Laboratory Considerations for the Use of Lightweight Aggregates for Hot-Mix Asphalt Pavements

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

Class I synthetic aggregates from seven sources were used with two different field sands to produce laboratory designs that were tested by several methods to determine their suitability for hot-mix asphalt pavements. 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, and (f) air permeability.

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.

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.

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.

Water susceptibility of selected hot-mix designs was determined by the immersion-compression test (ASTM 1074-60). 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.

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

•SINCE the introduction of lightweight synthetic aggregate as coverstone for seal coats and surface treatments on Texas highways in 1961, aggregate producers, contractors,

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highway personnel, and even the driving public have watched the performance of this material with a critical eye. Service records for the past 5 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 showing that this material is serving the driving public safely and economically are available on some 2000 miles of primary and secondary Texas highway with traffic volumes from 100 to 8000 vehicles per day.

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

The basic physical characteristics of synthetic aggregates that definitely influence 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 factorial design including the necessary basic research, laboratory evaluations, and field service trials. This 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 can be classified as Class I Group A, or Class I Group B, according to the proposed synthetic aggregate classification system (3).

OBJECTIVES AND PLAN OF RESEARCH

This research was conducted to determine the basic physical characteristics of synthetic (lightweight) aggregates and to relate their uses in hot-mix, hot-laid asphalt pavement surfaces. The secondary objective, an outgrowth of a previous study (1), was to determine the physical characteristics of synthetic aggregates affecting their use as aggregate in plant-mixed asphaltic concrete for thin overlays and anti-skid pavements. From this, it was anticipated that guidelines for the design and specification of asphaltic concrete using these aggregates could be produced.

The basic research plan was to examine mixtures containing lightweight aggregate and to consider 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; and
6. Permeability to air.

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

BACKGROUND

In 1955, Louisiana placed a field test section of asphalt pavement made from lightweight aggregate hot-mix. This experimental section of roadway was 200 ft long and 4 traffic lanes wide. The compacted layer was approximately 2 in. thick (4). The lightweight aggregate 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 12 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.

In 1955, the Southern Lightweight Aggregate Corporation also became interested in the potential use of lightweight aggregate for asphaltic-concrete surfaces. As reported by Wycott (5), their study included a design by the Hubbard-Field method and strength testing by the ASTM methods D 1074-60 and D 1075-54. The aggregate used was 100 percent lightweight aggregate, and the grading was the same as that for concrete masonry units (ASTM C 331-53T). Bitumen contents ranged from 9 to 12 percent by weight for the laboratory test. In 1957, a field trial of the optimum laboratory design was made in Richmond, Va. This test section was also 200 ft long and 4 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).

Texas, 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 State's first experimental section of synthetic aggregate was constructed on SH-6 in Fort Bend County in August 1963. The aggregate blend was approximately 68 percent calcined clay and 32 percent field sand and 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.

Since 1963, several districts 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 on I-20 near Mesquite on the inside lane of the Dallas-bound roadway. Average daily traffic in 1965 was approximately 33,000 vehicles. Two different sources of lightweight aggregate were used and both materials were evaluated to a limited extent in this research. Mixture designs were made using the Texas Highway Department modification of the Hveem method; laboratory designs yielded stabilities in the order of 45 to 50 percent and cohesiometer values of 100 to 150 gr per inch of width. The air voids of the laboratory specimens were approximately 2 to 5 percent. 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 7.0 percent by weight of mixture. These pavements have been in service about 17 months and are performing satisfactorily. The Texas Highway Department measured the skid properties or coefficient of friction of these surfaces after about 15 months of service. The coefficient of friction of the lightweight sections averaged about 0.48 at 50 mph, while that of the adjacent lane, placed at the same time but utilizing normal aggregates, was 0.31.

MATERIALS

Lightweight Synthetic Aggregate

The aggregates were secured from the six producers of lightweight aggregate in Texas and from one producer in Louisiana. These included both expanded clay and expanded shale products and fell into Class I of the proposed THD classification system for synthetic aggregates. The materials from all of the potentially available suppliers were used 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. However, production procedures should be adaptable to grading requirements.

Aggregates used were the same as those in the preceding phase of the study (1). In general, they were Type F, Grade 3 or 4, conforming to Texas Highway Department

TABLE 1

PHYSICAL PROPERTIES OF LIGHTWEIGHT AGGREGATES

Aggregate	Raw Material	Vacuum Sat. Density (% in.-No. 4, g/cc)	Dry Loose Unit Wt.[a] (pcf)	Los Angeles Abrasion (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[b]	25.4	21.2

[a] THD Item-1269, Grade 4.
[b] THD Item 1296, Grade 3.

Special Specification, Item 1269, Aggregates for Surface Treatments (Lightweight). Typical physical properties are given in Table 1. Since these aggregates are generally produced for concrete block and sealcoat 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. According to Kenneth Hawkins, field measurements show that lightweight aggregates used in this manner do not polish or become slick—as they 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 the lightweight material is the coarse fraction, the fine fraction should consist of some locally available filler material. This 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, arising 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.

Field sand was chosen for this study because of its economy and wide availability. It 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 are given in Table 2. These sands, typical of many sands found in Texas, are designated FS 1 and FS 2.

Asphalt

The asphalt was an 85-100 penetration grade with an intermediate susceptibility to hardening. This asphalt would be classified as to viscosity as between an AC-10 and an AC-20, according to present Texas specifications (Table 3).

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

TABLE 2

GRADATION OF FIELD SANDS

U. S. Sieve No.	Percent Passing	
	Field Sand No. 1	Field Sand No. 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 3

ASPHALT-CEMENT CHARACTERISTICS

Viscosity	
At 77 F and Sr + 5 × 10^{-2} sec^{-1}, poise	1,020,000
At 140 F, poise	1,760
At 275 F, poise	2.75+
Penetration, 100 g, 5 sec, 77 F, points	90
Specific gravity, 77 F/77 F	1.014
Ductility, 5 cm/min, 77 F, cm	150+

DESIGN DATA

Gradation

The Texas Highway Department uses a modification of the Hveem procedure for its design and control work. Modifications are essentially in the area of predicting an optimum asphalt content and in molding of the test specimens. The procedure involves the use of a gyratory shear-type molding press for forming both the laboratory and quality control specimens.

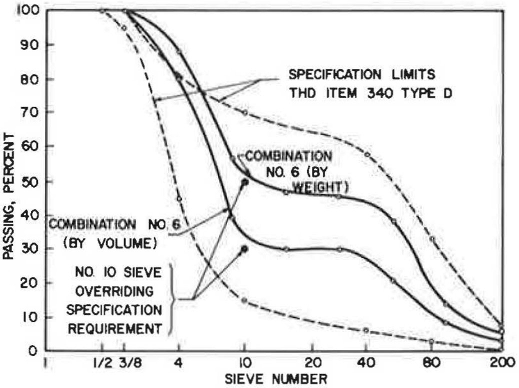

Figure 1. Aggregate blends by weight and volume methods.

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. Texas specifications for aspahltic concrete lend themselves to the latter type. 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 their stability will nearly always meet specified requirements and will probably be workable in the field.

Unit weight is another major factor in blending lightweight aggregates. 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 can result in serious difficulty if it is not considered when making the aggregate combination (Fig. 1). It is necessary to combine the materials on a volume basis and convert the 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 (Fig. 2). Combination No. 2 is a dense-graded blend containing approximately 70 percent lightweight aggregate by volume. It was seriously considered but was not used in the study because it was believed 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 might not be as economical as blends containing local materials. Combinations No. 4 and No. 6 were then considered as being the logical choices economically. 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 because it represented the maximum probable amount of lightweight material that could be incorporated in a bituminous mixture. It

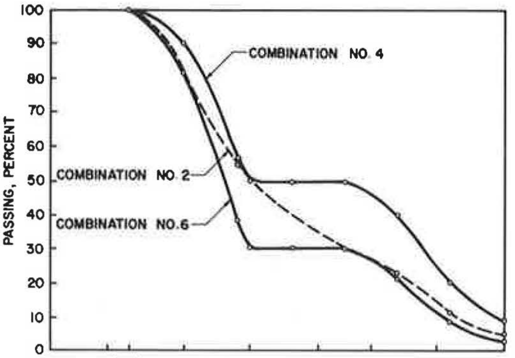

Figure 2. Gradation chart for various aggregate blends (volume combination).

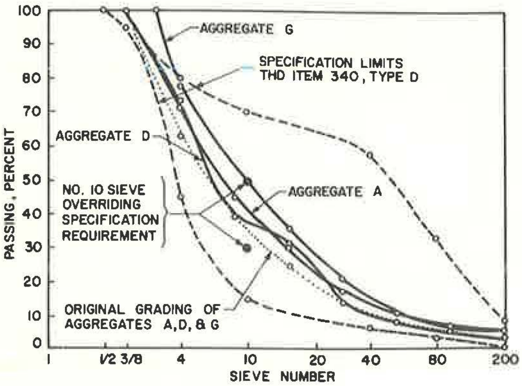

Figure 3. Original and recovered aggregate from a degradation study of 100 percent LWA mixtures.

was considered that this maximum blend would produce the most unfavorable conditions if the synthetic aggregate were not suitable for asphaltic concrete.

Laboratory Compaction Degradation

One of the more important problems of the study was in laboratory compaction-degradation; hence, such a study was undertaken. A dense-graded combination containing 100 percent lightweight aggregate was selected, for two reasons: (a) an all-lightweight design would be most susceptible to particle breakdown, and (b) 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.

The mixtures were prepared at three asphalt contents with the estimated optimum value being that determined by the California centrifuge kerosene equivalent method (6). Design details are given in Table 4. These mixtures were prepared by the Texas gyratory shear method in accordance with standard procedure (7). 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 anaylsis was made on the recovered aggregate to determine the change in particle size distribution. The surface area (6) was also computed and these data are tabulated in the Appendix. Typical data are shown in Figure 3.

TABLE 4

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. Data for these aggregates are given in Table 5. The differences in the original and final surface areas do not reflect which original particles received the most damage during compaction. For example, aggregate G has a smaller change in surface area, but the particles between the $^3/_8$ and $^1/_4$-in. sieves have disappeared (Fig. 3). 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 5

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
D	5.0	24.4
	6.0	4.5
	7.0	4.0
G	8.0	15.2
	9.0	28.9
	10.0	25.1

In addition, sieve analyses were also made on the recovered aggregate from hot-mix designs containing lightweight aggregate and field sand. The existence of errors due to differences in the unit weight of particles on a given sieve was recognized; however, it was felt that these data might still have some value. Since the aggregate blend used in this study 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 in Figure 4, which includes the original gradation of Combination No. 6 computed on both volume and weight basis and the gradation of the aggregates recovered from hot-mix designs made from field sand and aggregates D and E. Aggregate E had the most laboratory degradation, whereas the best aggregate, D, showed no appreciable breakdown. Figure 5 shows aggregate B broken down into the percent retained between individual sieves. The coarse aggregate was apparently breaking into smaller pieces with only minor changes taking place in the finer material.

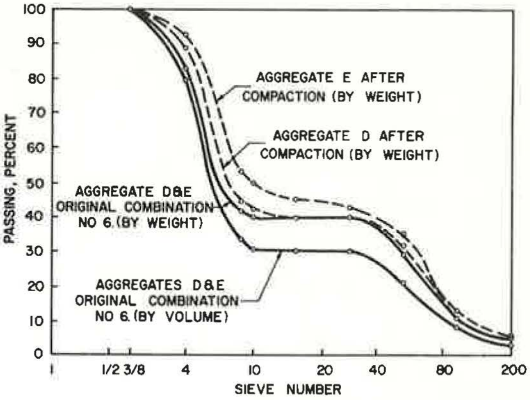

Figure 4. Original and recovered aggregate from a degradation study of LWA and field sand mixture.

The coarse material retained on the No. 4 sieve was reduced approximately 6 percent by weight and the total weight on the Nos. 8, 16, and 30 sieve sizes increased by about the same amount, indicating that the lightweight was degrading. Further examination of the material retained on the No. 50 sieve indicated the possibility of degradation in field sand.

Since there may have been differences in degradation characteristics due to different compactive efforts, a series of laboratory compaction tests was conducted using the Texas Highway Department manual molding press and the motorized press at two energy levels. Results in the form of a sieve analysis are given in Table 6.

These limited data indicate that there was 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.

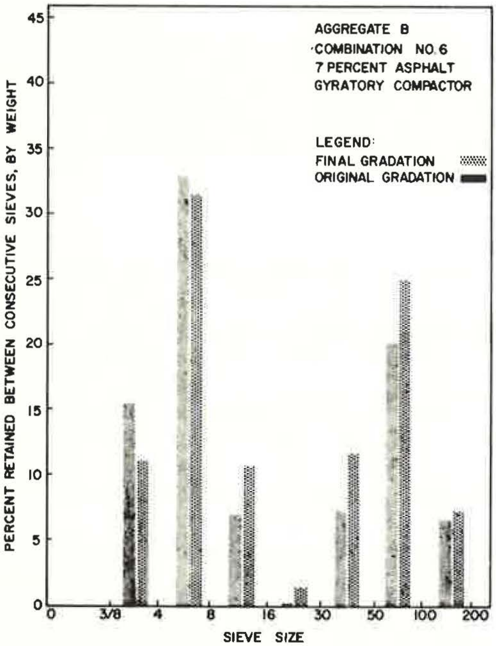

Figure 5. Aggregate degradation for individual sieves.

Strength Measurements

Texas uses a modification of the California design procedure for establishing

TABLE 6

EFFECT OF COMPACTIVE EFFORT ON COMPACTION DEGRADATION

(Aggregate A, Combination No. 6, 6.5 Percent 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
⅜ In.	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

compliance to hot-mix specifications. Current Texas specifications (12) 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, are shown in Figure 1.

TABLE 7

TYPICAL STRENGTH AND DENSITY MEASUREMENTS

Aggregate Source	Asphalt Content (% by wt.)	Laboratory Density (g/cc)	Specimen Voids[a] (%)	Stability (%)	Cohesiometer Value (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

[a] Based on Rice's method for maximum specific gravity (9).

Stability

The Texas Highway Department modified Hveem stability requirement 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 requirement. In fact, stabilities of 40 to 50 percent are common. The stability of such asphaltic surface mixtures is generally not very susceptible to change in asphalt content, for example, in the range of 1 or 2 percentage points. This is particularly advantageous because larger amounts of asphalt cement may be incorporated into the mixture for greater durability. Job control is not critical for mixtures containing lightweight aggregate 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 given in Table 7. In general, stability will increase with increasing asphalt to an optimum amount and then decrease. This is 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 mixtures are given in the Appendix.

Cohesion

Cohesion of mixtures containing lightweight as the coarse fraction generally increases with increasing asphalt content; however, the cohesion is highly influenced by the type, grade, and amount of asphalt cement used. The Texas Highway Department currently requires a cohesiometer value of 100 gr per inch of width when specification Item 346 is used, but this item is not in general use. Typical cohesiometer values are given in Table 7 and the Appendix.

Density

The specimen density and air voids as determined by the Rice method (9) were generally within the ranges specified by the Texas Highway Department. Specimen density increases with increasing asphalt content to the point of flushing or zero voids. In this sense, lightweight aggregate mixtures behave as ordinary "dense rock" mixtures. Air voids in the lightweight aggregate mixtures computed in the manner described in the Texas Highway Construction Bulletin C-14 (10) may exceed the allowable specified values. 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. 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.

Relative density and air voids computations were based upon the specific gravity of the loose mixture after Rice (9) instead of on the formula considerations of Texas Highway Department Bulletin C-14 (Table 7). This was done because the vacuum-saturation procedure takes into account the absorption characteristics of the aggregates, whereas the formula method does not. Hence, because of the absorptive nature of the lightweight aggregate, it was thought 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, but the relative density will never exceed 100 percent. The methods currently used do not account for asphalt absorption by the aggregate and may lead to unrealistic values of 103 to 104 percent relative density (11). Differences for highly absorptive materials such as synthetic aggregate may be expected to be even greater.

TABLE 8

ASPHALT ABSORPTION FOR LIGHTWEIGHT AGGREGATE

(Immersion Method)[a]

Aggregate Source	Absorption, % by Weight of Dry Aggregate	
	5/8-3/8 In.	3/8 In.-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

[a] Modified from method reported by Goshorn and Williams (13).

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.

Asphalt-Absorption

The effective asphalt film thickness for hot-mixed asphalt pavements in Texas is in the range of 5 to 11 μ (11). 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 (12) and based on the surface area concepts of Hveem and the California Highway Department (6). When so computed, assuming effective film thickness of 8 μ, aggregate A, for example, requires approximately 5.6 percent (by weight of 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 is increased to 10 μ, about 6.9 percent asphalt cement is required. 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.

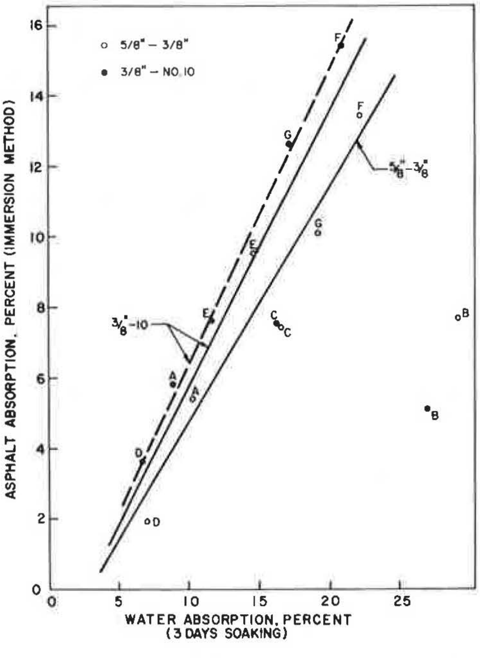

Figure 6. Correlation of asphalt and water absorption.

Since lightweight aggregates have a very porous structure and water absorption values may range up to 30 percent for an aggregate such as B^2, asphalt absorption may be a major factor in mix design considerations; hence, a laboratory study was performed to determine the asphalt absorption characteristics. Two methods for determining the asphalt absorption were used. One was to immerse the aggregate in hot asphalt (13) 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 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 (13). 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 (Table 8).

In the computation 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 data were plotted (Fig. 6), it was found that a definite correlation (coefficient of determination, $r^2 = 0.912$) existed between the two parameters for the ⅝ to ⅜-in. size aggregate. A good correlation, $r^2 = 0.86$, was found 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. Data for aggregate B were excluded from the regression analysis because production methods subsequently were changed to reduce water absorption.

Probably the most realistic method for obtaining the asphalt absorption was that outlined by Rice (9). This method is preferred since the absorption is calculated from data on actual mixtures. Data in Table 9 are based on the assumption that absorption in the sand is negligible with primary absorption by the lightweight aggregate. Table 9 also includes data from mixtures cured by different methods to determine the effects of time and temperature upon absorption.

The mixtures 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 more representative of a newly constructed pavement (curing No. 2). The data indicate that regardless of curing conditions, asphalt absorption is almost constant, i.e., approximately 2.0 to 3.0 percent by weight of aggregate.

Total Asphalt Demand

The total asphalt required in a hot-mixed asphaltic-concrete mixture is the sum of the components. For example, it was shown that the amount of asphalt cement needed to satisfy a film thickness requirement of 8 μ was 5.6 percent for aggregate A, and the absorption was 2.4 percent (Table 9). Hence, the total asphalt cement required to make a hot-mixed asphaltic concrete mixture using aggregate A to meet the grading requirements was 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. The computed asphalt demand was on a weight basis, which is more convenient for batching operations. However, one must also consider the volume of the mixture, and possibly consideration should be made for increasing asphalt content on a volume basis. Research in this area is continuing with the objective of producing design criteria and construction guides for utilizing this material in successful hot-mixed asphalt pavements.

TABLE 9

ASPHALT ABSORPTION FOR LIGHTWEIGHT AGGREGATE[a]

Aggregate Source	Absorption, % by Weight of Lightweight Aggregate in Mix ⅜ In.-No. 10	
	Curing No. 1[b]	Curing No. 2[c]
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

[a] Using method reported by Rice (9).
[b] Curing No. 1: 3 hr at 250 F.
[c] Curing No. 2: 1 hr at 250 F and 20 hr at 140 F.

Water Susceptibility

Hot-mixed asphaltic-concrete mixtures made with lightweight aggregate may be susceptible to water, since water absorption of these aggregates is quite high. Without the proper asphalt coating a loss in strength may occur. A study was made of the water susceptibility for the 70 percent lightweight aggregate and 30 percent field sand combination. Mixtures were made at two asphalt contents: (a) a high asphalt content of about 9 or 10 percent by weight of mixture, and (b) a low asphalt content of about 6 or 7 percent. These values were chosen to include the complete range of practical field mixtures. The samples were prepared and tested in accordance with procedures of the ASTM D 1074-60 and D 1075-54. The minimum recommended index of retained strength is 70 percent.

Results of these tests are shown in Figure 7. Aggregates A and D had lower asphalt and water absorption values and a higher index than the center group. Aggregates C, E, F, and G had intermediate water absorption and higher asphalt absorption and tended to fall into one grouping. Aggregate B had a very high water absorption and the slope of the curve was significantly different from the other five groupings. Hence, the asphalt and water absorptions appeared to influence the strength indexes. 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, the low absorption aggregates will produce the necessary retained strength at reasonable asphalt contents to make good mixes (Fig. 7). An asphalt content of approximately 9 percent is required for aggregates C and G; however, the entire problem may not lie with the lightweight aggregate. It was observed in the vacuum saturation procedure for specific gravity (9) evaluation of the loose asphalt aggregate mixture that the field sands had a tendency to strip, which might have contributed to the low values of retained strength. Additional research must be carried out with fine aggregate that is not water susceptible, since none of the tests thus far indicate such a weakness in the synthetic material.

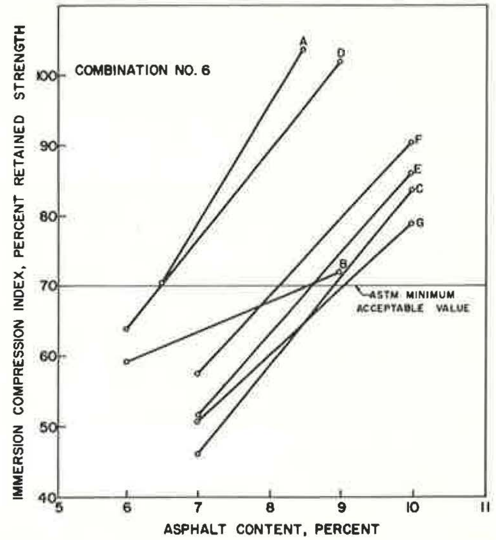

Figure 7. Immersion compression index vs asphalt content.

Expansion Pressure

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

A test used by the California Highway Department (6) to measure the expansion pressure was used. This is primarily a test for soil samples, but it was considered a reasonable method for determining the swell or expansion of compacted bituminous mixtures. A restrained specimen was soaked in the test device for a period of 24 hr and the upward force or expansion pressure was determined. The bituminous mixtures made from Combination No. 6

TABLE 10

AIR PERMEABILITY OF LIGHTWEIGHT AGGREGATE MIXTURES

Aggregate Source	Asphalt Content (%)	Air Voids (%)	Air Permeability[a] (ml/min)
B	6	8.3	398
	7	6.3	291
	8	6.9	233
	9	4.4	122
D	6	6.1	236
	7	5.6	259
	8	5.2	227
	9	1.7	169

[a] 4-in. diameter area; pressure differential 0.25 in. water.

(70 percent lightweight aggregate) and 8 percent asphalt cement yielded no measurable expansion pressure. As a further check on the expansion, aggregate B (highest water absorption) was tested for 120 hr. There was no expansion for the first 72 hr, and the maximum expansion pressure at the conclusion of the test was 1.3 psi.

Swell Characteristics

The swell test for bituminous mixtures THD Test Method Tex-209-F (7) was then used 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 in. Asphaltic concrete with this value or less is 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 in. Results of these tests indicate that hot-mix asphaltic concrete made with these synthetic aggregates has exceptionally low swell characteristics.

Permeability

The air permeability of the lightweight aggregate mixtures (Combination No. 6) was studied with the hope that such data could be related to the specimen density (Table 10). In general, air permeability increases with increasing air voids, but the coefficient of determination of such a relationship is 0.43, indicating that no definite correlation exists. In other words, as asphalt content increases, air permeability will generally decrease. The equation used to obtain the values in Table 10 and the Appendix is as follows:

$$K = \frac{u\,Q\,L}{A(P_1 - P_2)}$$

where u = viscosity of the air, Q = rate of flow, L = height of sample, A = area, and P_1-P_2 = pressure difference. The air permeability of these mixtures is very erratic Both the reproducibility and repeatability are not very good.

The air permeability apparatus used in this study is manufactured by Soiltest, Inc., under license from the California Research Corporation. The use of this equipment was first described by Ellis and Schmidt (14) and later by Hein and Schmidt (15). The particular testing procedure used in this study is that supplied by the manufacturer of the apparatus for testing 4-in. diameter laboratory test specimens.

SUMMARY AND CONCLUSIONS

The following summary of results and conclusions are tentative since they are based on limited laboratory data and field trials:

1. Research findings reveal that economical hot-mix designs can be produced by blending synthetic coarse aggregate ($^1/_2$ in. 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 three producers' products has been obtained.

2. Laboratory compaction degradation was found to be a minor problem even for designs containing 100 percent lightweight aggregate. The Texas gyratory shear compactor was used in the study; it is not known what results would be obtained with 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 produced stabilities in the range of 40-50. Large changes in asphalt content had little effect on measured stabilities. This characteristic has service advantages and economic potential.

3. Asphalt absorption of the synthetic aggregate 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, 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 nonselective. 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; the method used to make the evaluations is not absolute. However, at reasonable asphalt contents most of the designs were acceptable from the standpoint of water susceptibility.

5. The lightweight aggregates exhibited negligible expansion pressure and the swell as measured by Test Method Tex-209-F was in the range of 0.004 in. or less, compared to an allowable of 0.03 in. Therefore, the qualities measured by these tests were 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.

7. Since most lightweight aggregate particles are highly textured, workability of plant mixed designs containing these aggregates should receive special attention.

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Appendix

DATA SUMMARY
LIGHTWEIGHT AGGREGATE (LWA) MIXTURES

Source of Material	Aggregate Combination	Asphalt Content (%)	Specimen Density (g/cc)	Maximum Density[a] (g/cc)	Air Voidsa (%)	Theoretical Density (g/cc)	Theoretical Air Voids (%)	Air Permeability (ml/min) of Water[b]	Stability (%)	Cohesion (g/in. width)	Strength Index ASTM 1075-54 (%)	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	1.499	1.680	10.7	1.810	17.1	1659	46.5	61	—	19.7	19.7	26.2	33.1
		9.0	1.512	1.667	9.3	1.790	15.5	1339	47.0	94	—	19.7	19.7	26.5	34.6
		10.0	1.543	1.645	6.3	1.780	13.0	334	48.0	132	—	19.7	19.7	28.1	42.8
	No. 6	4.5	1.568	1.849	13.2	2.051	23.5	—	40.6	46	—	26.0	33.6	—	—
		5.5	1.579	1.803	11.4	2.029	22.2	—	40.2	51	—	26.0	33.6	—	—
		6.5	1.642	1.789	8.2	2.008	19.4	—	41.0	77	70.5	26.0	33.6	35.5	5.6
		7.5	1.637	1.773	7.7	1.987	17.6	—	41.3	82	—	26.0	33.6	—	—
		8.5	1.653	1.765	6.3	1.966	15.9	—	40.0	101	103.5	26.0	33.6	—	—
	No. 4	6.5	1.788	1.977	9.6	2.250	20.6	—	36.0	110	—	53.5	53.5	—	—
	No. 2	7.5	1.702	1.830	6.9	—	—	—	42.0	99	—	34.3	34.3	—	—
B	100% LWA	9.0	1.028	1.248	17.6	1.437	28.5	4041	49.9	67	—	19.7	19.7	22.3	13.1
		10.0	1.080	1.227	12.0	1.431	24.5	2475	49.5	73	—	19.7	19.7	25.9	31.8
		11.0	1.087	1.223	11.1	1.425	23.7	1368	48.0	133	—	19.7	19.7	28.4	44.3
	No. 6	6.0	1.372	1.496	8.3	1.693	19.0	398	43.8	104	59.3	28.0	40.7	42.0	3.1
		7.0	1.376	1.469	6.3	1.682	18.2	291	42.0	88	—	28.0	40.7	43.8	7.6
		8.0	1.383	1.486	6.9	1.669	18.2	233	42.0	76	—	28.0	40.7	42.5	4.5
		9.0	1.405	1.470	4.4	1.658	15.3	122	43.2	106	72.1	28.0	40.7	42.7	4.9
C	No. 6	6.0	1.316	1.462	10.0	1.659	20.7	261	47.0	65	—	27.9	41.4	44.1	6.5
		7.0	1.342	1.437	6.6	1.648	18.6	165	45.0	76	46.3	27.9	41.4	46.7	12.8
		8.0	1.348	1.418	4.9	1.628	17.2	95	44.0	67	—	27.9	41.4	49.4	19.3
		9.0	1.364	1.413	3.5	1.626	16.1	152	46.0	81	—	27.9	41.4	45.3	9.3
		10.0	1.362	1.411	3.5	1.615	15.7	227	45.0	104	83.6	27.9	41.4	41.8	1.0
D	100% LWA	5.0	1.374	1.688	18.5	1.715	19.8	2250	44.3	33	—	19.7	19.7	24.5	24.4
		6.0	1.408	1.674	15.9	1.702	17.4	3002	44.0	50	—	19.7	19.7	20.6	4.5
		7.0	1.411	1.672	15.6	1.690	16.5	3240	46.5	64	—	19.7	19.7	20.5	4.0
	No. 6	6.0	1.681	1.791	6.1	1.872	10.2	236	41.5	67	64.1	27.7	36.9	37.1	0.4
		7.0	1.696	1.824	5.6	1.855	8.6	259	40.0	86	—	27.7	36.9	37.8	2.4
		8.0	1.717	1.811	5.2	1.839	6.6	227	40.0	87	—	27.7	36.9	37.1	0.4
		9.0	1.741	1.771	1.7	1.822	4.4	169	36.5	233	101.8	27.7	36.9	38.0	3.1
E	100% LWA	8.0	1.347	1.572	14.3	1.599	15.8	2423	45.3	80	—	19.7	19.7	31.3	58.8
		9.0	1.337	1.561	14.3	1.589	15.9	2888	44.8	99	—	19.7	19.7	28.8	46.4
		10.6	1.390	1.540	9.7	1.573	11.6	2417	45.8	74	—	19.7	19.7	29.7	50.7
	No. 6	6.0	1.533	1.660	7.7	1.839	16.7	673	39.0	56.1	—	27.6	37.3	41.3	10.7
		7.0	1.551	1.691	8.3	1.822	14.9	485	40.7	50.6	51.9	27.6	37.3	41.8	12.1
		8.0	1.570	1.727	9.1	1.807	13.1	464	42.8	84	—	27.6	37.3	40.5	8.7
		9.0	1.588	1.734	8.4	1.791	11.3	458	41.5	96	—	27.6	37.3	41.8	11.9
		10.0	1.610	1.693	4.9	1.777	9.4	468	39.0	86	85.8	27.6	37.3	41.1	10.2
F	100% LWA	9.0	1.306	1.757	25.7	1.791	27.1	2070	47.3	33	—	19.7	19.7	33.0	67.8
		10.0	1.322	1.684	21.5	1.776	25.6	3248	49.0	56	—	19.7	19.7	35.0	78.0
		11.0	1.323	1.643	19.5	1.761	24.9	3940	46.8	65	—	19.7	19.7	34.0	—
	No. 6	6.0	1.474	1.657	11.0	1.931	23.7	706	44.3	70	—	27.6	32.9	35.6	8.3
		7.0	1.494	1.638	10.0	1.912	21.9	730	44.2	62	57.5	27.6	32.9	38.0	15.4
		8.0	1.523	1.702	10.5	1.894	19.6	489	44.8	76	—	27.6	32.9	36.5	11.0
		9.0	1.531	1.750	12.5	1.876	18.4	579	42.7	83	—	27.6	32.9	37.2	13.1
		10.0	1.550	1.665	6.9	1.859	16.6	762	41.7	141	90.1	27.6	32.9	36.8	11.9
G	100% LWA	8.0	1.286	1.655	22.3	1.722	25.3	2685	46.5	63	—	19.7	19.7	22.7	15.2
		9.0	1.331	1.592	16.4	1.709	22.1	1730	48.3	108	—	19.7	19.7	25.4	28.9
		10.0	1.303	1.548	15.8	1.696	23.2	2517	49.6	111	—	19.7	19.7	24.6	25.1
	No. 6	6.0	1.532	1.712	10.5	1.906	19.6	528	44.5	77	—	27.8	36.2	37.4	3.3
		7.0	1.539	1.462	6.3	1.888	18.5	547	45.0	63	50.7	27.8	36.2	36.9	1.8
		8.0	1.556	1.699	8.4	1.871	16.8	468	42.0	83	—	27.8	36.2	37.4	3.3
		9.0	1.592	1.665	4.4	1.853	14.1	349	44.0	84	—	27.8	36.2	38.3	5.9
		10.0	1.604	1.702	5.8	1.837	12.7	294	41.0	89	78.5	27.8	36.2	39.1	8.0

[a] Based on the Rice method (9).

[b] 4-in. diameter area; pressure differential 0.25 in. water.