

The total asphalt required in a hot-mixed asphaltic concrete mixture is the sum of the components discussed above. For example, it was previously shown that the amount of asphalt cement to satisfy a film thickness requirement of eight microns was 5.6 percent for aggregate A, and from Table IX, the absorption is 2.4 percent. Hence, the total asphalt cement required to make a hot-mixed asphaltic concrete mixture using aggregate A and to meet the grading requirements previously showed in 8.0 percent by weight of aggregate. This volume may be a little low to meet other specification requirements, but it is a good starting point. It may be stated again, that asphalt demand computed above is on a weight basis which is more convenient for batching operations. However, one must also consider the volume of the mixture, and possible consideration should be made for increasing the asphalt content on a volume basis. Research in this area is to continue in a proposed study with the objective of being able to produce design criteria and construction guides to the end of utilizing this material in successful hot-mixed asphalt pavements.

Water Susceptibility

Another primary concern of the researchers was that hot-mixed asphaltic concrete mixtures made with lightweight aggregate may be susceptible to water. This feeling was based upon the fact that the water absorption of these aggregates is quite high. A loss in strength might be in evidence should the aggregate not receive the proper asphalt coating. A study was made of the water susceptibility for the 70 percent lightweight aggregate and 30 percent field sand combination previously discussed. Mixtures were made at two asphalt contents: (1) a high asphalt content of about 9 or 10 percent (by weight of mixture), and (2) a low asphalt content of about 6 or 7 percent. These values were chosen to bracket the complete range of practical field mixtures. The samples were prepared and tested in accordance with procedures of the American Society for Testing and Materials, D 1074 and D 1075-54 (1961). The minimum recommended index of retained strength is 70 percent.

The results of these tests are illustrated in Figure 7. It is interesting to note that aggregates A and D posses the lower asphalt and water absorption values and they have a higher index than the center group. Aggregates C, E, F, and G have intermediate water absorption and higher asphalt absorption; and, they tend to fall into one grouping. Aggregate B has a very high water absorption and the slope of the curve is significantly different from the other five groupings. Hence, the asphalt and water absorptions appear to influence the strength index of the mixtures. Based upon these findings, a direct comparison of the strength index and water absorption was made, but no correlation was found to exist. Based on the strength index criteria, it is evident from Figure 7 that the low absorption aggregates will produce the necessary retained strength at low asphalt contents

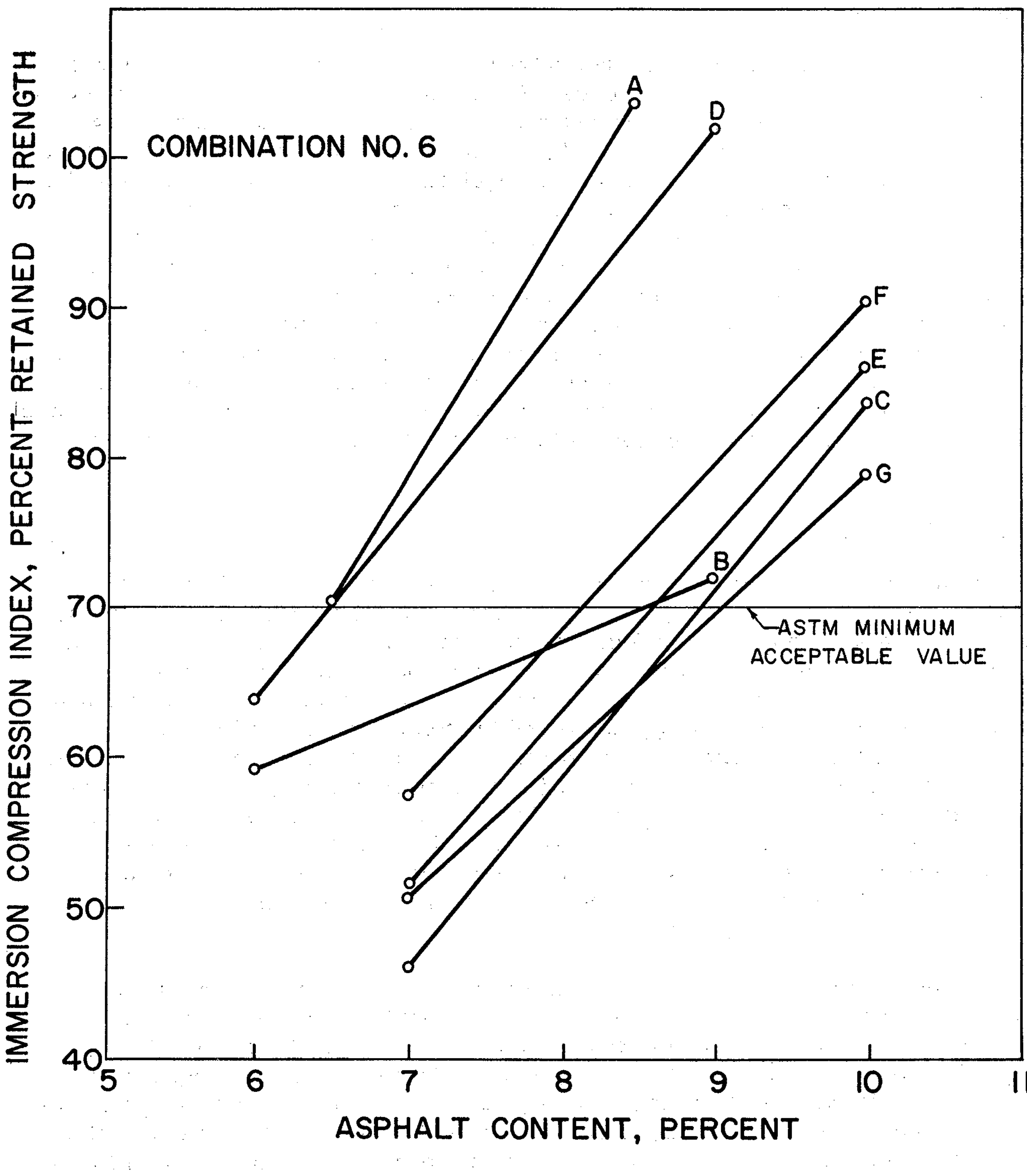

FIGURE 7. IMMERSION COMPRESSION INDEX VS. ASPHALT CONTENT

to make good mixes. An asphalt content of approximately 9 percent is required for the other aggregates; however, the entire problem may not lie with the lightweight aggregate. It was observed in the vacuum saturation procedure for specific gravity[13] evaluation of the loose mixture that the field sands used in this study had a tendency to strip. This would result in low values of retained strength. Additional research must be carried out with fine aggregate that is not water susceptible, since none of the tests made so far indicate such a weakness in the synthetic material.

Expansion of Asphaltic Concrete

Another phenomenon related to the introduction of water into the pavement and lightweight aggregate, or both, is that of swell and expansion of the confined hot-mixed asphaltic concrete. First, consideration was given to the expansion pressure of the molded mixtures; then the swell characteristics were studied to determine if there were any detrimental effects of the water.

Expansion Pressure

A test used by the California Highway Department[9] to measure the expansion pressure was incorporated into the research program. This expansion pressure determination is primarily a test for soil samples, but it was considered a reasonable method for determining the swell or expansion of compacted bituminous mixtures. The normal procedure provides for soaking of a restrained specimen in the test device for a period of 24 hours and then determining the upward force or expansion pressure. The bituminous mixtures made from Combination No. 6 (70 percent lightweight aggregate) and 8 percent asphalt cement yielded no measureable expansion pressure. As a further check on the expansion, aggregate B (highest water absorption) was tested for 120 hours. There was no expansion for the first 72 hours, and the maximum expansion pressure at the conclusion of the test was 1.3 pounds per square inch.

Swell Characteristics

Since the expansion pressure determination did not yield any measurable qualities, attention was turned to the swell test for bituminous mixtures (THD Test Method Tex-209-F)[10] to ascertain if any of the lightweight aggregate mixtures possessed undesirable swell characteristics. The maximum swell permitted by the Texas Highway Department Specifications as determined by the change in height of a confined specimen is 0.03 inches. Asphaltic concrete exhibiting this value or less, are considered to have a quality that will resist softening or disintegration when subjected to water. The maximum swell of any of the lightweight aggregate hot-mixed asphalt paving mixtures was 0.004 inches. The results of these and the preceding test seem to indicate that hot-mix asphaltic concrete made with these synthetic aggregates exhibit exceptionally low swell characteristics.

Permeability

The air permeability of the lightweight aggregate mixtures (Combination No. 6) was studied with hopes that such data could be related to the specimen density. Typical results are tabulated in Table X. There is a general relationship that air permeability increases with increasing air voids, but the coefficient of determination of such a relationship is 0.43, which indicates that no definite correlation exists. In other words, as the asphalt content increases, the air permeability will generally decrease.

Table X

Air Permeability of Lightweight Aggregate Mixtures

Aggregate Source	Asphalt Content %	Air Voids %	Air Permeability ml/in/min @ 0.25" Head
B	6	8.3	91
	7	6.3	71
	8	6.9	54
	9	4.4	30
D	6	6.1	49
	7	5.6	54
	8	5.2	49
	9	1.7	33

The air permeability of these mixtures is very erratic and both the reproducibility and repeatability is not very good.

The air permeability apparatus used in this study is manufactured by Soiltest, Inc. of Chicago, Ill. under license from the California Research Corporation. The use of this equipment was first described by Ellis and Schmidt[17] and later by Hein and Schmidt.[18] The particular testing procedure used in this study is that supplied by the manufacturer of the apparatus for testing 4-inch diameter laboratory test specimens.

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TEXAS HIGHWAY DEPARTMENT

SPECIAL SPECIFICATION

Item 1269

AGGREGATE FOR SURFACE TREATMENTS (LIGHTWEIGHT)

1. DESCRIPTION. This item establishes the requirements for lightweight aggregates to be used in the construction of surface treatments.

2. MATERIALS. Aggregates shall be composed predominately of lightweight cellular and granular inorganic material prepared by expanding, calcining, or sintering products such as clay or shale.

The aggregate shall contain not more than 1 percent of organic matter, impurities of objectionable matter when tested in accordance with Test Method Tex-217-F.

The dry loose unit weight of course lightweight aggregates shall not be less than 40 and shall not exceed 60 pounds per cubic foot. If the unit weight of any shipment of lightweight aggregate differs by more than 6 percent from that of the sample submitted for acceptance test, the aggregates in the shipment may be rejected. Tests shall be in accordance with Test Method Tex-404-A, except that the aggregate shall be tested in an oven-dry condition. The percent of wear, as determined by Test Method Tex-410-A (Part II), shall not exceed 35 percent.

The aggregate, when tested in accordance with Test Method Tex-411-A, shall show a loss of not more than 12 percent after five cycles of the sodium sulfate soundness test or 18 percent after five cycles of the magnesium sulfate soundness test.

3. GRADES. When tested by Test Method Tex-200-F, the gradation requirements for the several grades of aggregate shall be as follows:

		Percent by Weight
Grade 1:	Retained on 1" sieve	0
	Retained on 7/8" sieve	0-2
	Retained on 5/8" sieve	15-45
	Retained on 3/8" sieve	85-100
	Retained on No. 4 sieve	95-100
	Retained on No. 10 sieve	98-100

Grade 2:	Retained on 7/8" sieve	0
	Retained on 3/4" sieve	0-2
	Retained on 1/2" sieve	20-35
	Retained on No. 4 sieve	85-100
	Retained on No. 10 sieve	98-100
Grade 3:	Retained on 3/4" sieve	0
	Retained on 5/8" sieve	0-2
	Retained on 1/2" sieve	5-20
	Retained on No. 4 sieve	85-100
	Retained on No. 10 sieve	98-100

Grade 4:	Retained on 5/8" sieve	0
	Retained on 1/2" sieve	0-2
	Retained on 3/8" sieve	5-25
	Retained on No. 4 sieve	85-100
	Retained on No. 10 sieve	98-100
Grade 5:	Retained on 1/2" sieve	0
	Retained on 3/8" sieve	0-2
	Retained on No. 4 sieve	40-85
	Retained on No. 10 sieve	98-100
Grade 6:	Retained on 1/2" sieve	0
	Retained on 3/8" sieve	0-2
	Retained on No. 4 sieve	5-40
	Retained on No. 10 sieve	70-100
	Retained on No. 20 sieve	99-100
Grade 7:	Retained on 1/4" sieve	0
	Retained on No. 4 sieve	0-10
	Retained on No. 20 sieve	25-55
Grade 8:	Retained on No. 4 sieve	0
	Retained on No. 10 sieve	0-10
	Retained on No. 20 sieve	10-55

4. MEASUREMENT AND PAYMENT. Aggregates will be measured and paid for in accordance with the governing specifications for the items of construction in which these materials are used.

APPENDIX A

APPENDIX A - 1

Data Summary

Lightweight Aggregate (LWA) Mixtures

Source of Material	Aggregate Combination	Asphalt Content %	Specimen Density g/cc	Maximum Density* g/cc	Air Voids* %	Theoretical Density g/cc	Theoretical Air Voids %
A	100% LWA	8.0	1.499	1.680	10.7	1.810	17.1
		9.0	1.512	1.667	9.3	1.790	15.5
		10.0	1.543	1.645	6.3	1.780	13.0
	No. 6	4.5	1.568	1.849	13.2	2.051	23.5
		5.5	1.579	1.803	11.4	2.029	22.2
		6.5	1.642	1.789	8.2	2.008	19.4
		7.5	1.637	1.773	7.7	1.987	17.6
		8.5	1.653	1.765	6.3	1.966	15.9
	No. 4	6.5	1.788	1.977	9.6	2.250	20.6
	No. 2	7.5	1.702	1.830	6.9	---	---
B	100% LWA	9.0	1.028	1.248	17.6	1.437	28.5
		10.0	1.080	1.227	12.0	1.431	24.5
		11.0	1.087	1.223	11.1	1.425	23.7
	No. 6	6.0	1.372	1.496	8.3	1.693	19.0
		7.0	1.376	1.469	6.3	1.682	18.2
		8.0	1.383	1.486	6.9	1.669	18.2
		9.0	1.405	1.470	4.4	1.658	15.3

APPENDIX A - 1

(continued)

Source of Material	Aggregate Combination	Asphalt Content %	Specimen Density g/cc	Maximum Density* g/cc	Air Voids* %	Theoretical Density g/cc	Theoretical Air Voids %
C	No. 6	6.0	1.316	1.462	10.0	1.659	20.7
		7.0	1.342	1.437	6.6	1.648	18.6
		8.0	1.348	1.418	4.9	1.628	17.2
		9.0	1.364	1.413	3.5	1.626	16.1
		10.0	1.362	1.411	3.5	1.615	15.7
D	100% LWA	5.0	1.374	1.688	18.5	1.715	19.8
		6.0	1.408	1.674	15.9	1.702	17.4
		7.0	1.411	1.672	15.6	1.690	16.5
	No. 6	6.0	1.681	1.791	6.1	1.872	10.2
		7.0	1.696	1.824	5.6	1.855	8.6
		8.0	1.717	1.811	5.2	1.839	6.6
		9.0	1.741	1.771	1.7	1.822	4.4
E	100% LWA	8.0	1.347	1.572	14.3	1.599	15.8
		9.0	1.337	1.561	14.3	1.589	15.9
		10.6	1.390	1.540	9.7	1.573	11.6
	No. 6	6.0	1.533	1.660	7.7	1.839	16.7
		7.0	1.551	1.691	8.3	1.822	14.9
		8.0	1.570	1.727	9.1	1.807	13.1
		9.0	1.588	1.734	8.4	1.791	11.3
		10.0	1.610	1.693	4.9	1.777	9.4

APPENDIX A - 1
(continued)

Source of Material	Aggregate Combination	Asphalt Content %	Specimen Density g/cc	Maximum Density* g/cc	Air Voids* %	Theoretical Density g/cc	Theoretical Air Voids %
F	100% LWA	9.0	1.306	1.757	25.7	1.791	27.1
		10.0	1.322	1.684	21.5	1.776	25.6
		11.0	1.323	1.643	19.5	1.761	24.9
	No. 6	6.0	1.474	1.657	11.0	1.931	23.7
		7.0	1.494	1.638	10.0	1.912	21.9
		8.0	1.523	1.702	10.5	1.894	19.6
		9.0	1.531	1.750	12.5	1.876	18.4
		10.0	1.550	1.665	6.9	1.859	16.6
G	100% LWA	8.0	1.286	1.655	22.3	1.722	25.3
		9.0	1.331	1.592	16.4	1.709	22.1
		10.0	1.303	1.548	15.8	1.696	23.2
	No. 6	6.0	1.532	1.712	10.5	1.906	19.6
		7.0	1.539	1.642	6.3	1.888	18.5
		8.0	1.556	1.699	8.4	1.871	16.8
		9.0	1.592	1.665	4.4	1.853	14.1
		10.0	1.604	1.702	5.8	1.837	12.7

APPENDIX A - 2

Source of Material	Aggregate Combination	Asphalt Content %	Air Permeability ml/min/in at 0.5 head	Stability %	Cohesion g/in. width	Strength Index (ASTM 1075-54) %
A	100% LWA	8.0	390	46.5	61	---
		9.0	314	47.0	94	---
		10.0	83	48.0	132	---
	No. 6	4.5	---	40.6	46	---
		5.5	---	40.2	51	---
		6.5	---	41.0	77	70.5
		7.5	---	41.3	82	---
		8.5	---	40.0	101	103.5
	No. 4	6.5	---	36.0	110	---
	No. 2	7.5	---	42.0	99	---
B	100% LWA	9.0	1030	49.9	67	---
		10.0	687	49.5	73	---
		11.0	359	48.0	133	---
	No. 6	6.0	93	43.8	104	59.3
		7.0	71	42.0	88	---
		8.0	54	42.0	76	---
		9.0	30	43.2	106	72.1

APPENDIX A - 2

(continued)

Source of Material	Aggregate Combiaation	Asphalt Content %	Air Permeability ml/min/in at 0.5 head	Stability %	Cohesion g/in. width	Strength Index (ASTM 1075-54) %
C	No. 6	6.0	59	47.0	65	---
		7.0	38	45.0	76	46.3
		8.0	21	44.0	67	---
		9.0	34	46.0	81	---
		10.0	53	45.0	104	83.6
D	100% LWA	5.0	456	44.3	33	---
		6.0	681	44.0	50	---
		7.0	800	46.5	64	---
	No. 6	6.0	49	41.5	67	64.1
		7.0	54	40.0	86	---
		8.0	49	40.0	87	---
		9.0	33	36.5	233	101.8
E	100% LWA	8.0	697	45.3	80	---
		9.0	681	44.8	99	---
		10.6	595	45.8	74	---
	No. 6	6.0	152	39.0	56.1	---
		7.0	111	40.7	50.6	51.9
		8.0	111	42.8	84	---
		9.0	108	41.5	96	---
		10.0	114	39.0	86	85.8

APPENDIX A - 2

(continued)

Source of Material	Aggregate Combination	Asphalt Content %	Air Permeability ml/min/in at 0.5 head	Stability %	Cohesion g/in. width	Strength Index (ASTM 1075-54) %
F	100% LWA	9.0	483	47.3	33	---
		10.0	781	49.0	56	---
		11.0	939	46.8	65	---
	No. 6	6.0	163	44.3	70	---
		7.0	167	44.2	62	57.5
		8.0	195	44.8	76	---
		9.0	141	42.7	83	---
		10.0	188	41.7	141	90.1
G	100% LWA	8.0	702	46.5	63	---
		9.0	442	48.3	108	---
		10.0	597	49.6	111	---
	No. 6	6.0	128	44.5	77	---
		7.0	120	45.0	63	50.7
		8.0	111	42.0	83	---
		9.0	85	44.0	84	---
		10.0	76	41.0	89	78.5

APPENDIX A - 3

Source of Material	Aggregate Combination	Asphalt Content %	Original Surface Area sq. ft./lb. Volume Basis	Original Surface Area sq. ft./lb. Weight Basis	Final Surface Area sq. ft./lb. Weight Basis	Change in Surface Area % of Original
A	100% LWA	8.0	19.7	19.7	26.2	33.1
		9.0	"	"	26.5	34.6
		10.0	"	"	28.1	42.8
	No. 6	4.5	26.0	33.6	---	---
		5.5	"	"	---	---
		6.5	"	"	35.5	5.6
		7.5	"	"	---	---
		8.5	"	"	---	---
	No. 4	6.5	53.5	53.5	---	---
	No. 2	7.5	34.3	34.3	---	---
B	100% LWA	9.0	19.7	19.7	22.3	13.1
		10.0	"	"	25.9	31.8
		11.0	"	"	28.4	44.3
	No. 6	6.0	28.0	40.7	42.0	3.1
		7.0	"	"	43.8	7.6
		8.0	"	"	42.5	4.5
		9.0	"	"	42.7	4.9

APPENDIX A - 3

(continued)

Source of Material	Aggregate Combination	Asphalt Content %	Original Surface Area sq. ft./lb. Volume Basis	Original Surface Area sq. ft./lb. Weight Basis	Final Surface Area sq. ft./lb. Weight Basis	Change in Surface Area % of Original
C	No. 6	6.0	27.9	41.4	44.1	6.5
		7.0	"	"	46.7	12.8
		8.0	"	"	49.4	19.3
		9.0	"	"	45.3	9.3
		10.0	"	"	41.8	1.0
D	100% LWA	5.0	19.7	19.7	24.5	24.4
		6.0	"	"	20.6	4.5
		7.0	"	"	20.5	4.0
	No. 6	6.0	27.7	36.9	37.1	0.4
		7.0	"	"	37.8	2.4
		8.0	"	"	37.1	0.4
		9.0	"	"	38.0	3.1
E	100% LWA	8.0	19.7	19.7	31.3	58.8
		9.0	"	"	28.8	46.4
		10.6	"	"	29.7	50.7
	No. 6	6.0	27.6	37.3	41.3	10.7
		7.0	"	"	41.8	12.1
		8.0	"	"	40.5	8.7
		9.0	"	"	41.8	11.9
		10.0	"	"	41.1	10.2

APPENDIX A - 3

(continued)

Source of Materials	Aggregate Combination	Asphalt Content %	Original Surface Area sq. ft./lb. Volume Basis	Original Surface Area sq. ft./lb. Weight Basis	Final Surface Area sq. ft./lb. Weight Basis	Change in Surface Area % of Original
F	100% LWA	9.0	19.7	19.7	33.0	67.8
		10.0	"	"	35.0	78.0
		11.0	"	"	34.0	
	No. 6	6.0	27.6	32.9	35.6	8.3
		7.0	"	"	38.0	15.4
		8.0	"	"	36.5	11.0
		9.0	"	"	37.2	13.1
		10.0	"	"	36.8	11.9
G	100% LWA	8.0	19.7	19.7	22.7	15.2
		9.0	"	"	25.4	28.9
		10.0	"	"	24.6	25.1
	No. 6	6.0	27.8	36.2	37.4	3.3
		7.0	"	"	36.9	1.8
		8.0	"	"	37.4	3.3
		9.0	"	"	38.3	5.9
		10.0	"	"	39.1	8.0