EVALUATION OF GAP-GRADED ASPHALT CONCRETE MIXTURES

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Because of the increasing demand for high-quality and more durable paving mixture for modern traffic, the increasing costs for producing maximum density or well-graded aggregates in many parts of the country (especially near urban areas), and some possible advantages gap-graded asphalt paving mixtures may offer gap-graded aggregates in both portland cement and asphalt concretes have drawn some attention throughout the world. In this paper experimental results are reported on a comparative study involving 3 Fuller's curve gradings, 8 gap gradings, 2 aggregates, and 90 mixtures with varying asphalt contents. The physical properties of the mixtures were evaluated in terms of both Marshall design and Hveem design methods. Results have shown that gap-graded aggregates can produce mixtures with physical properties equal to or better than continuously graded aggregates at usually higher optimum asphalt contents.

•BITUMINOUS paving engineers generally agree that gradation of the aggregate in a paving mixture is one of the factors that must be carefully considered in a mixture design because it affects, directly or indirectly, the stability, durability, skid resistance, and economy of the finished pavement. Virtually all high-quality asphalt concrete used in the United States now contains a densely graded aggregate. However, there are differences of opinion in various localities as to what constitutes the "ideal" gradation for the densely graded aggregate.

Examination of the gradation requirements of specifications used by various state highway departments and other agencies in the United States, Canada, and some European countries reveals that, with few exceptions such as British Standard 594, they are approximate to the Fuller's maximum density curves (1, 2). It can also be observed that (a) specifications on aggregate gradation differ greatly, and tolerance of gradation limits vary widely; (b) under certain sets of conditions, a number of gradations can produce satisfactory paving mixtures; and (c) present knowledge on aggregate gradation, when coupled with economic considerations, may not justify the application of narrow gradation limits.

Of special significance is the fact that there are also reported experiences (3) where successful paving mixtures were associated with the most unconventional and irregular grading curves, and failures identified with gradings complied nicely with the ideal maximum density curves such as those presented by Fuller.

The demand is increasing for high-quality and more durable paving mixture for modern traffic. Costs for producing maximum-density or well-graded aggregates are also increasing in many parts of the country because of rapid depletion of natural deposits that meet the specifications of continuous grading and because of increased costs of labor, transportation, and processing. It, therefore, appears desirable to examine other types of aggregate gradings as compared with generally required well-graded maximum density gradations so that more efficient use can be made of locally available

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aggregates. One of these gradings that has been used with success is a gap-graded mixture (2, 3, 4, 5).

Grading of aggregates to conform to a curve of maximum density, developed by Fuller and Thompson (6) and later modified and confirmed by a number of others, is generally accepted as the most desirable grading for the production of good, economical portland cement and asphalt concretes. These gradings are also referred to as well-graded or continuously graded and are generally expressed by the relationship $P = 100 (d/D)^{1/2}$ where P is the percentage by weight of the aggregate passing or finer than the sieve d, and D is the maximum size of the aggregate. On the other hand, an aggregate is said to be gap-graded (or skip or discontinuously graded) when certain particle sizes in the grading of aggregate are missing. The absence of certain particle sizes can be achieved either by using natural aggregates as they are obtained or by deliberately omitting them to obtain certain desired properties of the mixture.

Various investigators (7, 8, 9, 10, 11) have suggested the following possible advantages of gap-graded asphalt concrete mixtures over continuously graded aggregate mixtures: (a) It may be more economical to produce in some localities; (b) it may allow more asphalt to be used in the mixture, and thus, produce thicker asphalt films and more durable paving mixture; (c) it may have better flexibility, higher fatigue life, and higher value of strain at failure because of higher content of low penetration asphalt; (d) it is more skid resistant; and (e) it may tolerate more asphalt content variations.

On the other hand, the continuous grading has been criticized for at least 3 disadvantages that deserve reexamination. Some countries, such as Japan, that traditionally specify continuous grading for their high-quality asphalt mixtures have already been studying the feasibility of using gap-graded mixtures (5). The major disadvantages of well-graded mixtures are the following: (a) They are more expensive to produce, especially for some states where suitable aggregates sources are depleting and where narrow limits are specified; (b) they are more sensitive to variation of asphalt content change, leading to disintegration or slipperiness (12); and (c) they are difficult to handle and tend to segregate (7).

A large amount of literature, especially theoretical, can be found on the packing of aggregate particles and maximum density or minimum porosity gradings, including the classic work on concrete proportioning by Fuller and Thompson and more recent work on dense asphaltic mixtures by Lees (13). There is also abundant published information on gap-graded concretes as compared to the corresponding continuously graded concretes (14, 15, 16). However, reported data on gap-graded asphalt concrete mixtures are few and scattered.

The purpose of this investigation was to make a comparative study of the gap-graded and the well-graded asphalt concrete mixtures in terms of Marshall and Hveem design methods.

MATERIALS AND PROCEDURES

Eleven aggregate gradations involving 3 maximum sizes, 2 aggregate types, 1 asphalt cement, and a range of asphalt contents were studied.

Four aggregate gradings were examined for ¾ in. maximum size, including one grading following Fuller's maximum density curve and 3 gradings following Fuller's curve but with gaps between ½ in. and No. 4 sieves, between No. 4 and No. 8 sieves, and between No. 8 and No. 30 sieves (Fig. 1). Four aggregate gradings were examined for ½ in. maximum size, including 1 Fuller's curve grading, 2 gradings with gaps between No. 4 and No. 8 sieves and between No. 8 and No. 30 sieves, and 1

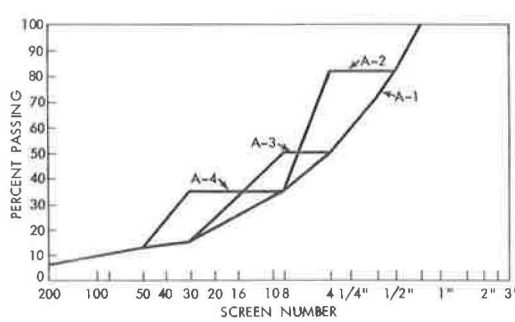

Figure 1. Grading curves for ¾-in. maximum size aggregates.

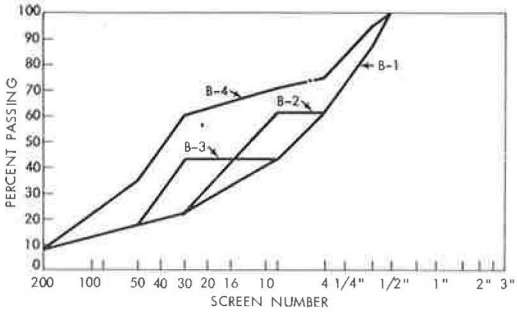

Figure 2. Grading curves for ½-in. maximum size aggregates.

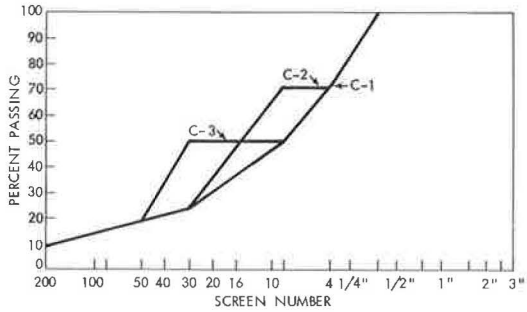

Figure 3. Grading curves for ⅜-in. maximum size aggregates.

TABLE 1

PROPERTIES OF CRUSHED LIMESTONE AGGREGATE

Aggregate	Specific Gravity		Water Absorption (percent)
	Apparent	Bulk	
Menlo, Adair County			
Coarse	2.666	2.542	2.55
Fine	2.654	2.489	2.61
Alden, Hardin County			
Coarse	2.645	2.508	2.91
Fine	2.628	2.514	3.10

TABLE 2

PROPERTIES OF 120 TO 150 PENETRATION ASPHALT CEMENT

Property	Value
Penetration, 77/100/5, dmm	138
Specific gravity	1.023
Flash point, COC, deg F	605
Fire point, COC, deg F	685
Softening point, R and B, deg F	112.0
Viscosity	
140 F, poise	687
77 F, megapoise	0.52
Solubility in CCl_4, percent	99.87
Asphaltenes, percent[a]	15.4

Note: Data supplied by American Oil Company, Sugar Creek, Mo.

[a]Insoluble in 86 to 88 degree petroleum naptha.

grading corresponding to the British Standard 594 (2, 8) (Fig. 2). Three aggregate gradings were examined for ⅜ in. maximum size, including 1 Fuller's curve grading, 1 grading with gap between No. 4 and No. 8 sieves, and 1 grading with gap between No. 8 and No. 30 sieves (Fig. 3).

Two crushed limestone aggregates and one 120 to 150 penetration asphalt cement were used in the investigation. The properties of the aggregates and asphalt are given in Tables 1 and 2 respectively.

Crushed aggregates were first separated by ¾ in., ½ in., ⅜ in., No. 4, No. 8, No. 30, No. 50, and No. 200 sieves. Required weights of each fraction were then combined to produce gradation curves shown in Figures 1 to 3. Twenty-pound batches of asphalt concrete mixtures were made in a 50-lb laboratory pug-mill mixer at asphalt contents from 4 to 9 percent. From each batch of mix, 3 Marshall specimens and 3 Hveem specimens were compacted following standard procedures (17). Maximum theoretical specific gravities of mixtures were determined on duplicate samples by Rice's method using aerosol solution. Bulk density of compacted specimens, Marshall stability and flow, and Hveem stability and cohesiometer values were determined by procedures recommended by The Asphalt Institute.

RESULTS AND DISCUSSION

Marshall Specimens Made With Menlo Aggregates

Results of Marshall specimens made with Menlo aggregates are shown in Figures 4, 5, and 6. Regardless of the maximum aggregate size and where the gap is in the grading, gap-graded mixtures behaved the same way as did the Fuller's curve mixtures.

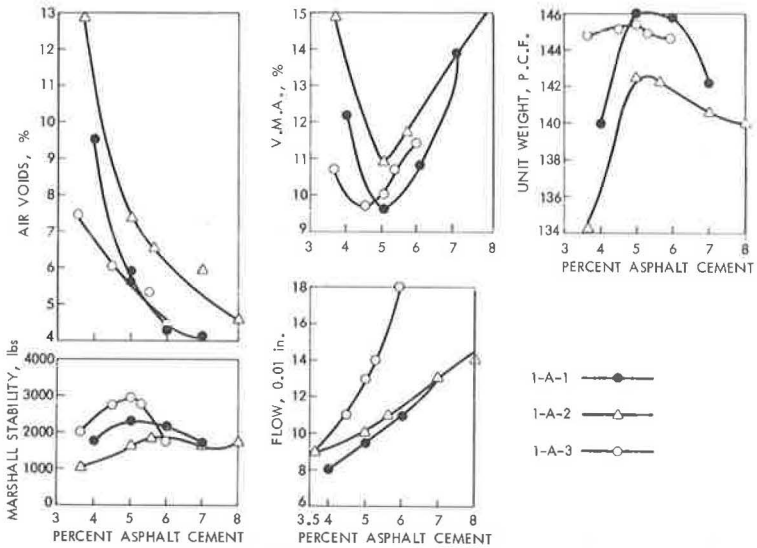

Figure 4. Mixture property curves by Marshall method, $^3/_4$-in. Menlo aggregates.

In all cases, Fuller grading produced mixtures of higher density, the differences between maximum densities being in the order of 1 to 3 pcf. The higher maximum density of Fuller gradings was also reflected in the percentage of air voids; i.e., they produced mixtures of lower voids at respective optimum asphalt contents. However, some of the gap-graded aggregates resulted in mixtures of higher maximum stability (1-A-3 and 1-B-4). Because gap gradings produced mixtures of higher VMA at equivalent asphalt content and stability was very much more than the design criteria of 500 to 750 lb for all mixtures, it was possible to arrive at optimum asphalt contents to meet all design

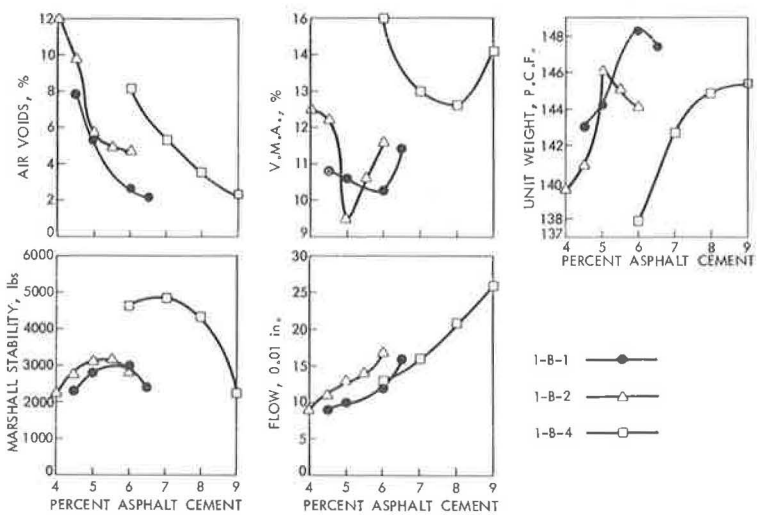

Figure 5. Mixture property curves by Marshall method, $^1/_2$-in. Menlo aggregates.

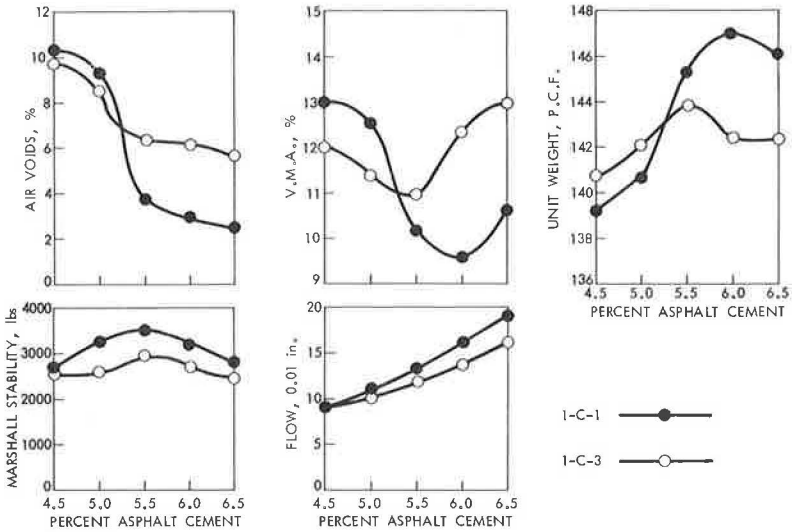

Figure 6. Mixture property curves by Marshall method, $^3/_8$-in. Menlo aggregates.

requirements for gap-graded mixtures. The optimum asphalt contents for gap-graded mixtures were in most cases higher than those for equivalent continuously graded mixtures. In any case, the unnecessary requirement for aggregates to meet the Fuller grading and the advantage of being able to use more binder in gap-graded mixtures (such as in 1-A-2 and 1-B-4) are obvious. Table 3 gives the optimum asphalt contents for all gradings and evaluation of design properties at optimum asphalt contents. Evalua-

TABLE 3

OPTIMUM ASPHALT CONTENT AND PROPERTY EVALUATION BY MARSHALL AND HVEEM METHODS

Mix	Aggregate	Marshall Method					Hveem Method			
		Optimum Asphalt Content (percent)	VMA	Stability	Flow	Voids (percent)	Optimum Asphalt Content (percent)	Stability	Cohesiometer	Voids (percent)
1-A-1	Menlo	5.7	10.3[a]	2,350	11	4.7	5.6	60	250	4.0
1-A-2	Menlo	7.0	13.9	1,600	13	5.3[b]	5.5	52	300	4.0
1-A-3	Menlo	5.7	11.1[a]	2,200	16	4.8	3.8	56	265	4.0
1-B-1	Menlo	5.4	10.5[a]	2,900	10	3.9	4.6	50	228	4.0
1-B-2	Menlo	5.8	11.1[a]	3,000	15	4.7	4.6	64	292	4.0
1-B-4	Menlo	7.5	12.7[a]	4,700	18	4.2	6.0	56	218	4.0
1-C-1	Menlo	5.7	9.7[a]	3,460	14	3.4	5.1	50	236	4.0
1-C-3	Menlo	5.9	12.0[a]	2,800	13	6.0[b]	5.4	55	248	4.0
2-A-1	Alden	5.2	10.6[a]	3,480	12	4.6	4.4	63	415	4.0
2-A-2	Alden	5.3	13.7[a]	4,060	15	6.8[b]	5.5	42	485	5.0
2-A-3	Alden	5.7	14.5	2,980	15	6.6[b]	5.3	53	510	4.0
2-A-4	Alden	5.1	10.0[a]	3,540	9	4.8	4.8	69	325	4.0
2-B-1	Alden	5.2	10.4[a]	4,650	13	4.0	4.9	65	395	4.0
2-B-2	Alden	5.7	12.4[a]	3,800	14	4.0	5.5	60	555	4.0
2-B-3	Alden	6.9	17.0	3,150	10	4.2	6.5	66	265	4.0
2-B-4	Alden	7.5	15.0	3,200	14	5.0	6.0	70	300	4.0
2-C-1	Alden	6.5	18.0	2,900	14	7.5[b]	6.8	35	350	7.0[a]
2-C-2	Alden	6.7	16.6	3,730	11	6.2[b]	7.0	50	345	4.0
2-C-3	Alden	6.8	17.8	2,940	16	4.5	6.2	50	360	4.0

[a]Low. [b]High.

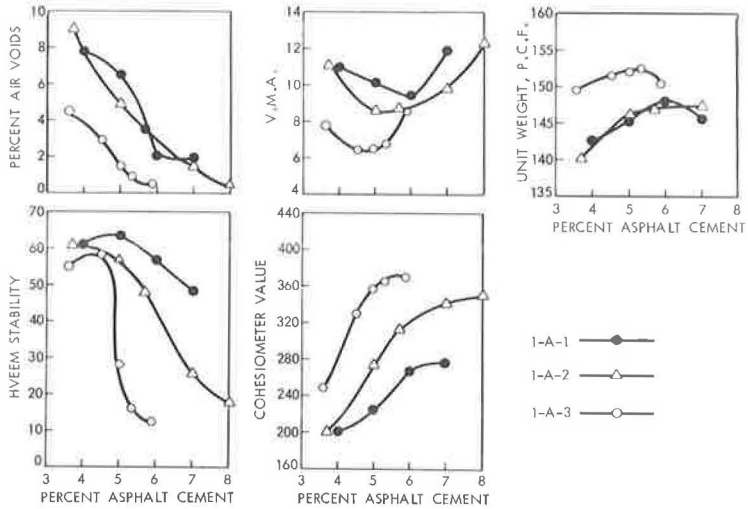

Figure 7. Mixture property curves by Hveem method, $^3/_4$-in. Menlo aggregates.

tion was based on The Asphalt Institute criteria for medium traffic by the Marshall method (17). In nearly all cases, the optimum asphalt contents for gap-graded mixes were higher than those for Fuller gradings and possessed properties equal to or better than the Fuller grading mixtures.

Hveem Specimens Made With Menlo Aggregates

Property curves for Hveem specimens made with Menlo aggregates are shown in Figures 7, 8, and 9. The optimum asphalt contents, determined by criteria recommended by The Asphalt Institute for medium traffic (17), and property evaluation at optimum asphalt contents are given in Table 3. The same statements made for Mar-

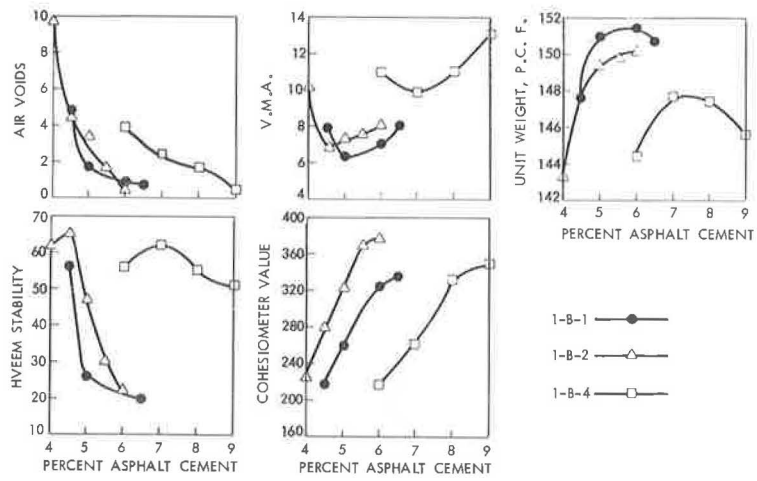

Figure 8. Mixture property curves by Hveem method, $^1/_2$-in. Menlo aggregates.

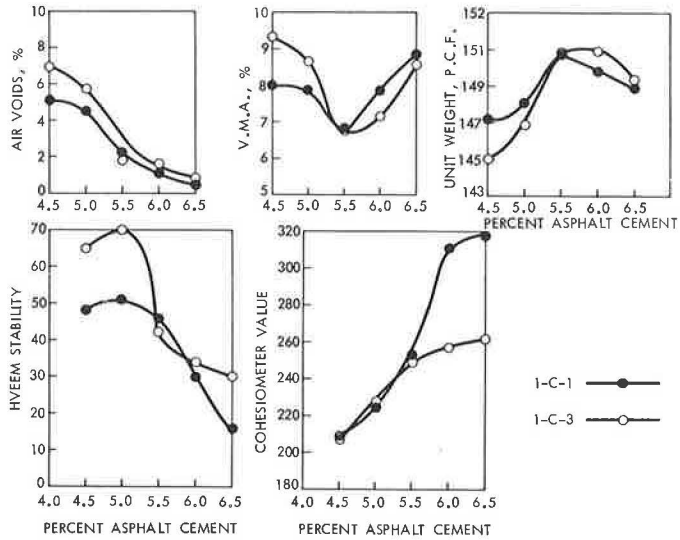

Figure 9. Mixture property curves by Hveem method, $^3/_8$-in. Menlo aggregates.

shall specimens can be made here; that is, mixtures can be made with gap-graded aggregates that are equivalent to or better than those made with Fuller or continuously graded aggregates, except that gap-graded mixtures: may tolerate more asphalt, can be compacted into equal or higher density (1-A-3 and 1-C-3), and may have higher cohesiometer values or tensile strengths and maximum stability values.

Marshall Specimens Made With Alden Aggregates

Figures 10, 11, and 12 show property curves for Marshall specimens made with Alden aggregates. The optimum asphalt contents, based on the criteria for medium

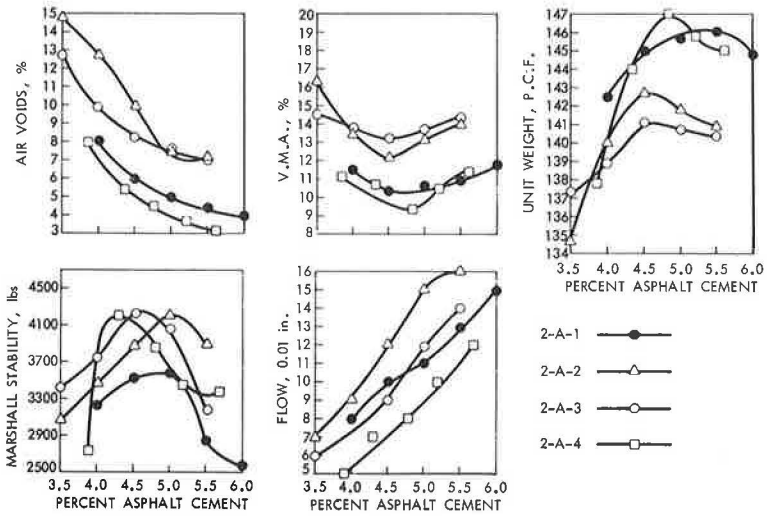

Figure 10. Mixture property curves by Marshall method, $^3/_4$-in. Alden aggregates.

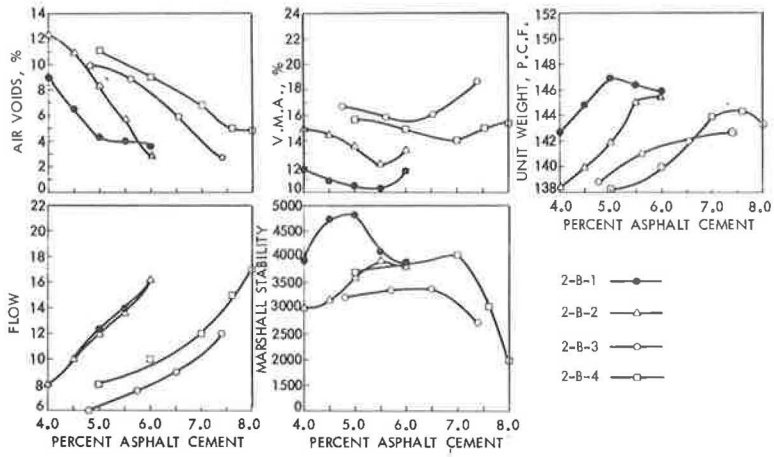

Figure 11. Mixture property curves by Marshall method, ½-in. Alden aggregates.

traffic, were estimated and are given in Table 3. It can be readily seen that all mixtures, continuously graded as well as gap-graded, at their optimum asphalt content satisfied stability and flow criteria and that, with no exception, the optimum asphalt contents for gap-graded mixtures were at higher values than those for the Fuller gradings.

It should be noted that the VMA and air void values were calculated from first principles (17). Because of the high absorption and low bulk specific gravity obtained for the aggregates, calculated volumes of aggregate in specimens could be larger than true volumes, resulting in smaller VMA values. When VMA was calculated as the sum of effective asphalt volume and air voids in a specimen, its value would be somewhat higher, depending on the accuracy of the asphalt absorption determination.

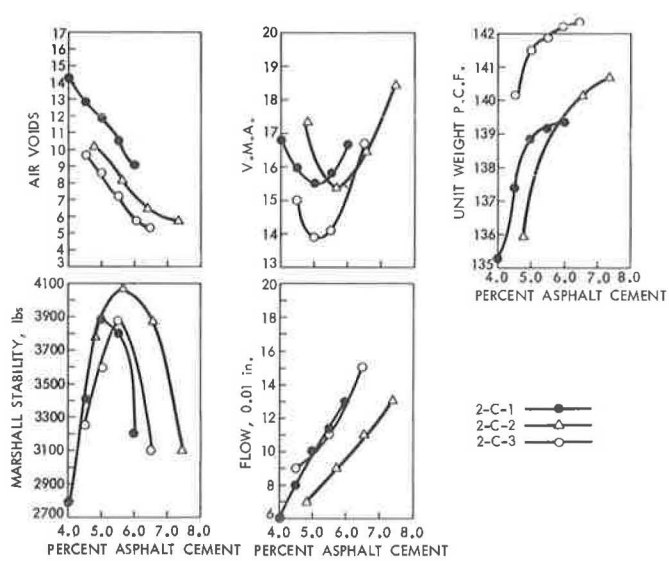

Figure 12. Mixture property curves by Marshall method, ⅜-in. Alden aggregates.

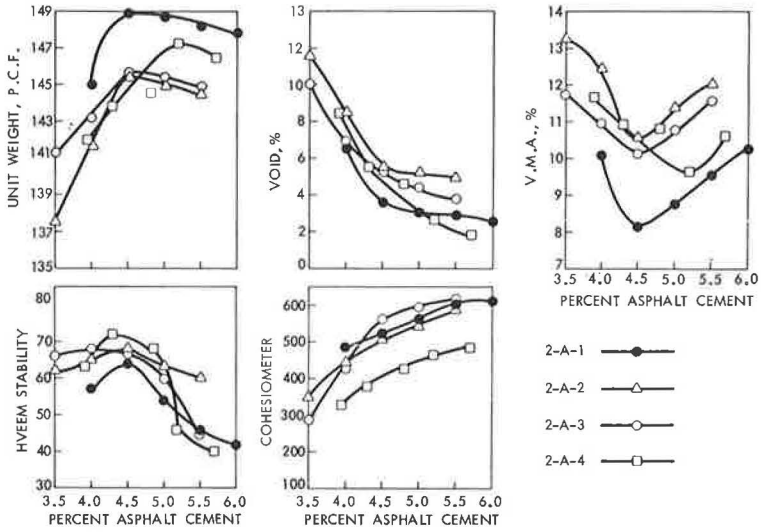

Figure 13. Mixture property curves by Hveem method, $^3/_4$-in. Alden aggregates.

Hveem Specimens Made With Alden Aggregates

Property curves for Hveem specimens made with Alden aggregates are shown in Figures 13, 14 and 15. The estimated optimum asphalt contents for medium traffic and property evaluation at optimum asphalt content are given in Table 3. It can be observed again that all mixtures, both continuously graded and gap-graded, meet design criteria for stability, cohesion, and air voids at optimum asphalt contents and that nearly all gap-graded mixtures could accommodate more asphalt than continuously graded aggregates.

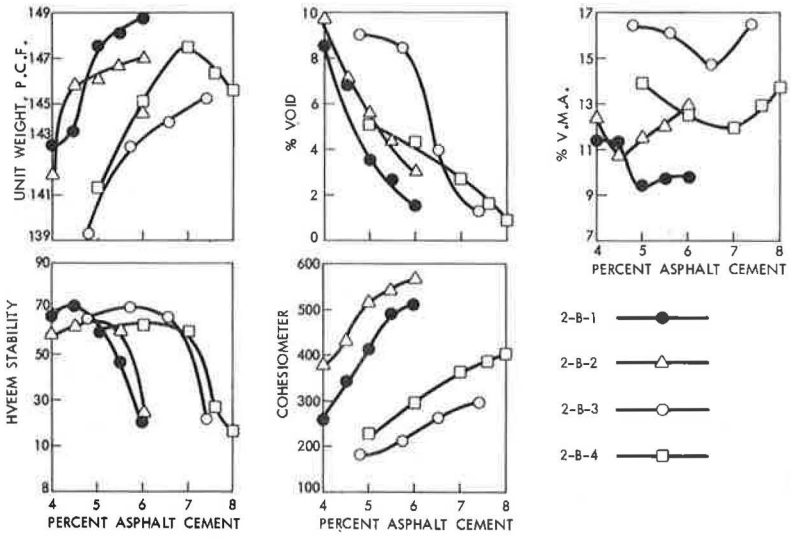

Figure 14. Mixture property curves by Hveem method, $^1/_2$-in. Alden aggregates.

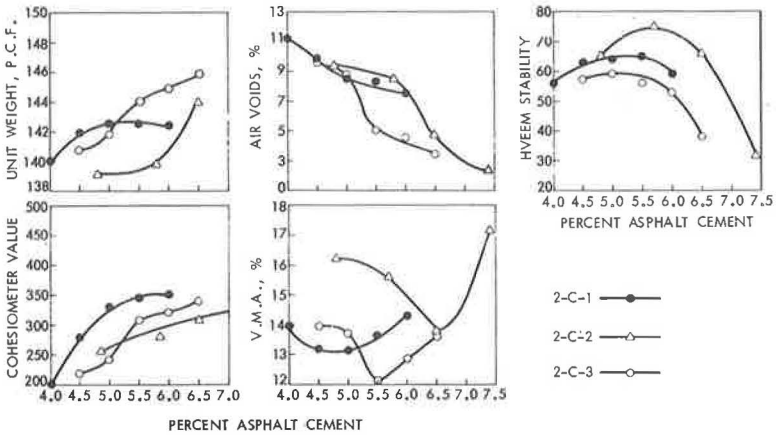

Figure 15. Mixture property curves by Hveem method, $^3/_8$-in. Alden aggregates.

When Hveem specimens of all aggregates, all gradings, and all asphalt contents are compared, the following can be noted: (a) Fuller gradings generally yielded the densest compacted mixtures with lowest voids, except that for $^3/_8$-in. mixtures, both Menlo and Alden aggregates, gradings with No. 8 to No. 30 (0.094 in. to 0.023 in.) gap resulted in highest densities; (b) gradings that produced mixtures of highest density did not necessarily produce mixtures of highest stability or cohesiometer values; and (c) for $^3/_4$-in. and $^1/_2$-in. mixtures, gradings with gap between No. 4 and No. 8 (0.187 in. and 0.094 in.) sieves seemed to give high maximum stability and cohesiometer values. The $^3/_8$-in. aggregates with gap in between No. 8 and No. 30 sieves seemed to give the best mixtures for stability and cohesion.

When all Marshall specimens are compared, the following can be noted: (a) Fuller's gradings gave the densest compacted mixture in most cases and (b) either Fuller's gradings or gradings with gap between No. 4 and No. 8 sieves could produce mixtures of highest maximum stability.

Although outside the scope of this investigation, it was noted with regard to the selection of optimum asphalt content that (a) for certain aggregate types and gradation, the optimum asphalt content determined by Hveem method may not necessarily be the same as determined by Marshall method and (b) with the same gradation and method of design, the optimum asphalt content can be quite different for different aggregate types.

CONCLUSIONS

Ninety asphalt concrete mixtures involving 8 gap gradings and 3 Fuller's maximum density gradings were evaluated in terms of the Marshall and Hveem design methods. The general conclusions that can be drawn within the premises of this investigation are as follows:

1. Mixtures can be designed by either the Marshall or the Hveem method for all aggregates, both continuously graded and gap-graded, to meet recommended design criteria for all relevant properties.
2. Although in most cases the Fuller grading yielded mixtures of highest density, gap-graded mixtures often resulted in better stability or cohesion.
3. With almost no exception, gap-graded mixtures had higher optimum asphalt content than equivalent Fuller graded mixtures.
4. At least for the aggregates studied, rigid requirements for the aggregate to meet Fuller's grading or stringent gradation tolerance control, especially involving additional cost of processing and transportation, may not be justified.

5. The results presented here, though they have shown some of the advantages of gap-graded over continuously graded asphalt concretes, are by no means exhaustive. Additional systematic studies of gap-graded asphalt mixtures are needed to include more aggregate types, asphalt grades, and mechanical and durability properties. Such investigation may result in wider use of gap grading in asphalt aggregates and more economical asphalt paving mixtures in certain areas.

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