Influence of Coarse Aggregate Shape on the Strength of Asphalt Concrete Mixtures

MO C. LI, Associate Professor of Civil Engineering, New York University, and
I. KETT, Associate Civil Engineer, New York State Department of Public Works

The objective of this research was to study the effect of coarse aggregate shape on the strength of asphalt-concrete mixtures. A single, dense-graded, asphalt-concrete paving mixture was used throughout. The test procedures consisted mainly of the Marshall method supplemented by data obtained from the Hveem method. The work performed consisted of a study of the problem and selection of the method for evaluating the strength property of asphalt-concrete mixtures, and a laboratory testing program. The testing program included (a) a study of the influence of particle angularity on Marshall stability, (b) a study of what constitutes a critical particle shape in the coarse aggregate fraction, and (c) a study of the allowable percentage of flat-shaped coarse aggregates that a mixture may contain without adversely affecting its strength.

It was concluded that a close correlation exists between particle angularity index and the Marshall stability. Also, a definite boundary seems to exist with respect to the influence exercised by particle shape. If an asphalt-concrete mixture contains a sufficient proportion of particles, whose width to thickness or length to width equals or exceeds 3 to 1, its strength is adversely affected. Furthermore, the extent by which this ratio is exceeded does not appear to alter the results. For the purpose of this investigation a flat-shaped particle is defined as one that possesses a dimension ratio, in either direction of 3 to 1 or greater.

Furthermore it was concluded that the percentage of flat-shaped particles that may be included without causing undesirable effects upon an asphalt-concrete mixture is as high as 30 percent, and may possibly be 40 percent.

•SECURING high quality aggregates, while still avoiding excessive costs, is a mounting problem in many areas of the United States. At the same time, engineers are faced with the urgent need for economical bituminous paving mixtures that will possess even greater load bearing capacities. This is particularly true because of the increasingly heavier loads to which highways and airport pavements are being subjected. According to a recent survey reported in Circular No. 416 of the Highway Research Board Correlation Service, 37 out of 46 states that responded to a questionnaire stated that they were compelled to downgrade their aggregate specifications; 22 of these states indicated the problem as being moderately serious to serious.

There is, therefore, an important need for extensive research on those characteristics which cause aggregates to be marked "inferior." The challenge of accurately defining the pertinent properties of aggregates as they affect bituminous mixtures opens up broad fields for investigation. Probably the phase of most immediate concern has to

---

Paper sponsored by Committee on Characteristics of Aggregates and Fillers for Bituminous Construction and presented at the 46th Annual Meeting.

do with factors affecting the stability of asphalt-concrete mixtures. Among these are the following:

1. The angularity of both the coarse and fine aggregates.
2. The shape of the individual particles—this differs from the term "angularity" since the latter implies the sharpness of the corners and edges of the particles; thus, geometric solids may have similar shapes yet will differ markedly in angularity.
3. The surface texture of the coarse aggregates and probably that of the fine aggregates as well.
4. The gradation of the aggregates in the mixture.
5. The properties of the mineral filler.
6. Mineral fatigue, degradation, heat absorption and undoubtedly other factors largely overlooked.

In recent years the trend in the design and the specifications for asphalt-concrete mixtures has emphasized measured strength or stability as a criterion of performance. However, there appears to be no consensus as to what constitutes a valid yardstick of strength or stability. Much needed in the field of bituminous mixtures is the development of new laboratory techniques which simulate actual field conditions on the basis of fundamental physical properties.

The original aim of this study concerned itself solely with the effects of flat-shaped particles in dense-graded asphalt-concrete mixtures. The ensuing data showed that particle angularity and surface texture also had to be considered. However, the principal effort has been to isolate particle shape from the other physical properties of aggregate commonly associated with it. Once this was accomplished, it was then possible to try to answer the essential question of the research: How does the shape of coarse aggregate particles influence the strength of asphalt-concrete mixtures?

LABORATORY-STUDY PROGRAM AND PROCEDURES

Special Considerations

The results of tests on 269 specimens are included in this study. The total number of specimens molded and tested was actually much greater because some tests were rerun if the results did not follow a consistent pattern. In a few cases, particular groups were retested several times until either the unexpected nature of the information yielded was verified or the suspicions concerning the reliability of the original results were confirmed.

Materials

The various physical properties of the asphalt cement, aggregates, and mineral filler, together with the applicable ASTM and AASHO specifications are given in Table 1. Type IVb, dense-graded asphalt-concrete mixture, of The Asphalt Institute was used throughout this study.

Methods of Test Evaluation

The procedures as outlined in The Asphalt Institute Mix Design Manual were followed. The Marshall method of mix design was selected as the primary research tool in view of the availability of test data and established design criteria. As an adjunct to the Marshall method, the Hveem method was adopted and the Marshall test data were compared with the Hveem results.

Determination of Particle Angularity

F. A. Shergold's (2) method for the determination of particle angularity was used. Briefly the procedure is based on the computation of the percent of voids in an aggregate-filled cylinder.

$$V = 100\,(1 - W/CP) \tag{1}$$

where

V = voids, %;
W = mean weight of the aggregates in the cylinder;
C = weight of water required to fill the cylinder; the value of C for the cylinder used was 3,255 g.; and
P = apparent specific weight of the aggregate.

The resultant angularity number (AN) is derived from

$$AN = V - 33 \tag{2}$$

The value 33 represents the average voids for very smooth gravel.

Separation of Aggregate Particles by Shape

In the first part of the work it was necessary to sort the already graded aggregates into four basic shapes.

1. Rhombic consisted of aggregate particles with dimension ratios of between 1 and 2.
2. Slightly flat consisted of aggregate particles with dimension ratios of between 2 and 3.

TABLE 1

PHYSICAL PROPERTIES OF MATERIALS

(a) Asphalt Cement	
Sample Order A-193 obtained from the Shell Oil Co. Plant at Sewaren, New Jersey on September 2, 1964.	
Specific gravity, AASHO Designation: T43-54	1.02
Penetration, AASHO Designation: T49-53, ASTM: D5-52 at 25 C, 100 g weight, 5 sec.	94
Saybolt viscosity—AASHO Designation: T72-52, ASTM Designation:	
D88-56	
250 F-300 + sec	
300 F-93 + sec	
275 F-275 + sec	
Ductility at 77 F—AASHO Designation: T51-44; ASTM Designation: D113-44, cm.	150
Solubility in CS_2—AASHO Designation: T-44-60, % Wt.	99.9
Required Marshall mixing and compaction temperature based on Saybolt viscosity:	
Mixing—85 ± 10 sec Saybolt Furol	300 F
Compacting—140 ± 15 sec Saybolt Furol	275 F

(b) Aggregates and Mineral Filler
a. Coarse crushed traprock from New Haven, Conn.; bulk sp. gr. 2.82, apparent sp. gr. 2.93, angularity No. 14, Los Angeles abrasion 18 percent.
b. Fine crushed traprock from New Haven, Conn.; bulk sp. gr. 2.82, apparent sp. gr. 2.96, angularity No. 14.
c. Coarse gravel from Port Washington, N.Y.; bulk sp. gr. 2.59, apparent sp. gr. 2.65, angularity No. 6, Los Angeles abrasion 5 percent.
d. Type II sand from Port Washington, N.Y.; bulk sp. gr. 2.59, apparent sp. gr. 2.65, angularity No. 6.
e. Coarse crushed shale from Kingston, N.Y.; bulk sp. gr. 2.63, apparent sp. gr. 2.72, angularity No. 15, Los Angeles abrasion 21 percent.
f. Fine crushed shale from Kingston, N.Y.; bulk sp. gr. 2.53, apparent sp. gr. 2.72, angularity No. 10.
g. Mineral filler, limestone dust 100 percent passing U.S. Standard Sieve No. 200; apparent sp. gr. 2.54.

3. Flat consisted of aggregate particles with dimension ratios of between 3 and 5.
4. Very flat consisted of aggregates between dimension ratios of 5 and over.

In the second phase of this part of the laboratory work, the aggregates were separated into only two shape classifications.

1. Rhombic, which comprised those aggregate particles with dimension ratios between 1 and 3.
2. Flat, which comprised those aggregate particles with dimension ratios of 3 or greater.

In both cases only three sizes were segregated by shape: those retained on the No. 4, ⅜ in., and ½ in. U. S. Standard Sieve sizes. The same number of specimens were tested under the two and the four shape ratios. As shown in Figures 5 and 6, the percentage of flat-shaped particles in the specimens varied between 0 percent and 100 percent in increments of 20 percent. This increment was developed empirically, since smaller increments did not yield any appreciable differences in the results.

ANALYSIS OF RESULTS

Influence of Fundamental Aggregate Properties on Marshall Stabilities

Before the actual start of the laboratory work, it was thought possible to study the effects of particle shape by making use of aggregates of different characteristics. This was the classical approach to the problem (3, 4). It was only at a later date that sufficient laboratory evidence was obtained which confirmed the conclusion that this initial method was unworkable for the purposes of this study. A comparison of the test results between the Esopus shale series and the traprock series was quite unexpected. The discrepancy between the original premise and the data obtained was so great, that a substantial part of both groups was retested. When the second set of data confirmed the findings in the first, the entire problem was reevaluated in the light of other physical properties. The two which came in for the most careful consideration were surface texture and angularity. While other investigators (5) have voiced the opinion that surface texture is of very great importance in this overall area, no recognized procedure has yet been developed for quantitatively evaluating this property.

However, it was found possible to define mathematically the property of angularity by reference to the index method that was developed by Shergold (2). The relationship found to exist between this angularity index and the maximum Marshall stability turned out to be a very consistent one. The results are summarized in Figures 1 and 2. In order to determine the best-fit curve, a statistical analysis (6) was made (Tables 2 and 3). The results also indicate that both coarse and fine aggregates contributed to the Marshall stability in direct proportion to their weight in the mixture. Type IVb dense-graded mix, which was used throughout this investigation, consisted of 57½ percent coarse aggregate, 35½percent fine aggregate, and 7 percent mineral filler. In evaluating the angularity index number, the resultant composite index number for a mixture was based on the weighted average angularity in accordance with the following formula:

$$AN_{ag} = \frac{P_{ca} + P_{fa}}{\dfrac{P_{ca}}{AN_{ca}} + \dfrac{P_{fa}}{AN_{fa}}} \tag{3}$$

where

P_{ca} = coarse aggregate, %;
P_{fa} = fine aggregate, %;
AN_{ca} = angularity number of coarse aggregate; and
AN_{fa} = angularity number of fine aggregate.

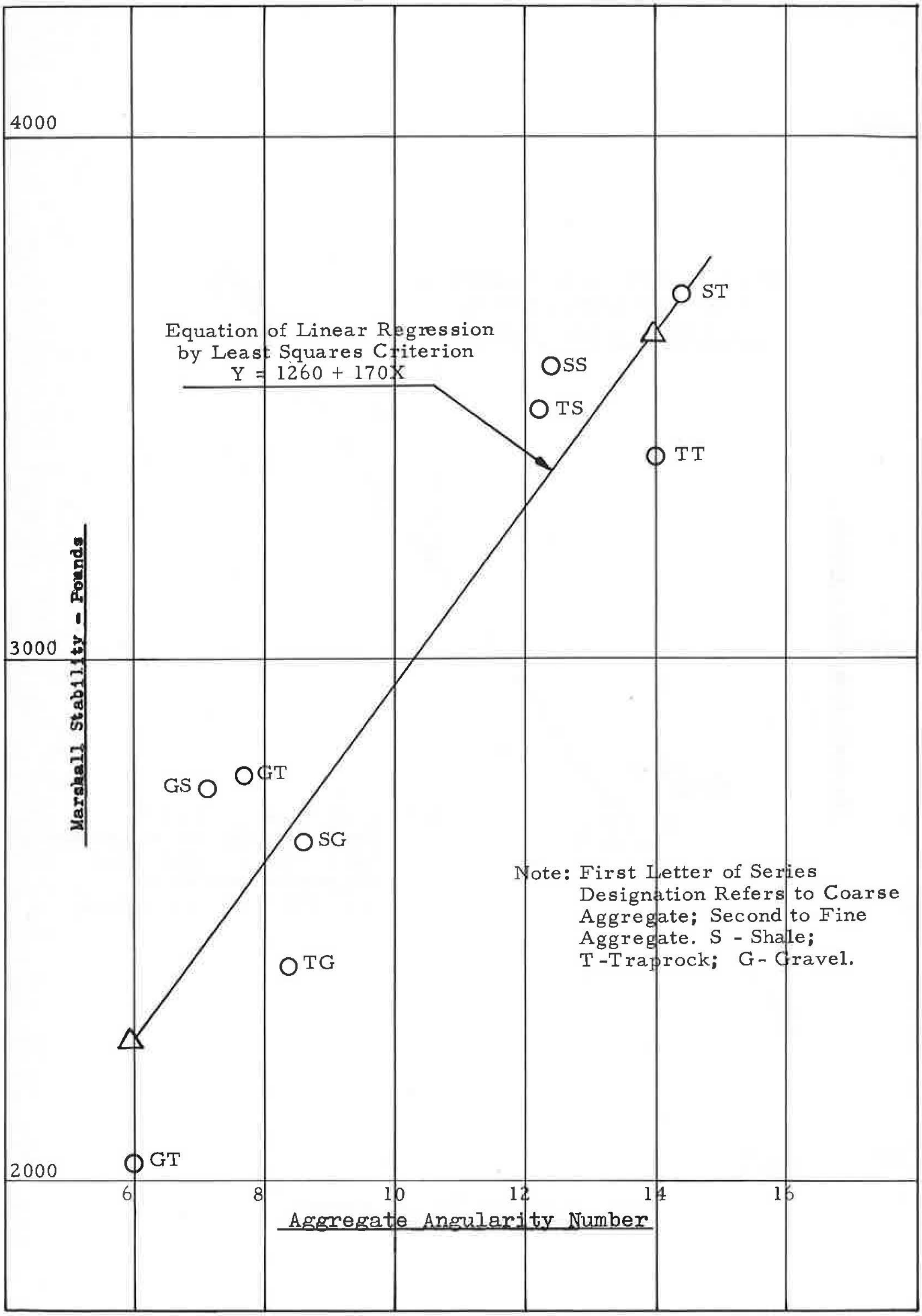

Figure 1. Aggregate angularity vs maximum Marshall stability linear regression.

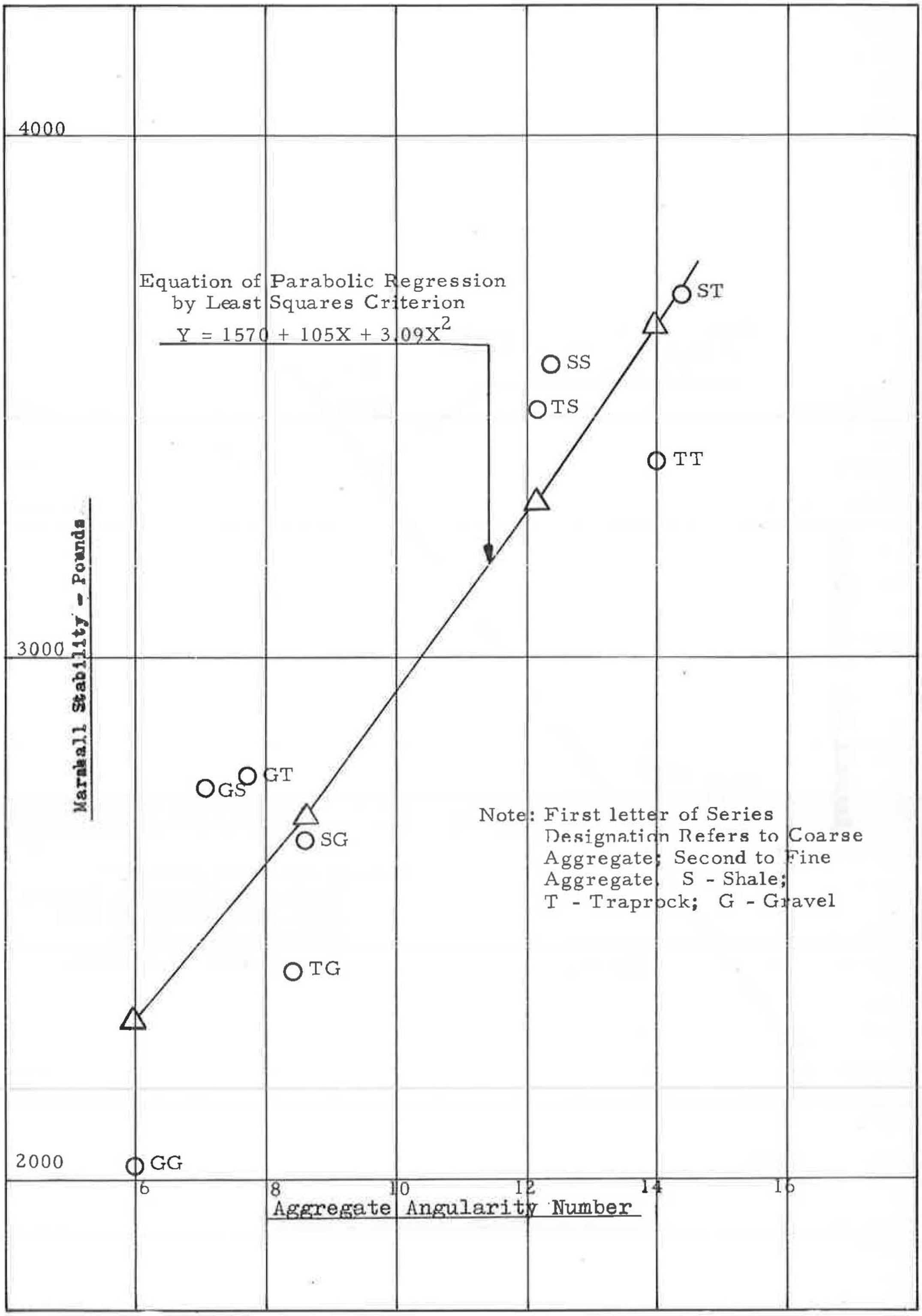

Figure 2. Aggregate angularity vs maximum Marshall stability parabolic regression.

TABLE 2

CORRELATION COEFFICIENTS OF THE LINEAR REGRESSION
$(Y = 1260 + 170 X)$

Series	Composite Angularity Number X	Maximum Marshall Stability		$Y - \bar{Y}$	$Y_1 - \bar{Y}$	$\frac{(Y - \bar{Y})^2}{10^3}$	$\frac{(Y_1 - \bar{Y})^2}{10^3}$	$\frac{(Y - Y_1)^2}{10^2}$
		Actual Y	Computed Y_1					
TT	14.0	3380	3630	410	660	168	435	625
TS	12.2	3480	3330	510	360	260	130	225
TG	8.4	2410	2680	-560	-290	312	84	730
SS	12.4	3560	3360	590	390	346	151	400
ST	14.4	3700	3700	730	730	530	530	00
SG	8.6	2650	2720	-320	-250	102	63	49
GG	6.0	2030	2280	-940	-690	880	475	625
GS	7.1	2750	2460	-220	-510	48	260	840
GT	7.7	2770	2560	-200	-410	40	168	440
Summation		26730 $\bar{Y} = 2970$				2686	2296	3934

Coefficient of determination $= \frac{\Sigma(Y_1 - \bar{Y})^2}{\Sigma(Y - \bar{Y})^2} = 0.855$

Coefficient of correlation = square root of the coefficient of determination = +0.927

TABLE 3

CORRELATION COEFFICIENTS OF THE PARABOLIC REGRESSION
$(Y = 1570 + 105 X + 3.09 X^2)$

Series	Composite Angularity Number X	X^2	Maximum Marshall Stability		$Y - \bar{Y}$	$Y_1 - \bar{Y}$	$\frac{(Y - \bar{Y})^2}{10^3}$	$\frac{(Y_1 - \bar{Y})^2}{10^3}$	$\frac{(Y - Y_1)^2}{10^2}$
			Actual Y	Computed Y_1					
TT	14.0	196	3380	3640	410	670	168	450	675
TS	12.2	148	3480	3310	510	340	260	115	290
TG	8.4	70	2410	2670	-560	300	312	90	675
SS	12.4	154	3560	3350	590	380	346	144	440
ST	14.4	207	3700	3710	730	750	530	560	1
SG	8.6	74	2650	2700	-320	270	102	73	25
GG	6.0	36	2030	2310	-940	660	880	430	325
GS	7.1	50	2750	2470	-220	500	48	250	780
GT	7.7	59	2770	2560	-200	430	40	184	440
Summation			26730 $\bar{Y} = 2970$				2686	2296	3650

Coefficient of determination $= \frac{\Sigma(Y_1 - \bar{Y})^2}{\Sigma(Y - \bar{Y})^2} = 0.855$

Coefficient of correlation = square root of the coefficient of determination = + 0.927

These findings are at variance with those of several other investigators who also used the Marshall test as a basis for their results. Wedding and Gaynor (4) concluded that in the fine aggregate fraction, the particle shape had only a minor effect on stabilities. On the other hand, Lottman and Goetz (7) and Griffith and Kallas (8) arrived at the opposite conclusion; that is, that the effect of fine aggregate on the stabilities of asphalt-concrete mixtures exceeds in importance a like weight of coarse aggregate. The findings in this study, therefore, seem to fit between these two divergent views.

Influence of Flat-Shaped Coarse Aggregate Particles

The results for this portion of the investigation are summarized in Figures 3, 4, 5, and 6.

The research of Puzinauskas (9) proved to be of considerable significance for this study in several ways. It was especially valuable in helping to answer the question about particle-shape ratios in the area of the finer particle sizes. Only particles retained on the No. 4 sieve were separated according to shape. The smaller sizes require the use of a microscope, which is a very time-consuming technique (10). However, Puzinauskas' paper showed that particle alignment becomes much less pronounced as aggregates are graded from coarse to fine. In other words, particle shape loses much of its significance in the fine aggregate fraction. He uses the term "aggregate structure index" to define the ratio of compressive strength in the direction parallel to compaction to the compressive strength in the direction perpendicular to compaction. An index value of unity would indicate a thoroughly random particle alignment. A value of less than one would signify that the long axes of the aggregate particles were aligned parallel to the compactive effort. This, of course, never happened. The converse was always the case; that is, the index was in every case greater than unity. In a mixture, where the maximum size particle was $\frac{3}{4}$ in., as is true in all of the test specimens, the structure index was approximately 3.5. For an asphalt-concrete mixture, where the maximum size particles all passed the No. 8 sieve, this index was approximately 1.3. Except for gradation, all other conditions such as type of aggregates for the above tests were identical.

Critical Percentage of Flat-Shaped Particles

Once a definition had been established as to what constituted a flat-shaped particle, namely one whose dimension ratios equaled or exceeded 3 to 1, the next research objective was to determine what percentage of flat-shaped particles would be harmful to the mixture, and another series of tests was conducted. The results are shown in Figures 5 and 6. The particles retained on the No. 4 sieve were separated into only two shape classifications: non-flat (dimension ratios of < 3) and the flat (dimension ratios of ≥ 3).

The test results were not nearly as definitive as in the previous research objective which established the dimension ratios of a flat-shaped particle. This is true concerning the results within either the Marshall or Hveem test series and when comparing the two series. With respect to any differences due to the use of two different aggregates at two specific asphalt contents, it is quite evident that no definable pattern resulted from these factors. Three of the four test groupings tested by the Marshall method showed a definite break in the curve between 40 percent and 60 percent flat-shaped particles (Fig. 5). Even in the case of the traprock group at 5 percent AC, the stability of the mixture containing 40 percent flats almost equaled that with 0 percent flats. The Marshall test would, therefore, indicate that an asphalt-concrete mixture may contain up to 40 percent flat-shaped particles without the stability of the mixture being impaired.

The pattern of results obtained with the Hveem stabilometer (Fig. 6) is not as conclusive. The two groups tested at 5 percent AC both show a definite break between the 20 and 40 percent content of flat-shaped particles. The traprock at 4 percent AC shows a decisive break between 40 and 60 percent flats, while the Esopus shale maintains an almost consistent drop-off from the point of 0 percent flat-shaped particles.

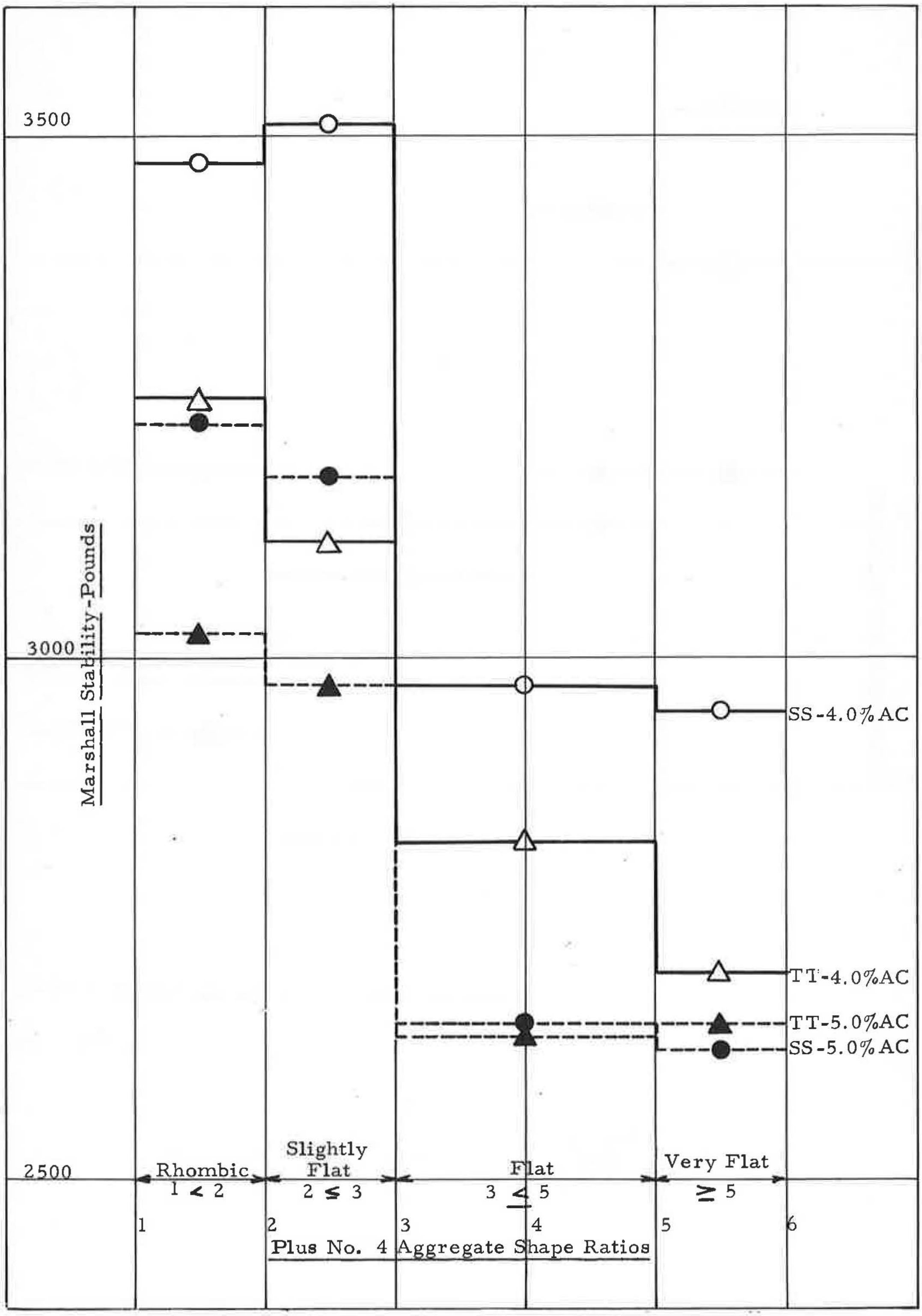

Figure 3. Aggregate shape vs Marshall stability.

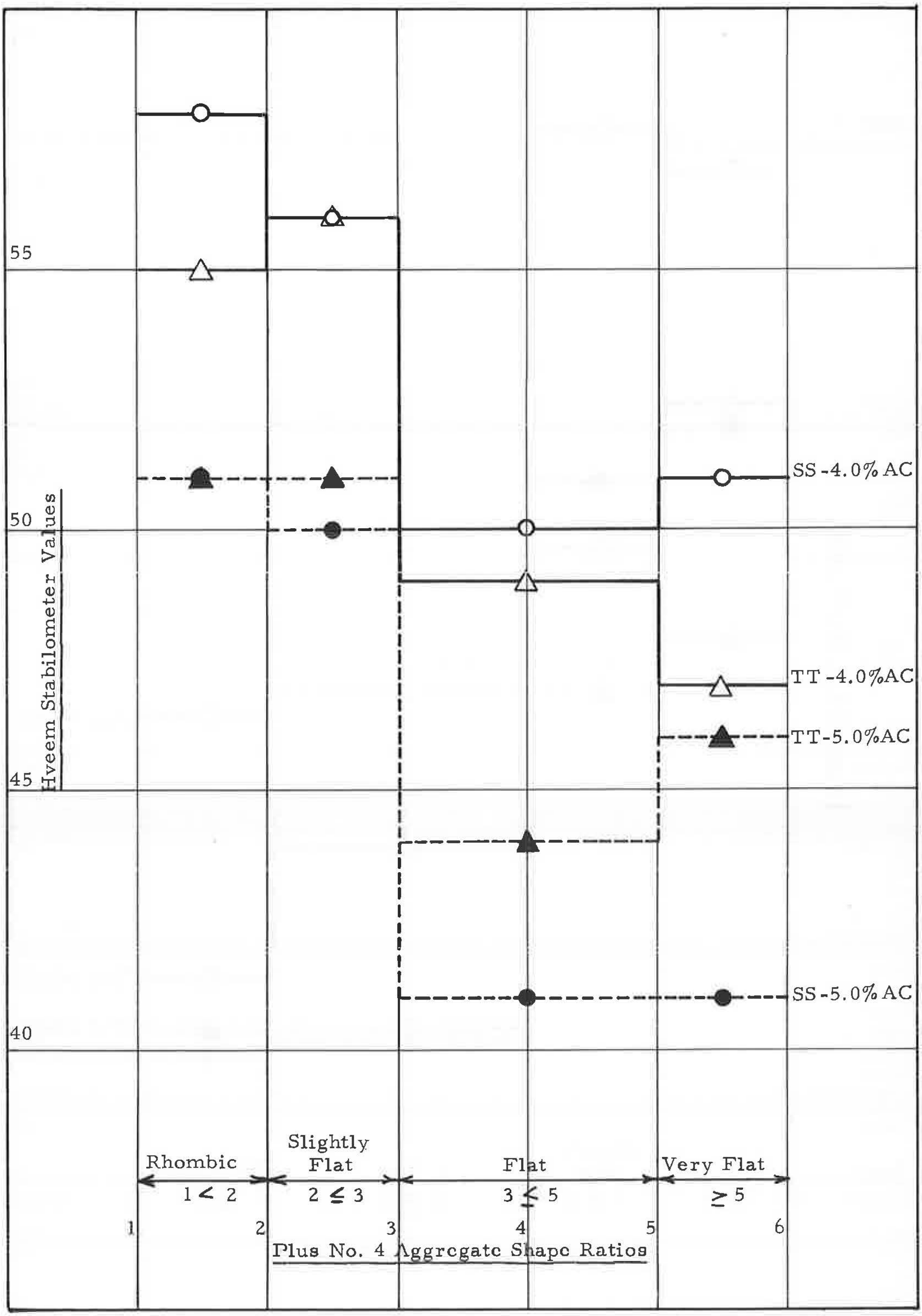

Figure 4. Aggregate shape vs Hveem stability.

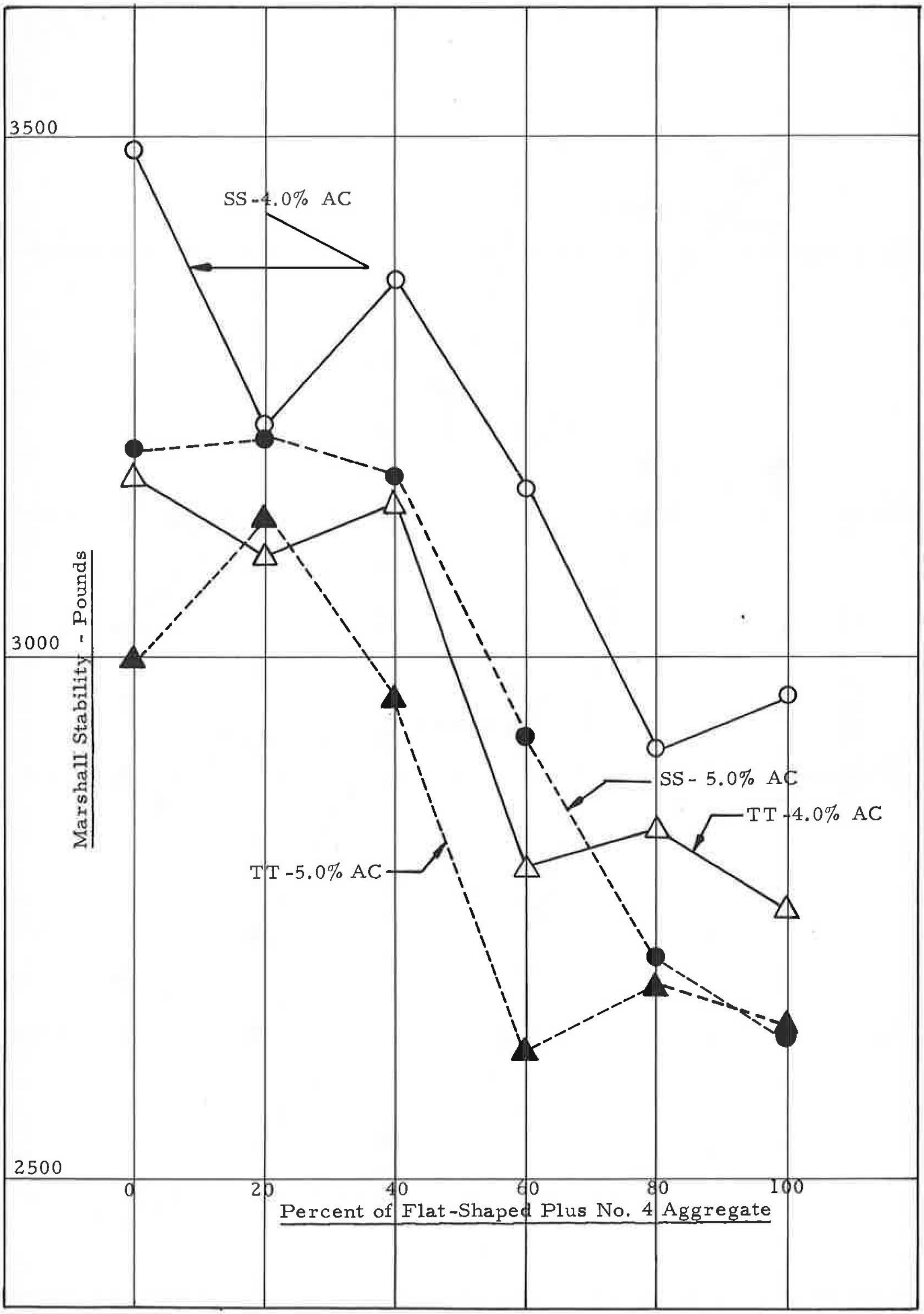

Figure 5. Composite aggregate shape vs Marshall stability.

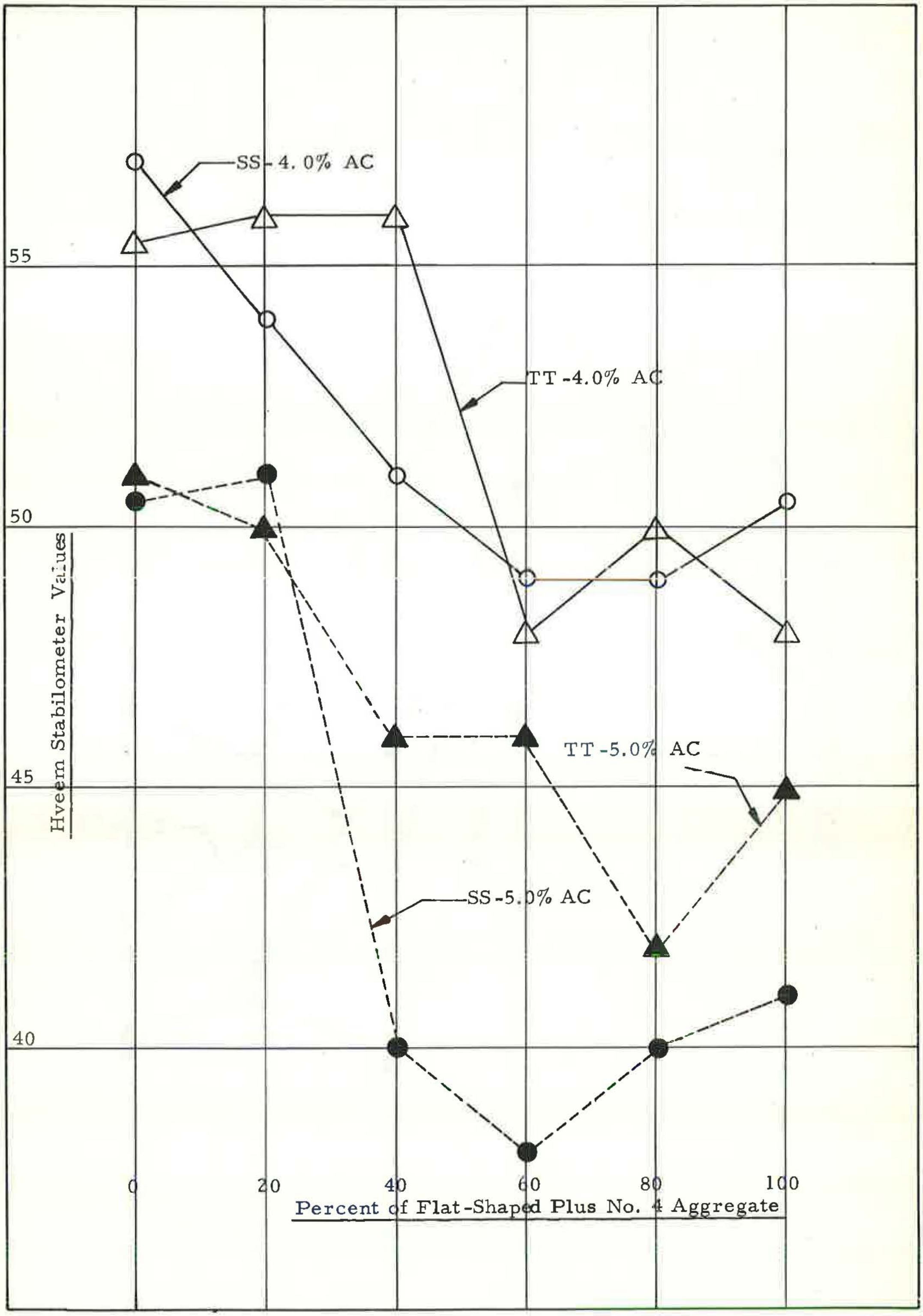

Figure 6. Composite aggregate shape vs Hveem stability.

Therefore, one is safe in concluding that in 3 out of the 4 groups tested, the Hveem stabilities dropped off when the percentage of flat-shaped particles in the mixture exceeded 20 percent.

CONCLUSIONS

The aim of this laboratory investigation was to study the manner in which certain commonly associated properties of aggregates influence the stability of asphalt-concrete mixtures. The properties referred to are angularity, shape, and surface texture. The test procedures were carried out in three distinct phases. In the first, angularity was held as the independent variable. During the course of phases 2 and 3, the particle shape was carefully maintained as the independent variable. In all three phases, stability was the dependent variable. The third physical property, surface texture, could not be considered except by inference.

The first phase involved a series of nine different aggregate combinations used to establish the relative importance of certain physical properties of aggregates on the stability of dense-graded asphalt-concrete mixtures. Three representative aggregates were used in both the coarse and fine fractions. The same mixture gradation was used for all nine groups of tests with the Marshall method of mix design as the testing procedure.

1. A close relationship was found to exist between the maximum Marshall stability and the composite aggregate angularity index as developed by Shergold. Using the least squares method and a digital computer, a set of equations was developed to express this relationship. The most appropriate regression for the laboratory data was found to be

$$Y = 1260 + 170X \tag{4}$$

where Y represents the maximum Marshall stability and X the particle angularity index. The coefficient of determination is 0.855, which is indicative of a fairly high degree of correlation.

2. This correlation was determined from a composite aggregate index to which both the fine and the coarse aggregates contributed in direct proportion to their respective weights in the mixture. The particle angularity in one fraction is as important as in the other.

3. Surface texture, whose importance was determined only by inference, was found not to exert a significant influence on the stability of asphalt-concrete mixtures if the mixture is at or above optimum asphalt content, and the aggregates possess good hydrophobic characteristics. At present there is no recognized technique for evaluating surface texture quantitatively.

The second and third phases developed basic research data for measuring the influence of flat-shaped coarse aggregate particles on asphalt-concrete stabilities. However, before this could be accomplished it was necessary to isolate shape from angularity and surface texture. The method chosen was to use the same aggregate for all the shapes considered in each of the four separate groups of tests. This was accomplished by physically separating all the aggregates that were larger than the No. 4 sieve size by use of a proportional caliper (11). Two different aggregates were used, each of two asphalt-cement contents. The four groups were then tested with both the Marshall apparatus and the Hveem stabilometer.

The objective was attained in two successive steps.

1. The coarse aggregates were separated into four shape categories, rhombic, slightly flat, flat, and very flat. The findings were conclusive, with the Marshall and the Hveem tests in almost perfect agreement. Particle shape had no harmful effect on asphalt-concrete stabilities as long as the dimension ratios (the width to the thickness or the length to the width) were less than 3 to 1. Once this condition was reached, it did not seem to matter by how much the ratio of the degree of flatness or elongation was exceeded. In other words, the particles with a 4 to 1 dimension ratio were no

more desirable than those with a 5 to 1 ratio. Insofar as the term flat when it refers to aggregate shape connotes an undesirable physical property, it may be defined as having a shape in either direction of 3 or more. Thus, in this second phase, the investigator determined what constitutes a flat-shaped particle.

2. Phase 3 sought to determine what percentage of flat-shaped particles could be contained in an asphalt-concrete mixture without reducing its stability. The No. 4 particles were separated into only two shape classifications, non-flat and flat. Test results were not nearly as definitive as in phase 2; however, they indicate that the permissible percentage of flat and/or elongated-shaped particles that could be permitted in a mixture without adverse effect on its strength is 30 percent and that this figure may possibly be increased to 40 percent.

ACKNOWLEDGMENT

This paper is based on a thesis submitted by Irving Kett to the School of Engineering and Science in partial fulfillment of the requirements for the degree of Doctor of Engineering Science at New York University.

REFERENCES

1. Mix Design for Asphalt Concrete and Other Hot-Mix Types. The Asphalt Institute, 2nd Ed., May 1963.
2. Shergold, F. A. The Percentage Voids in Compacted Gravel as a Measure of Its Angularity. Magazine of Concrete Construction, Vol. 5, No. 13, p. 3, 1953.
3. Herrin, M., and Goetz, W. H. Effect of Aggregate Shape on Stability of Bituminous Mixes. HRB Proc. Vol. 33, pp. 293-308, 1954.
4. Wedding, P. S., and Gaynor, R. D. Effect of Using Crushed Gravel as the Fine and Coarse Aggregate in Dense Grade Bituminous Mixtures. National Sand and Gravel Association, Circular 87, 1961.
5. Vallerga, B. A., Seed, H. B., Monismith, C. L., and Cooper, R. S. Effect of Shape, Size and Surface Roughness of Aggregate Particles on the Strength of Granular Materials. ASTM Special Publication No. 212, 1957.
6. Ezekiel, M., and Fox, K. A. Methods of Correlation and Regression Analysis. Section II, 3rd Ed., John Wiley and Sons, Inc., New York, 1959.
7. Lottman, R. P., and Goetz, W. H. Effect of Crushed Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures. National Sand and Gravel Association, Circular No. 63, March 1956.
8. Griffith, J. W., and Kallas, B. F. Influence of Fine Aggregate on Asphaltic Concrete Paving Mixture, HRB Proc. Vol. 37, pp. 219-255, 1958.
9. Puzinauskas, V. P. Influence of Mineral Aggregate Structure on Properties of Asphalt Paving Mixtures. The Asphalt Institute, Jan. 1964.
10. Method of Test for Flat and Elongated Particles in Coarse Aggregates. CRD-C119-55, Concrete Research Division, Waterways Experiment Station, U. S. Army Corps of Engineers, Jackson, Miss., 1955.
11. Method of Test for Flat and Elongated Particles in Coarse Aggregate. CRD-C119-53, Concrete Research Division, Waterways Experiment Station, U. S. Army Corps of Engineers, Jackson, Miss., 1953.