Final Report

EFFECT OF AGGREGATE SHAPE ON BITUMINOUS MIX CHARACTER

by

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LIST OF ILLUSTRATIONS

EFFECT OF AGGREGATE SHAPE ON BITUMINOUS MIX CHARACTER

Introduction

There has long been question as to the effect of shape on the character and use of aggregates. Water deposited gravels are well rounded while crushed aggregates are of various angular shapes. Traditionally, specifications have had a limit concerning flat, elongated or otherwise deleterious material. The assumption being that flat and elongated particles are detrimental in some way to mixing, compaction, stability or other characteristics of paving material.

Of course, an economic factor must be considered in that the sorting of particle shapes to meet whatever content is ideal could well be expensive. Studies to control the shape of crusher products cannot be justified unless the shape of particle is proven of importance. There are long recognized crushing principles used in ore reduction that could make shape control possible. Type of crusher and reduction factor affect both cost and shape of product. For some crushes a reduction in the size reduction factor sharply lowers the percentages of both flat and elongated pieces and may be accompanied by a decrease in production costs. Two crushers with reduction factors of four in series can handle more material than two with factors of sixteen in parallel and result in much less dust and undersize material.

Since ways can be visualized for controlling shape, this study was undertaken to determine if shape of aggregate is of significance in the use of bituminous paving material. Possible areas affected are stability, voids, density, required asphalt content, and durability. The first three can be measured or computed for laboratory mixes. The effect on the latter two can be surmised from the first three.

Study Procedure

Three tons of trap rock were obtained and passed through a three-inch laboratory crusher. No precautions as to reduction factor, jaw settings, or rate of feed were taken other than those needed to insure a full range of particle sizes. The crusher output was sieved and each fraction hand sorted for shape. All particles were placed in one of three shape categories. The shape divisions were 1) equidimensioned, 2) flat, two large dimensions and one small, and 3) rod, two small dimensions and one large. For the latter two classifications, the single dimension was less than one third and more than three times the next closest one, respectively. For practical reasons, the dimensions could only be visually estimated during this sorting. As a check on the procedure, a sample of each size aggregate was processed by each sorter and the percentages of shapes found compared. It was anticipated that the difference would be greater as the size decreased. This did not prove true as only 2-3 percent difference appeared at any size. Only the coarse aggregate, that above the number eight sieve, was sorted. Natural sand was used for all sizes finer than the number eight sieve and though unsorted remained a constant through the test program.

A commercial 85-100 pen asphalt was secured in quantity sufficient for the entire program. An aggregate gradation in the center of the Connecticut Department of Transportation Gradation specification band was selected. The weights necessary for a 2 1/2 inch high by a 4 inch diameter sample of typical aggregate under the compaction to be used were determined by trial (Table I). As the blend of aggregate shapes was varied, it was

Table I, Aggregate Gradation

Sieve Size	Percent Passing
3/4 "	100
3/8 "	84
#4	62
10	42
20	28
40	18
100	10
200	5

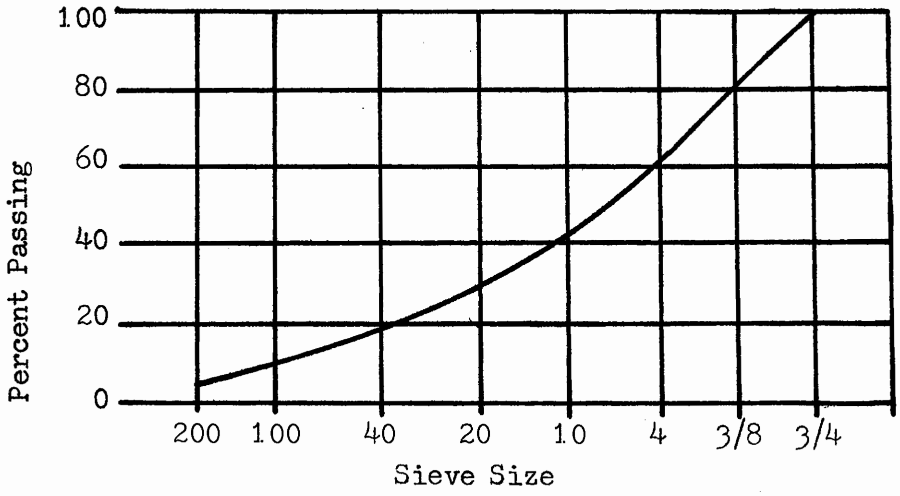


Figure 1, Gradation Curve

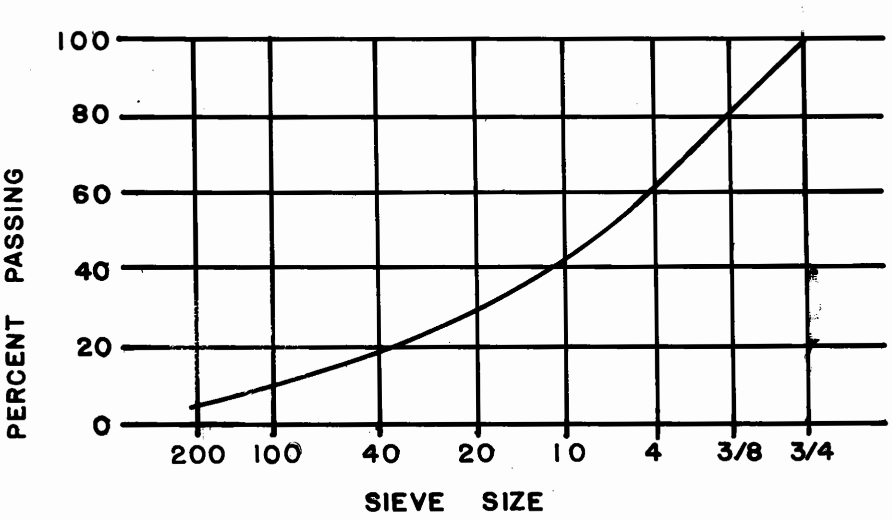


FIGURE I GRADATION CURVE

expected that the weights would not result in exact 2 1/2 inch specimens. All samples were compacted with an air-hydraulic kneading compactor.

Exact asphalt contents were difficult to control by the amount of asphalt added to the mix. In mixing small batches, a disproportionate amount of asphalt is left on the equipment. As a consequence, an allowance was made in the asphalt used and extractions made on the test samples after all other tests were complete in order to define the actual contents. A range of asphalt from 5.5 to 6.5 percent was intended.

As the work progressed, it became apparent that density was the most difficult factor to measure accurately. This was due to difficulties in measuring the sample volume. The maximum material density was, as expected, found by the Rice method, ASTM D-2041. This method very closely approaches the computed density based on aggregate and asphalt densities and quantities. As the test is performed on uncompacted material, voids natural at normal compaction are not included. Rice density should be slightly less than the computed density if aggregate density for calculations was found by uncorrected weight of aggregate in water.

A bulk density or unit weight was found by 'weight of sample in water' method. The simple assumption used is that loss of weight when weighed in water is equal to the buoyancy due to volume. The volume thus used is that impermeable to water. As would be expected, this unit weight and the Rice density were similar for high asphalt contents, but separated sharply at low asphalt. To offset this effect, density was also found by loss of weight when weighed in water of a saturated sample, ASTM test method D-2726. It was nearly impossible to keep the more open samples saturated for weighing and this method was abandoned.

The best results were obtained for bulk densities by the general method of ASTM D-1188, but with the substitution of a plastic coating for paraffin.

Ordinary plastic-bag food packaging was used. Each sample was placed in a plastic bag, a vacuum applied to pull the bag tight to the sample, and a closure clamped around the neck. After the surplus bag material was cut away, the sample thus encased was weighed in water. A correction for the bag and closure was used as in the paraffin method. Unit weights so determined were found more representative of the compacted samples and were used for calculation of void content.

Stability tests followed ASTM method D-1560 with minor timing adjustments. When 20 hours old, density tests were started. Sequence of steps was:

- Weigh sample
- Plastic wrap
- Weigh in water
- Remove plastic and saturate
- Weigh saturated sample
- Weigh saturated sample in water
- Bring to stability-test temperature
- Stability test in Hveem stabilometer

Samples were thus tested for stability at an age of 24 hours.

- Determine Rice density
- Dry sample and make extraction for asphalt content

Discussion of Test Results

For clarity, the variation in density with asphalt content was plotted for each blend of aggregate shape. Within the accuracy of the measurements, maximum mix density calculated from the densities of the aggregate and of the asphalt decreases linearly with increasing asphalt content. As these calculations assume no voids, increased asphalt must displace aggregate and would result in lower density.

Rice density of maximum experimental density also decreases with increased asphalt content. For most blends, the Rice density is always two or three lbs. per cubic foot less than the calculated maximum density. There is a trend for the difference to decrease with increasing asphalt content but several blends show a strong increase with asphalt content. Apparently, an unexplained variable was encountered. That the two are different should be expected, as the calculated density was based on a density for the aggregate computed from volumes uncorrected for permeability to water. That is, internal aggregate voids permeable to water were not considered part of the aggregate volume. Thus, calculations for maximum density assumes all such voids are available to be filled with asphalt. The trap rock used has ± 1.5% of small uniformly distributed voids largely impermeable to asphalt. Even though the molded sample is broken up for the Rice test, the asphalt coating seals the aggregate surface and prevents water from penetrating the aggregate pores. Thus, the Rice density should be lower than the calculated density.

As neither the calculated nor the Rice density reflect compaction, both are only estimates of potential character. Stability and durability are not direct functions of either. One of the two densities must be used in computing voids.

The bulk density, hereafter referred to as unit weight and determined frequently by coating the samples, demonstrates an optimum within the test range of asphalt content, (See Fig. 2). At 5.5% asphalt in the compacted condition, substantial voids in the mineral aggregate remain unfilled with asphalt. Thus, the addition of asphalt fills a greater portion of these voids. Further increases in asphalt may fill additional voids, but simultaneously thicken the films at aggregate contact points thus increases voids between the mineral

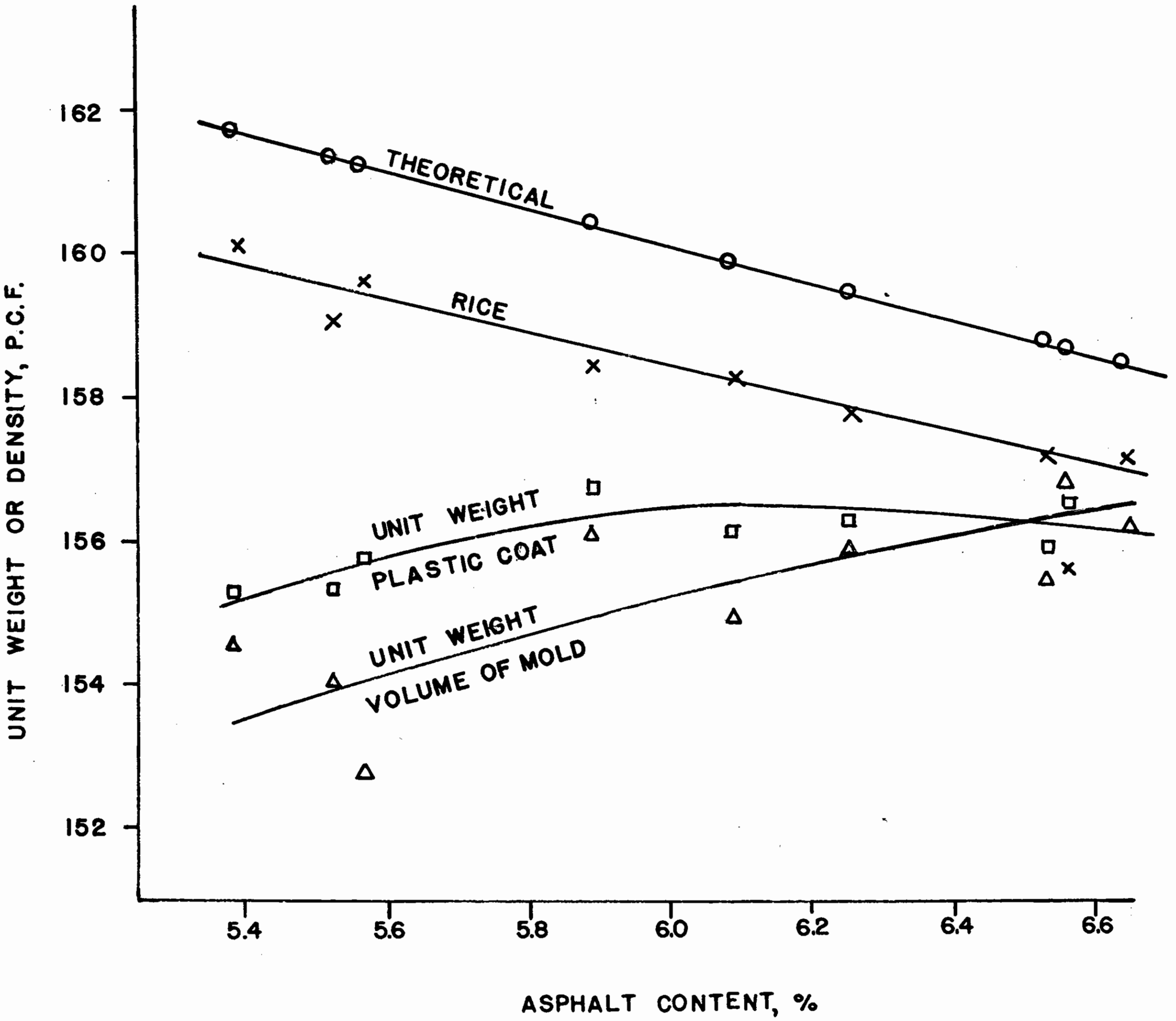


FIGURE 2 UNIT WEIGHT VERSUS ASPHALT CONTENT

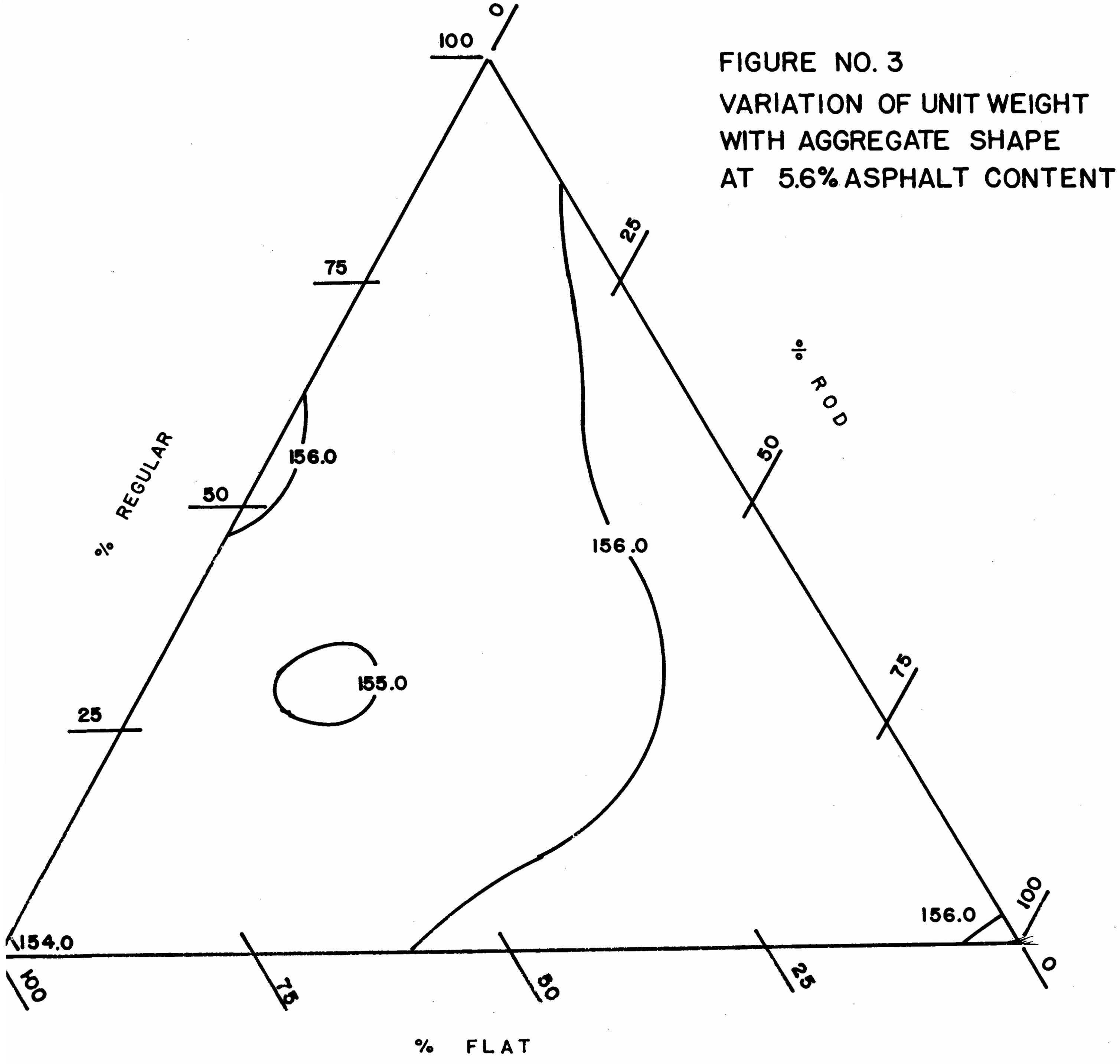
aggregate. Eventually, increasing the asphalt content would replace aggregate with asphalt and lower the end-product density. If all voids were filled, compacted pavement density would equal the Rice density. The curve of unit weight should then be asymptotic to the Rice curve at some higher content.

The calculated maximum density is a function of aggregate shape only to the extent that shape affects permeability of aggregate in the determination of aggregate density. As the material is broken up for the Rice test, no great variation with shape blend was expected or found. As the unit weight is a function of compaction which could be expected to vary with shape, a large variation in this property was expected. The three factor plots of Figures 3, 4, and 5 do not show the expected large variations in the unit weight.

The density found by simple weight in water smoothly changed from approximately the Rice density to the plastic coated density as the asphalt content increased. Of course, the Rice density and plastic density approach each other as asphalt content increases, (Fig. 2). At low asphalt content, during weight in water, water penetrates the sample much as it does the loose material in the Rice test. At high asphalt contents, the voids are isolated by asphalt and are impermeable to water with or without a plastic coating, thus making simple weight-in-water results and coated results very similar.

This condition bears a high degree of concern for open material such as most base coarse mixes. In addition, the degree of shape present conditions the need for sample protection. For example, a given gradation of uniformly shaped particles may be dense enough to give a usable density without a coating, but the same gradation of irregular shaped particles may be open and need protection.

FIGURE NO. 3
VARIATION OF UNIT WEIGHT WITH AGGREGATE SHAPE AT 5.6% ASPHALT CONTENT



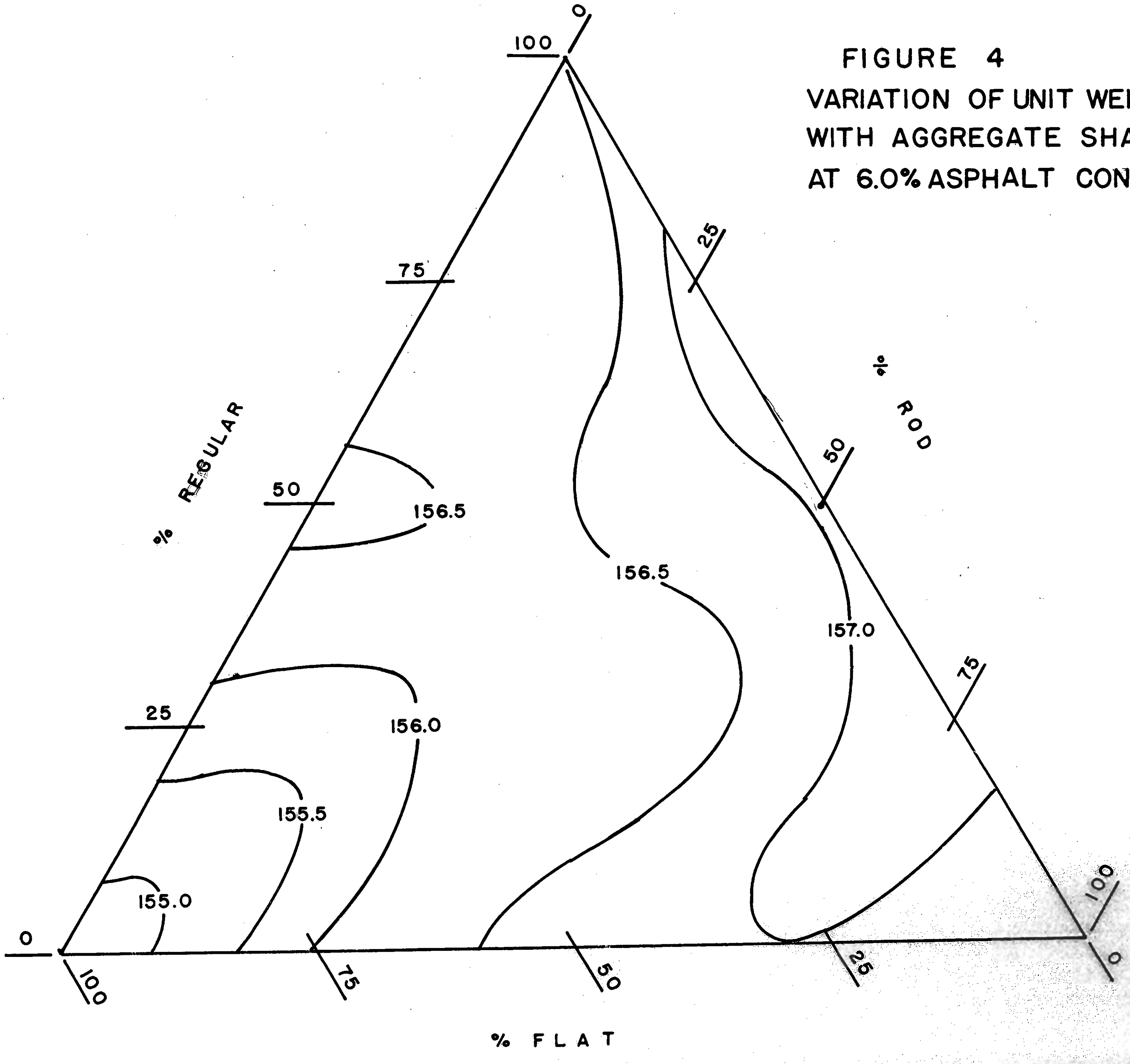


FIGURE 4
VARIATION OF UNIT WEIGHT
WITH AGGREGATE SHAPE
AT 6.0% ASPHALT CONTENT

Unit weight is largely used for compaction control. Typically, the density is determined for material under both standard and field compaction and compared. If the laboratory density is found by weight in water for an open sample, the result is approximately the theoretical or Rice density which is independent of compaction. Field cores will then appear to be similar and the method of control has lost all sensitivity. This condition being especially important for mixes of irregular shaped aggregates may be very serious in mixes of curshed stone using manufactured sand. For 6% asphalt and trap rock, the theoretical density would be (1.00 x .06 + 2.82 x .94) x 62.4 - 172.67 lb/c.f. Using natural sand the theoretical density would be more nearly (1.00 x .06 + 2.82 x .34 + 2.65 x .60) x 62.4 = 162.79 lb/c.f. Either a laboratory mix or field core that comes within 10 lb of the theoretical density should be suspect and retested using a coating.

Other density effects can be noted such as a continual rise in unit weight with increasing asphalt content. This is due to the presence of asphalt easing compaction and filling of some voids. If asphalt contents were continually increased, the asphalt must eventually take the place of more dense stone and the sample density falls. At 20% asphalt, a theoretical (and actual density) of (1.00 x .20 + 2.82 x .53 + 2.65 x .27) x 62.4 = 150 lb c.f., and at 30% a lower density of (1.00 x .30 + 2.82 x .46 + 2.65 x .24) x 64.4 = 139 lb/ c.f. are to be expected. As practical pavements are limited to under 10%, no peak in the density-asphalt content curve need be found.

Considering the main variable of this study which is coarse-aggregate shape, the tri-dimension plots of Fig. 3 to 5 are self-explanatory. At 5.6 and 6% asphalt, the highest unit weight was found at zero flats contents. 100% rods gave higher unit weight than 100% regular shapes. There seems to be no explanation of why this should occur. Fig. 6 may present little

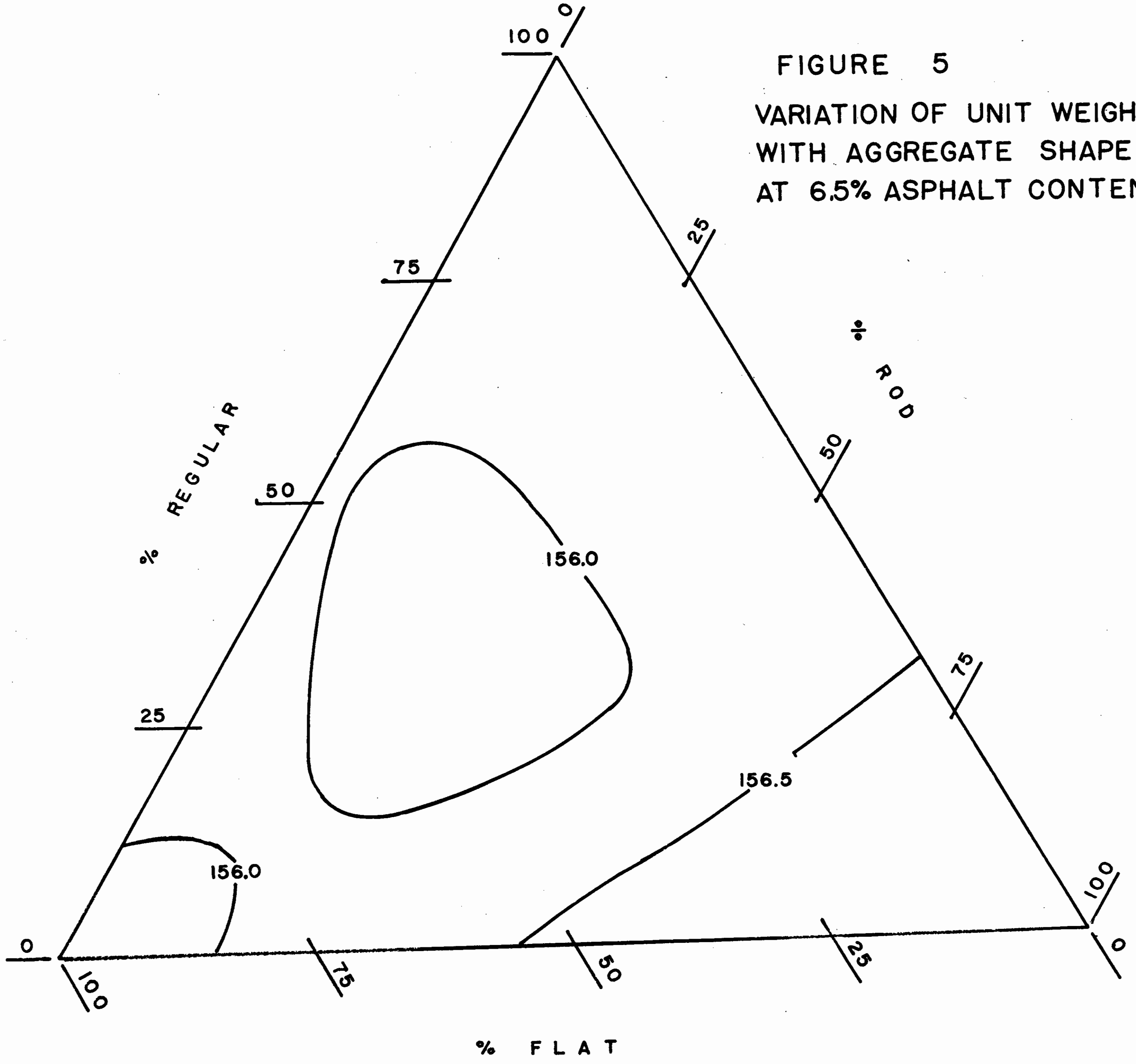
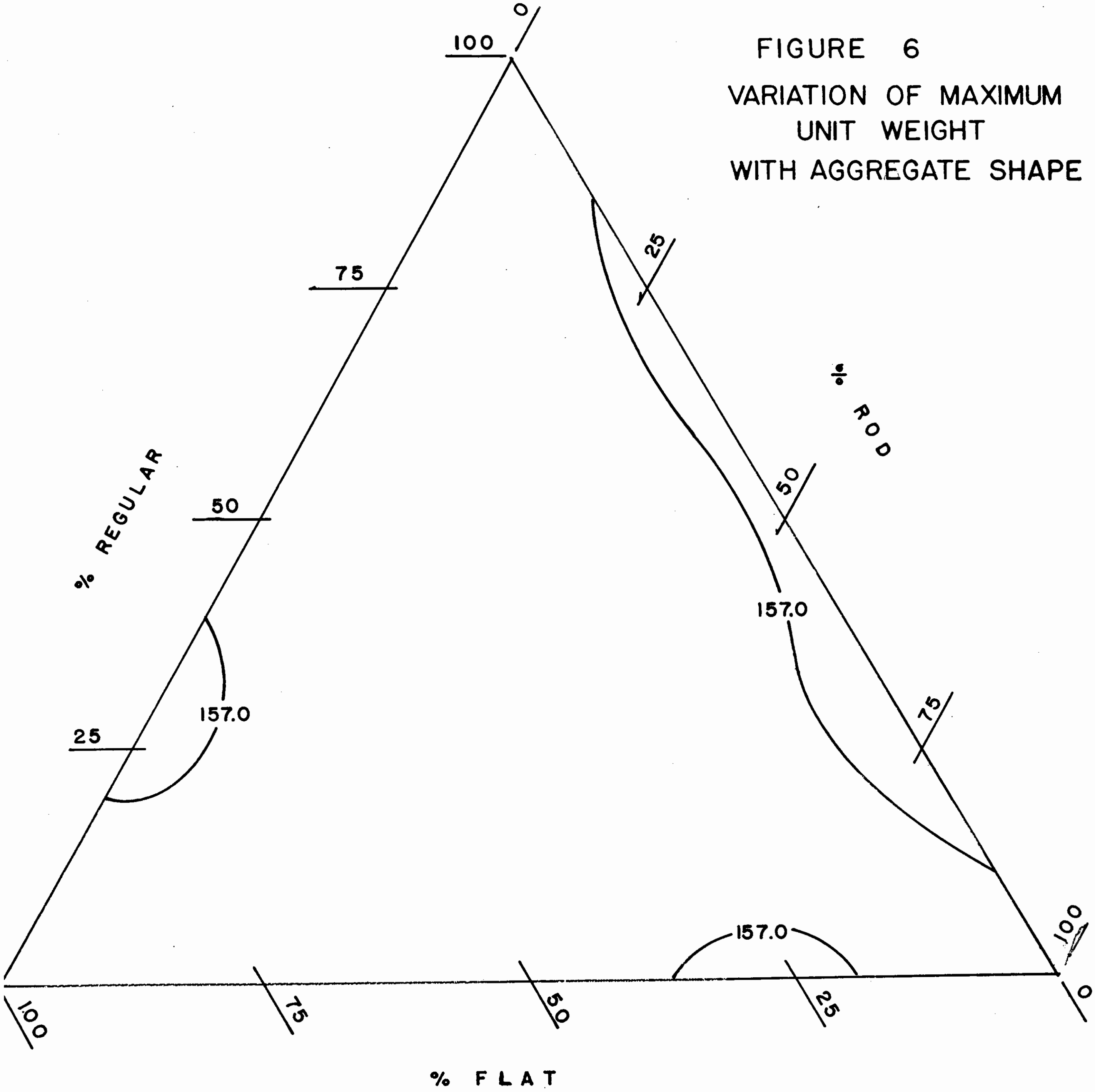


FIGURE 5

VARIATION OF UNIT WEIGHT
WITH AGGREGATE SHAPE
AT 6.5% ASPHALT CONTENT

FIGURE 6

VARIATION OF MAXIMUM
UNIT WEIGHT
WITH AGGREGATE SHAPE



more than a coincidence but the trend there shown is too strong to be ignored. If the maximum unit weight for each aggregate blend regardless of asphalt content is examined, the result to an accuracy of 0.25 pound is a constant. Or restated, for every blend of aggregate shapes there is an asphalt content which results in reaching the maximum unit weight.

Stability behaves somewhat differently than unit weight. The maximum stability for regular shapes occurs at lower asphalt content than for either rod or flat shapes. This is logical, since the latter shapes will interlock to a much greater degree than the regular shapes. The Marshall test and the Hveem test should give different results for stability. Under the kneading compaction, both flat and long particles tend to orient horizontally. In the Hveem test, the load is perpendicular to the thus oriented particles; in this case, lateral flow is resisted and, stability increased. In the Marshall test, the load is parallel to the flat or long particles and lateral motion is relatively unrestrained.

As the samples were all molded at a single level of compaction, the differences in unit weight indicate compactibility. That is at a selected level of asphalt, higher densities indicate that the constant weight samples under constant compactive effort were compacted to a smaller height. Regrettably, no density versus compactive effort data for individual samples were taken. When specifying compaction, percent of laboratory density is usually used. Two hypothetical mixes might have density-compactive effort curves as shown in Fig. 7. In this study, both have the same density as molded and would be considered as equal in ease of compaction. In the field it will be easier to secure 95% of laboratory compaction for material A.

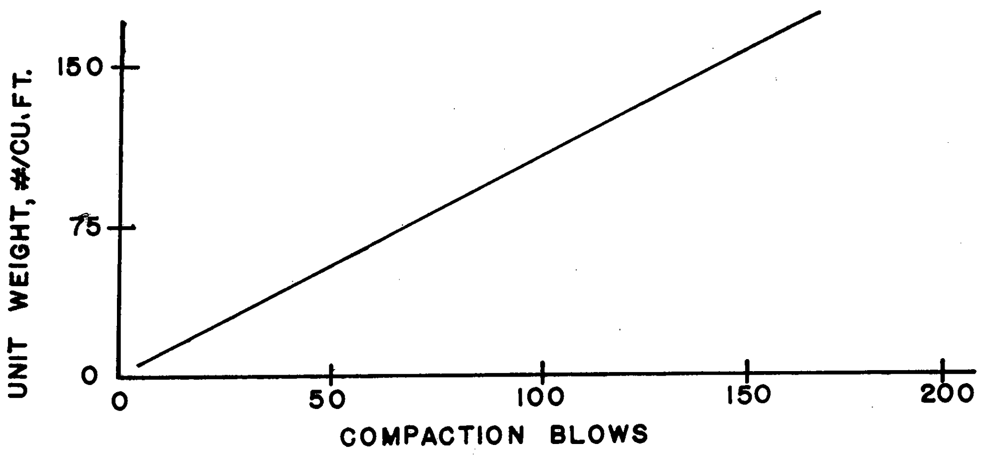


FIGURE 7 UNIT WEIGHT VERSUS COMPACTION

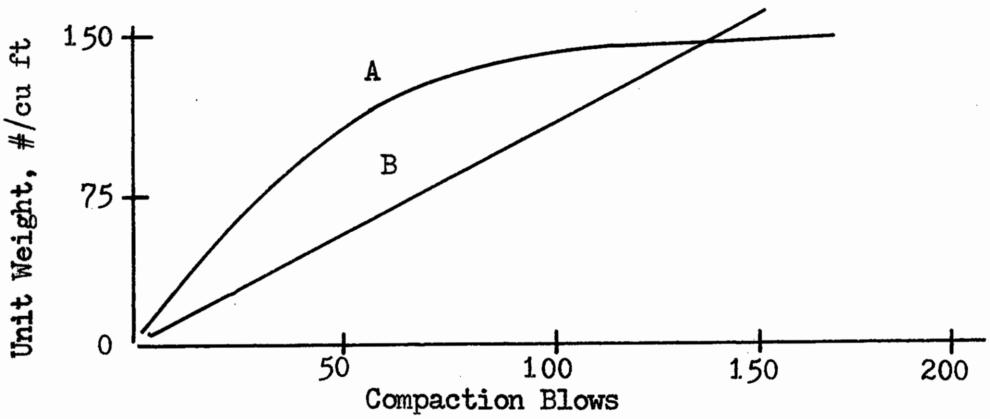


Figure 7. Unit Weight Versus Compaction

Stability as a function of asphalt content was plotted for all shape blends in the test program. Figures 8, 9, 10 are for blends of two shapes with limiting curves for 100% of one shape repeated in the figures to make progressive comparison of the curves convenient. That is in Fig. 8, A_1 represents 100% flat aggregate and A_2 100% rod aggregate. A_{10}, A_{11}, A_{12} contain progressively higher concentrations of rod aggregate ranging from 30% to 70%.

Blends represented in Fig. 9 and 10 progress in a similar manner for the shapes used in each. Progression from curve to curve as blend changes appears smooth and reasonably logical.

Three-shape blends were also prepared and stability asphalt content relations are presented in Fig. 11. No judgements were made concerning the relative position or shape of the different curves due to the difficulties of anticipating the effect of changing three shapes. It was assumed that each curve should be smooth.

From the smoothed graphs, stability was read and tabulated at 5.6, 6, 6.5% A.C. The tabulated stabilities were plotted on the triangular coordinate system and lines of equistability drawn (see Figs. 12-14). At 5.6%, the highest stabilities occur in a band representing blends of 50% flat aggregate.

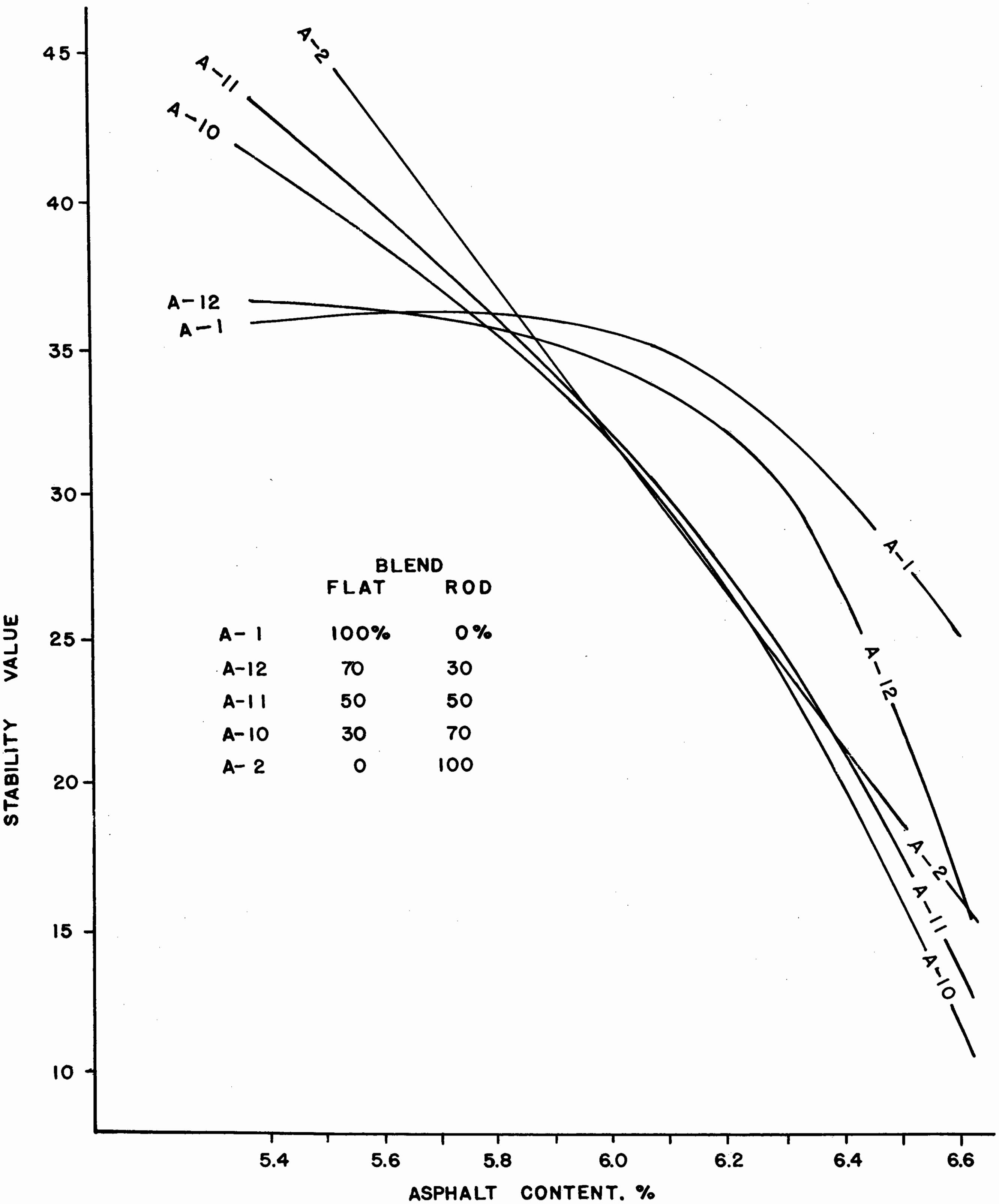


FIGURE 8 STABILITY VALUE VERSUS ASPHALT CONTENT
BLENDS OF FLAT AND ROD SHAPES

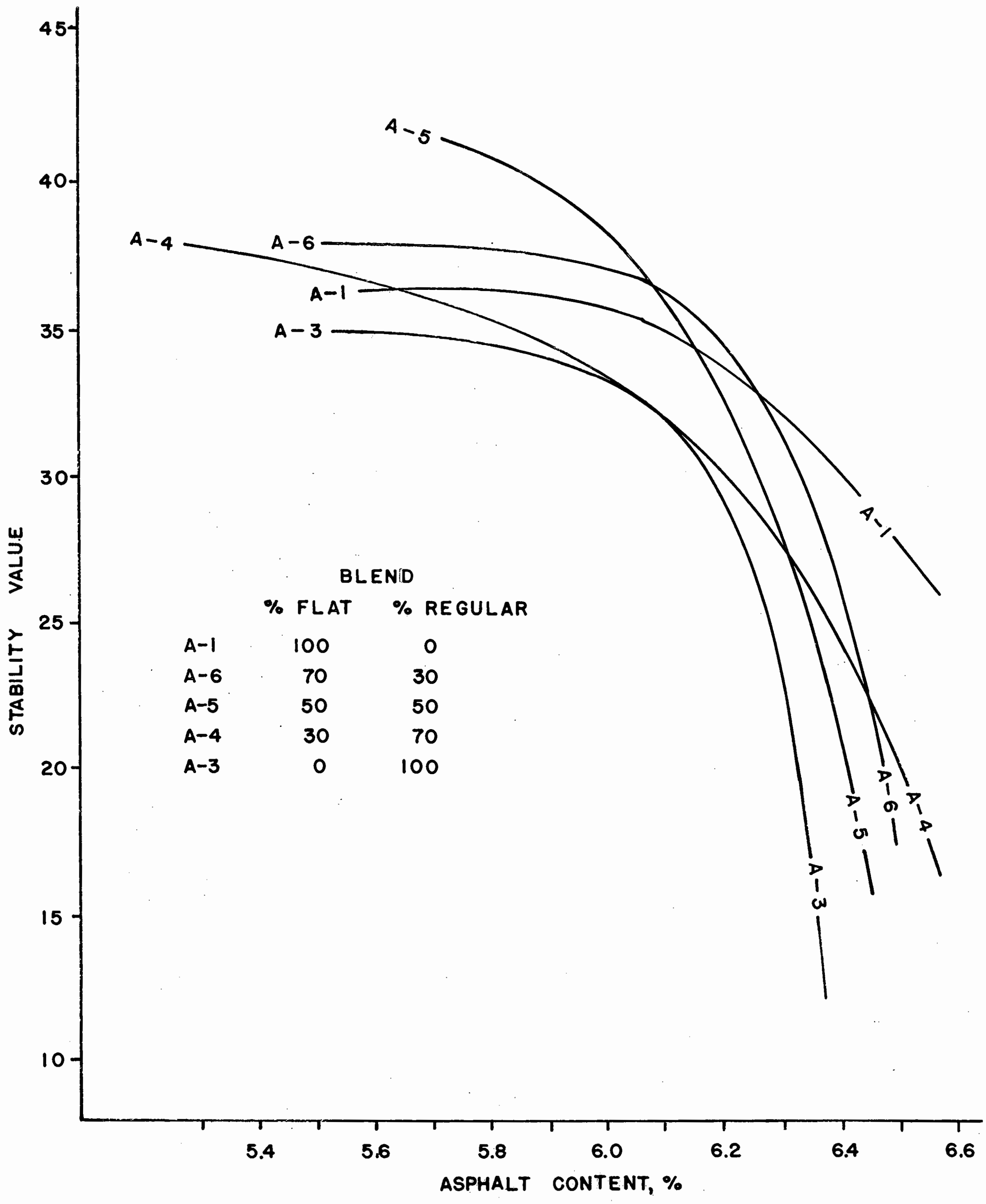


FIGURE 9 STABILITY VALUE VERSUS ASPHALT CONTENT
BLENDS OF FLAT AND REGULAR SHAPES

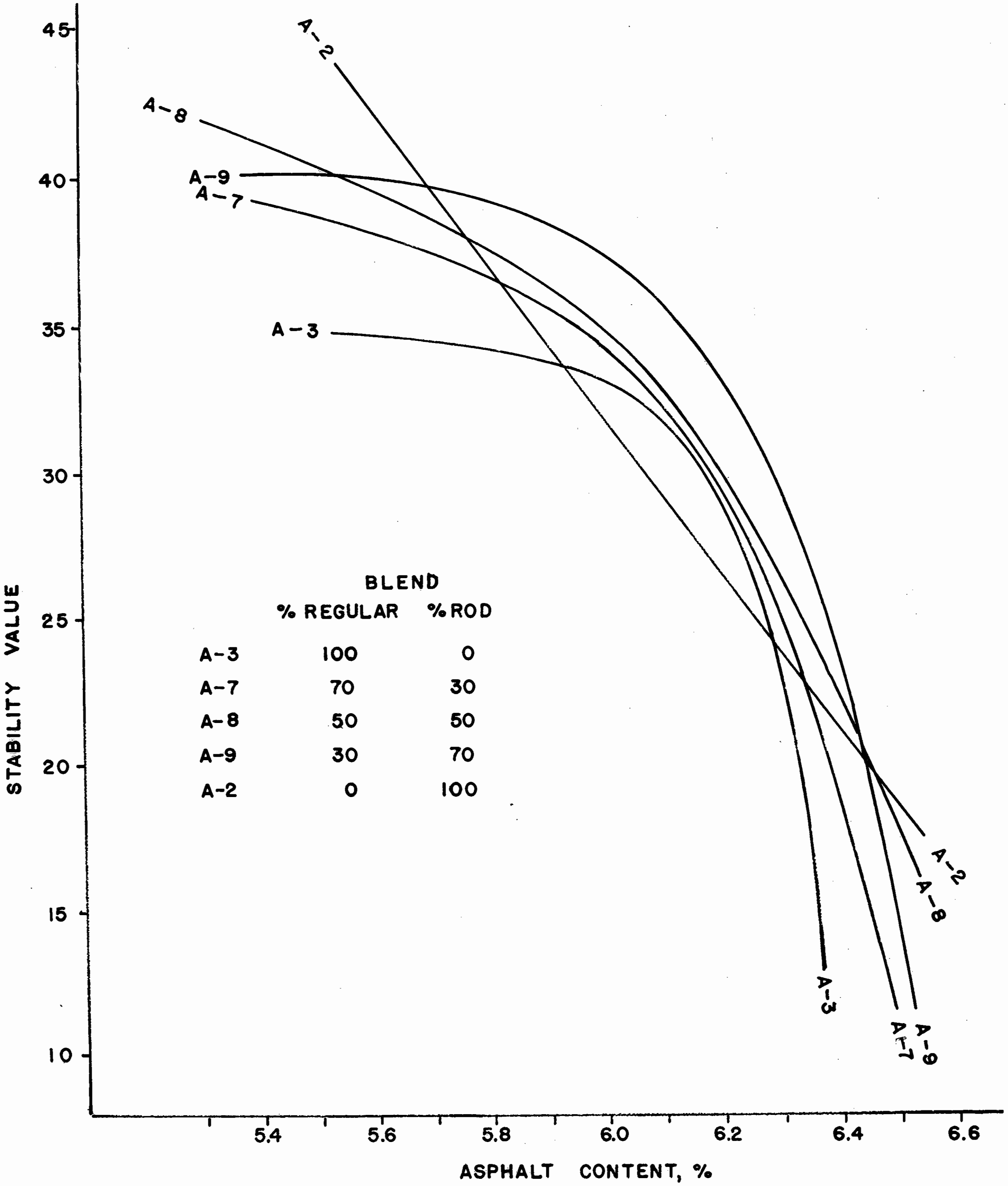
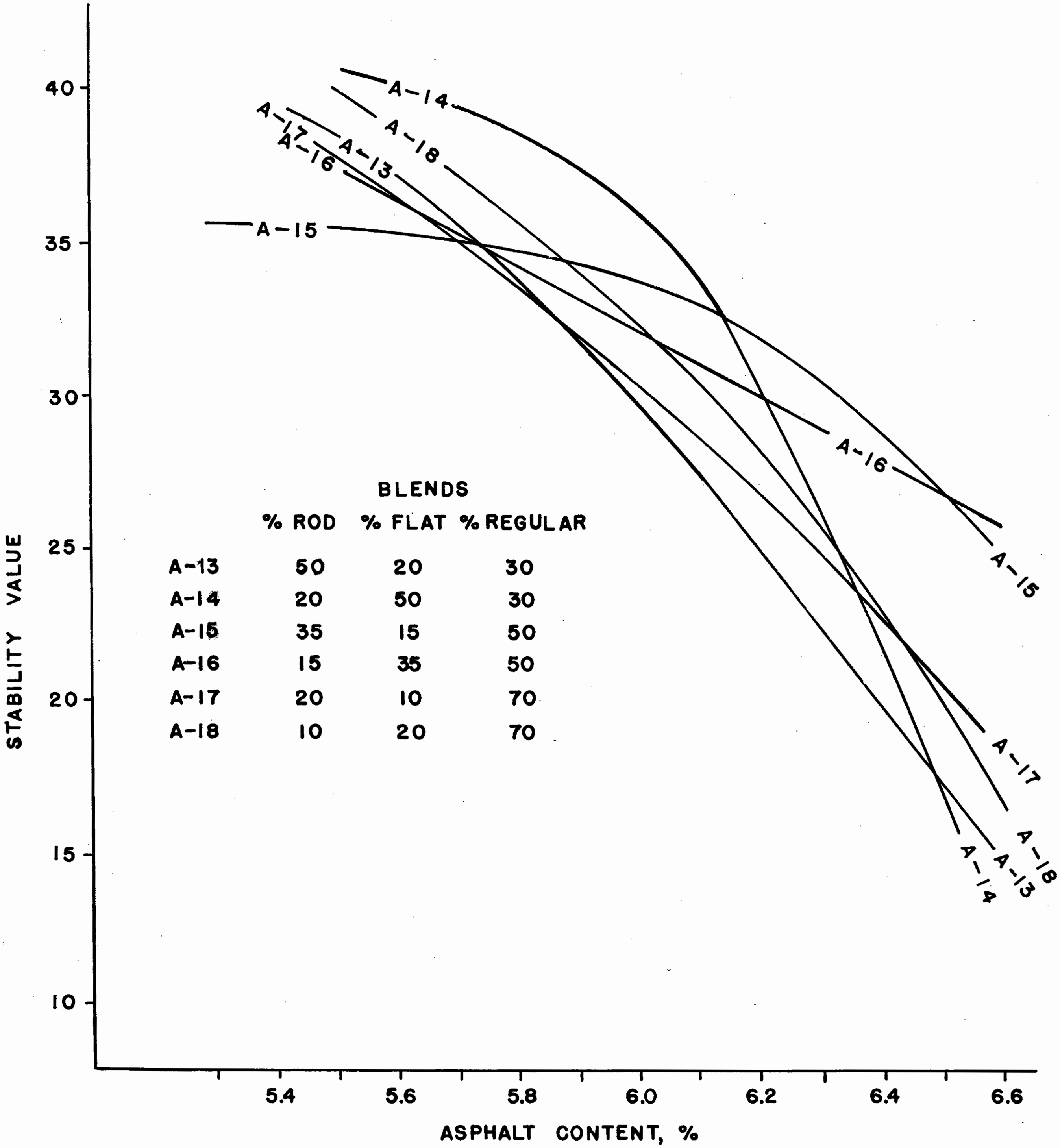


FIGURE 10 STABILITY VALUE ASPHALT CONTENT
BLENDS OF ROD AND REGULAR SHAPES



BLENDS

	% ROD	% FLAT	% REGULAR
A-13	50	20	30
A-14	20	50	30
A-15	35	15	50
A-16	15	35	50
A-17	20	10	70
A-18	10	20	70

FIGURE 11 STABILITY VALUE VERSUS ASPHALT CONTENT
BLENDS OF THREE SHAPES

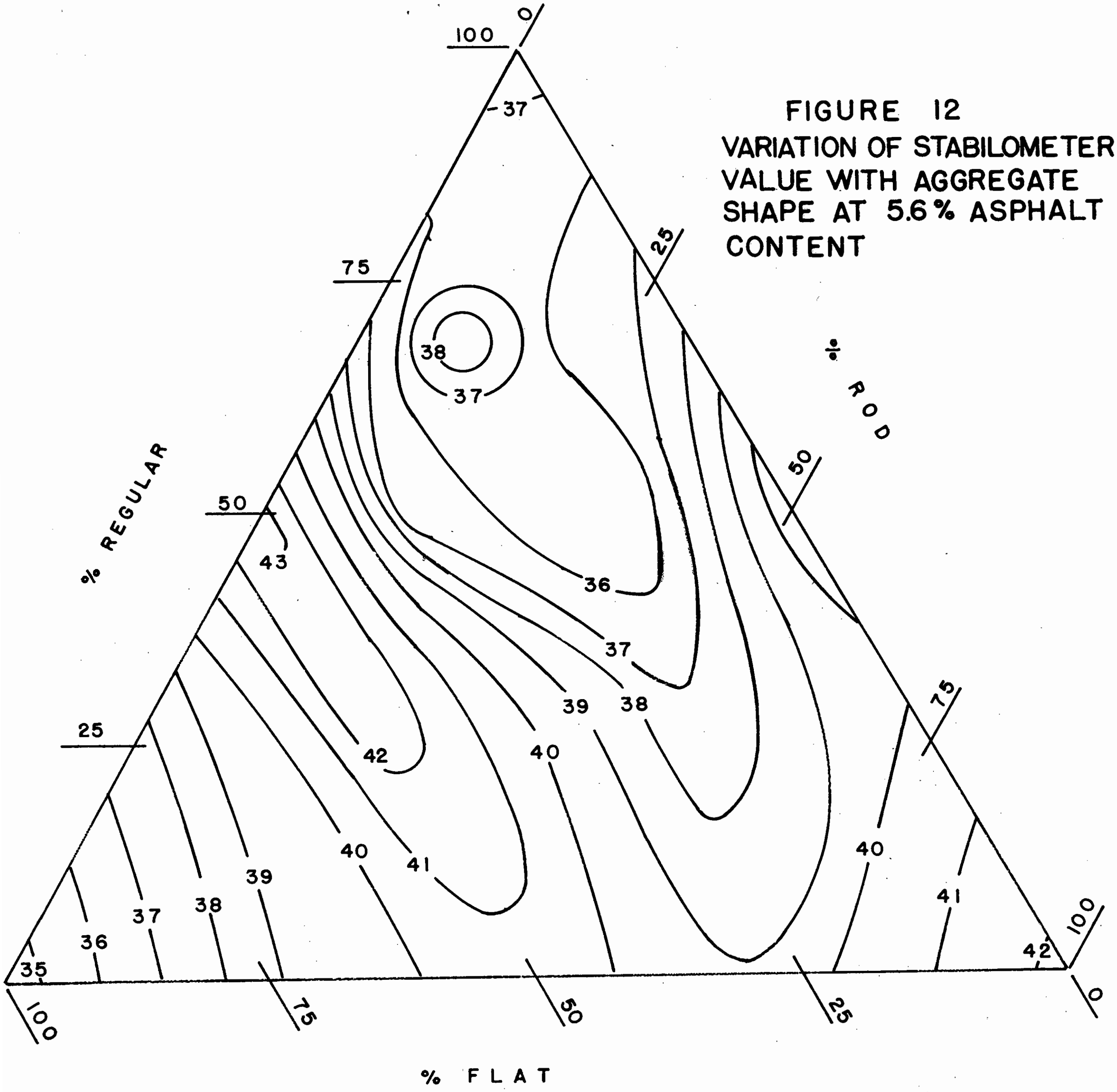


FIGURE 12
VARIATION OF STABILOMETER VALUE WITH AGGREGATE SHAPE AT 5.6% ASPHALT CONTENT

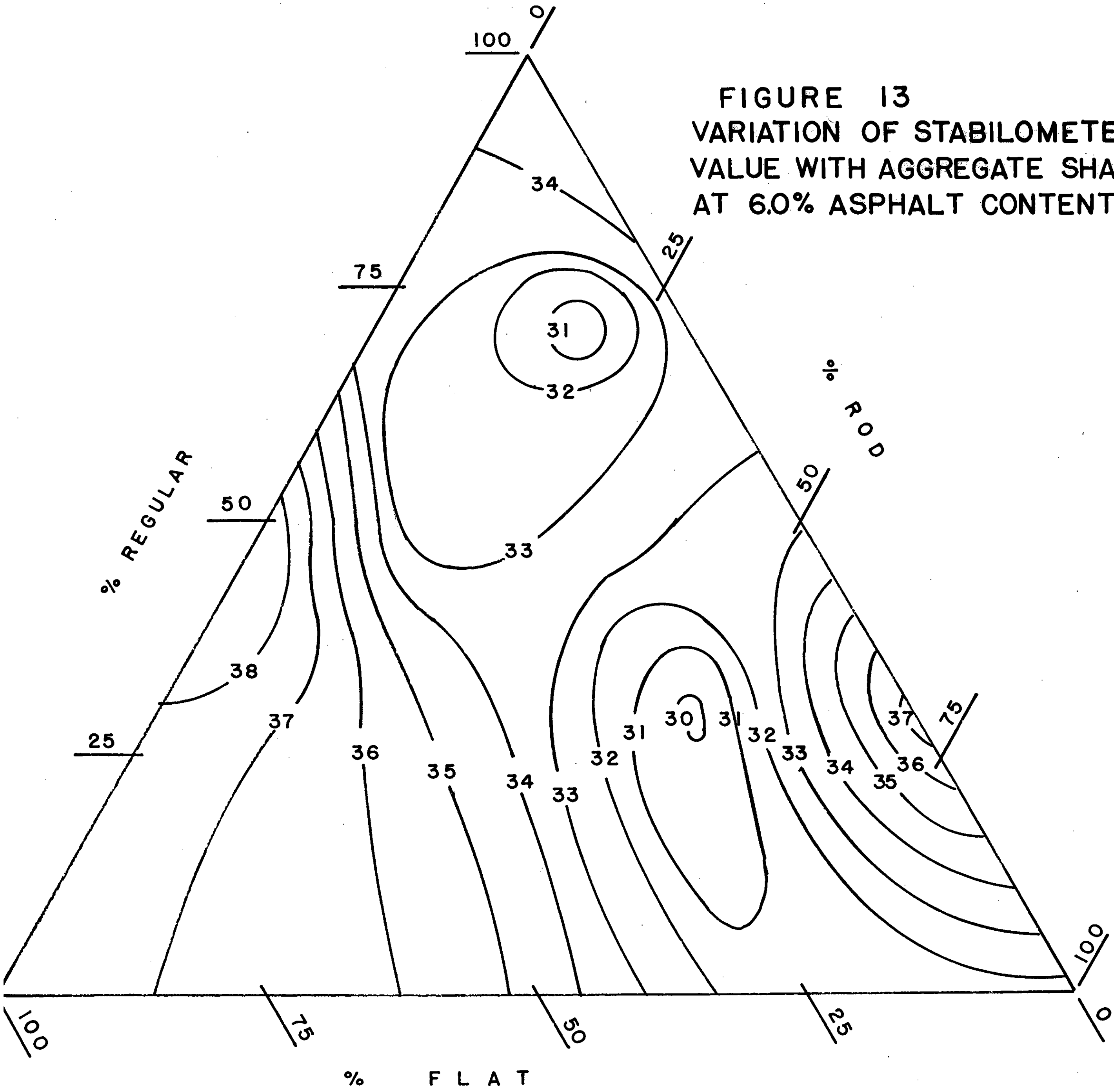
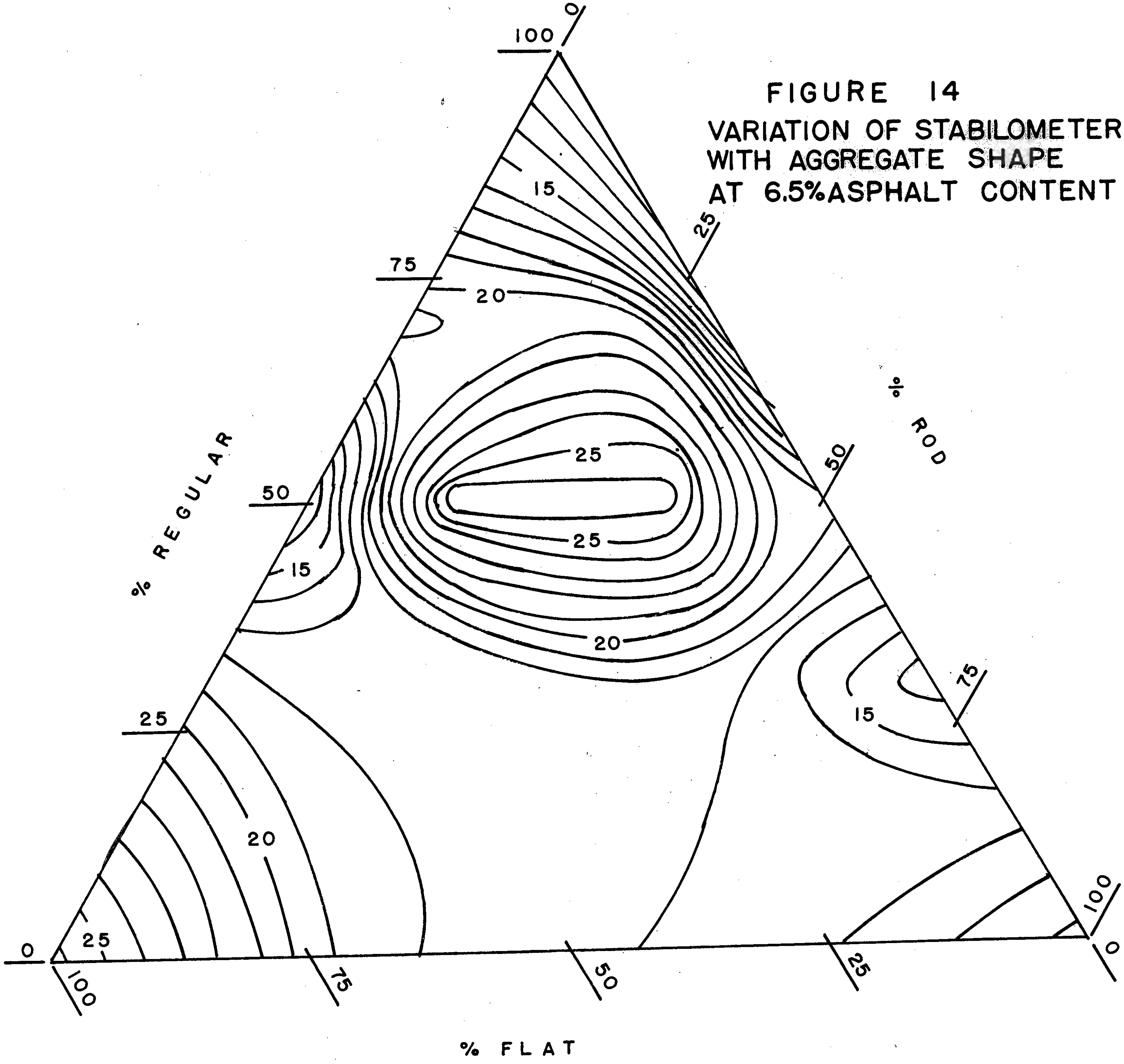


FIGURE 13
VARIATION OF STABILOMETER VALUE WITH AGGREGATE SHAPE AT 6.0% ASPHALT CONTENT

FIGURE 14

VARIATION OF STABILOMETER VALUE
WITH AGGREGATE SHAPE
AT 6.5%ASPHALT CONTENT



A second zone of high stability occurs in the vicinity of 100% rod shapes. Stability for 100% regular and 100% flat are 80% of the highest values.

Increasing the asphalt content to 6% causes the high ridge of stability at 50% flat blend found at 5.6% to disappear. All mixes with more than 50% flats then tested in the upper thirties. Equally surprising, nearly all mixes with no flats were in the middle thirties. A low band did exist from the vicinity of 30% flat - 70% rod blend toward a blend of 100% regular aggregate. That increased asphalt might reduce the stability is attributable to the lubricating effect of the additional asphalt. Essentially, the stability of all blends decreased.

Further increase to 6.5% asphalt caused further rearrangement of the stabilities. The 100% regular mix decreased to 1/3 of the stability for 5.6% asphalt content. Mixes of 20% flat - 80% rod to 80% flat - 20% rod dropped to 1/2 of the 6% asphalt values. Mixes with no flats tested low in much the same degree. However, the area around 50% regular and 20 - 30% flat and rod remained nearly the same as that for 6% asphalt. In summary, a small range of blends centered around 50% regular, 22-1/2 flat, 22-1/2% rod dropped slightly but within the method of test can be considered as remaining constant, while stability for all other blends decreased, (Fig. 15).

Traditionally, stability has been assumed to be related to unit weight. There is a slow trend in Unit weight, Fig. 3, from a low of 153.9 at 100% flat aggregate to a high of 156.8 at 50% regular - 50% rod. Unit weight then falls as the blend varies toward either 100 regular or 100 rod. Although not perfect, a degree of correlation does exist at 5.6% A.C. with higher unit weight indicating higher stability.

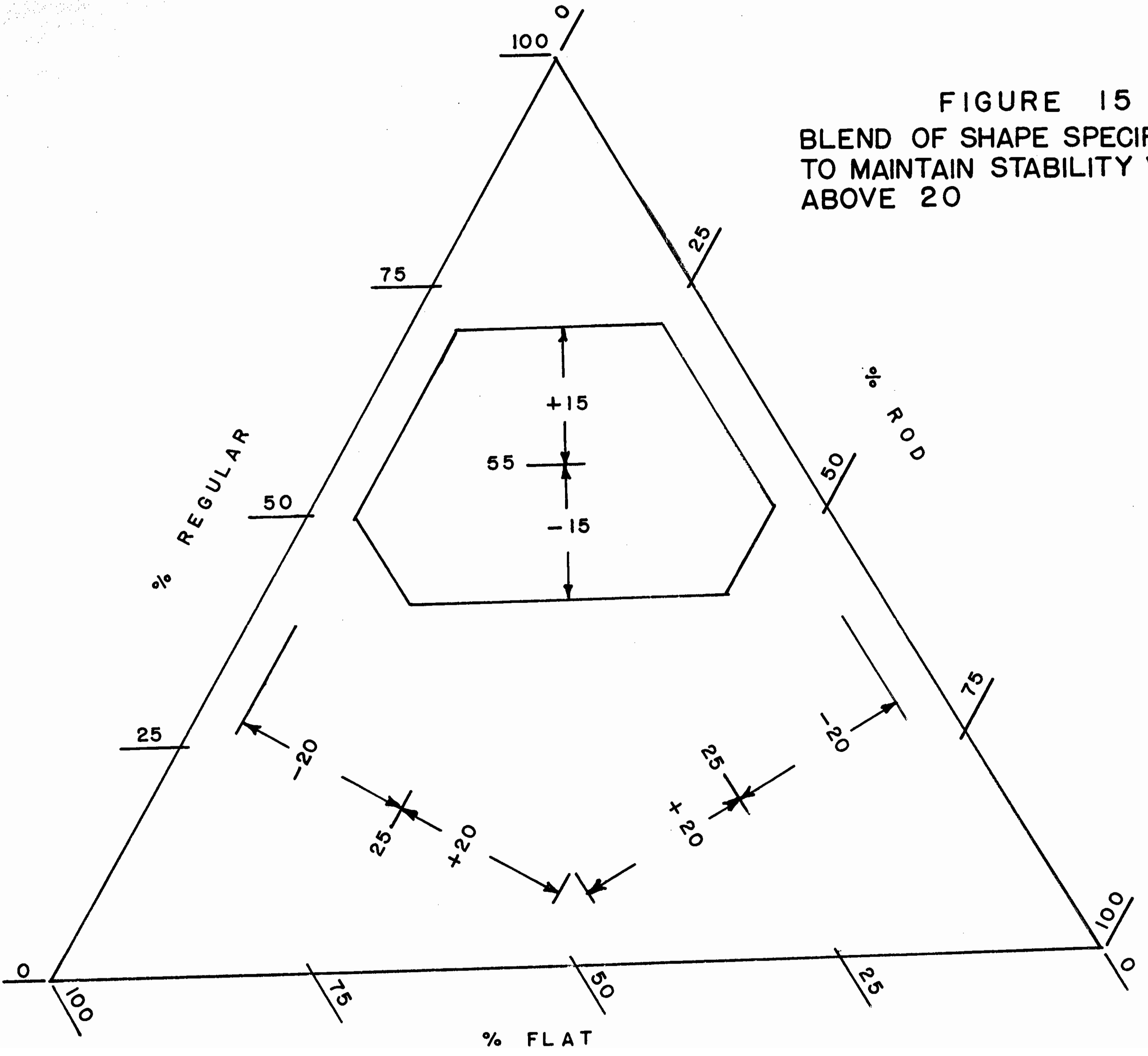


FIGURE 15
BLEND OF SHAPE SPECIFICATION
TO MAINTAIN STABILITY VALUE
ABOVE 20

At 6.0% asphalt content, the trend of unit weight, Fig. 4, is up from 154.7 at 100% flat to 157.3 at 0% flat. 100% regular and 100% rod gave equal unit weights. Although poor, some resemblance of increased stability with increased unit weight appears.

At 6.5% asphalt content there is no significant change in unit weight with aggregate shape (see Fig. 5). Total change is 155.5 to 157.5 or 2 pcf. Part of the figure (75% or less regular aggregate) does show minor unit weight changes varying directly with stability but no relation is apparent throughout the remainder of the diagram. At all asphalt levels, the degree of accuracy required in unit weight measurements to establish the density-stability correlations is above the routine testing level.

As a stable mix must also be durable, the effect of shape on voids must be considered. In Figures 16-18, the percent voids have been plotted for various shape blends. At 5.6% asphalt, Fig. 16, the lowest percent voids occurs at a blend of 70% rod - 30% regular shaped aggregate. With the exception of a small area along the regular-flat blend line, a line from 100 regular to 45% flat - 55% rod divide the chart into two parts. This line defines blends resulting in a void content equal to that of the 100% regular shaped aggregate. Those blends with a ratio of rod to flat greater than 1.222 will have a void content less than that of the 100% regular and, of course, a ratio less than .8181 will have a value above the 100% regular mix. For the total chart, high values tend to occur for blends of 50% or more flat aggregate.

Increasing the asphalt content to 6% reduces the voids at essentially all blends of shapes. The general contours of the void-shape blend relation are similar. A line from 100% regular blend to a blend of 50-50 flat regular again separates blends with voids less than those of a 100% regular shape

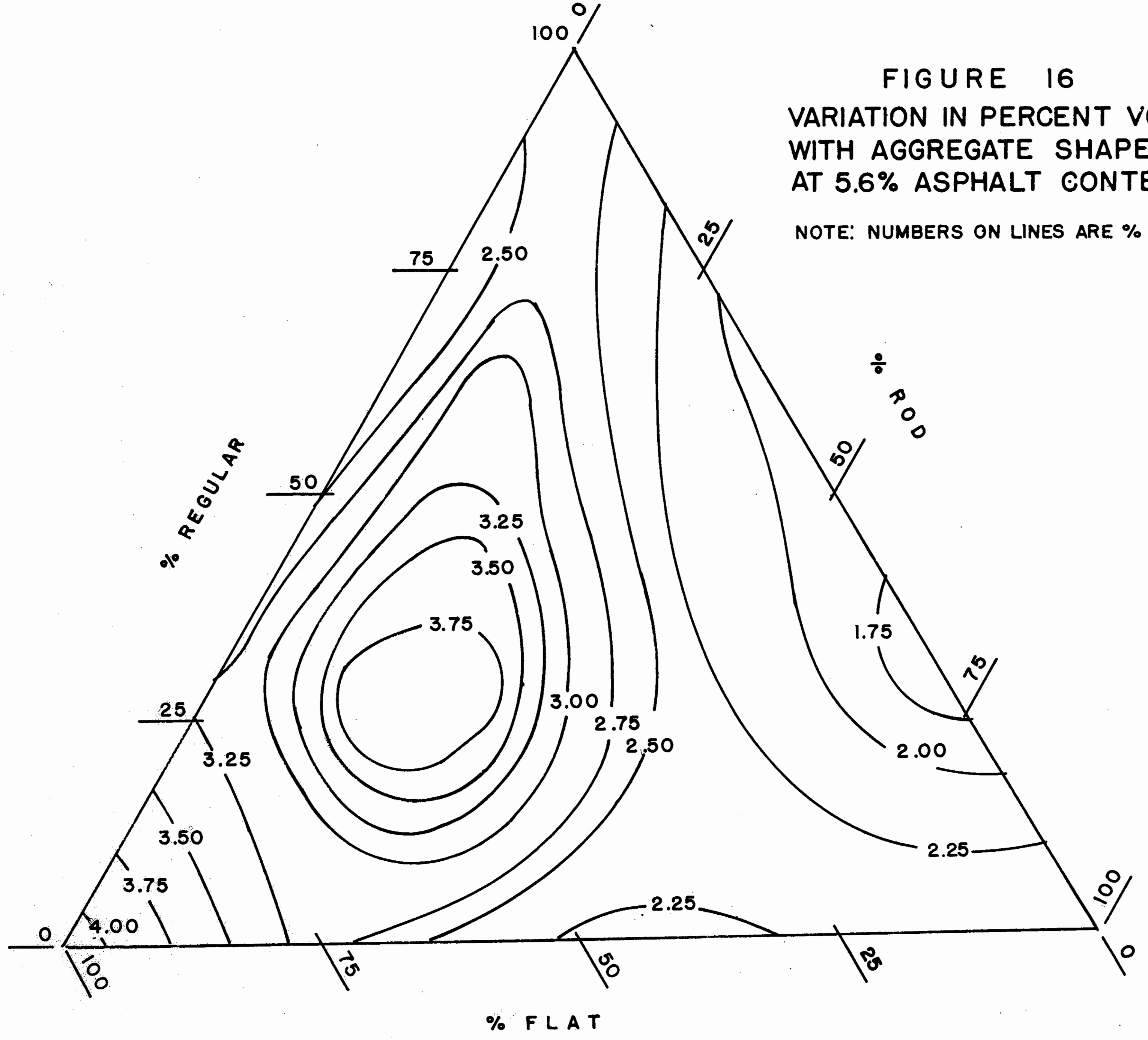


FIGURE 16
VARIATION IN PERCENT VOIDS
WITH AGGREGATE SHAPE
AT 5.6% ASPHALT CONTENT

NOTE: NUMBERS ON LINES ARE % VOIDS

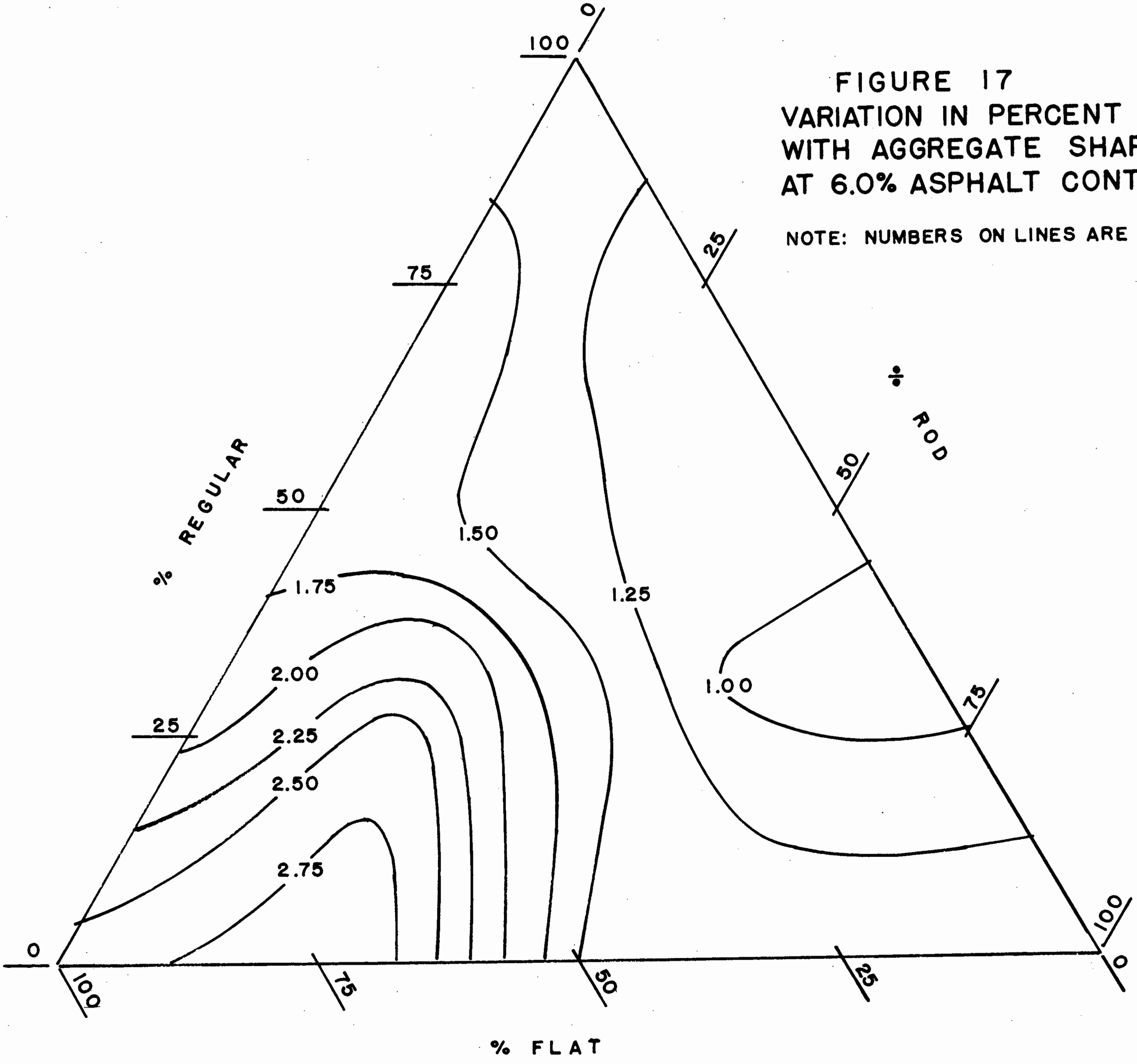


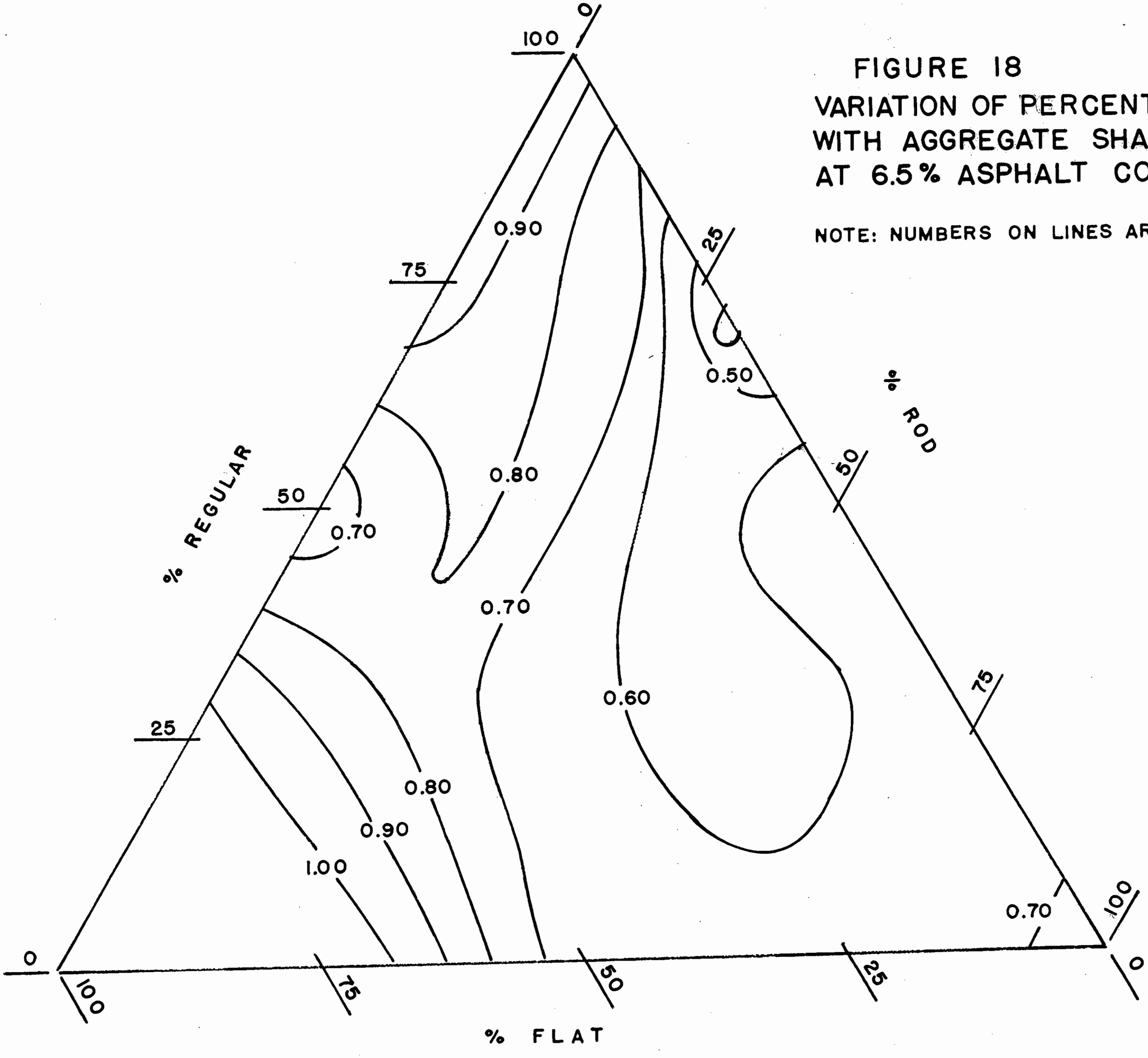
FIGURE 17
VARIATION IN PERCENT VOIDS
WITH AGGREGATE SHAPE
AT 6.0% ASPHALT CONTENT

NOTE: NUMBERS ON LINES ARE % VOIDS

FIGURE 18

VARIATION OF PERCENT VOIDS WITH AGGREGATE SHAPE AT 6.5% ASPHALT CONTENT

NOTE: NUMBERS ON LINES ARE % VOIDS



from those with voids greater. Of course, any point along this line has a one-one ratio of flat to rod aggregate.

A further increase in asphalt content to 6.5% causes further shifting in the same general direction. The area representing blends of regular - flat and up to 65% flats have voids less than the 0.96% of the one shape regular aggregate mix. Of course, the highest voids are found with 100% flat particles.

Discussion of Trends

Any explanation of the trends requires thorough understanding of the test methods used. The Hveem stability reported for these mixes was based on samples prepared by the use of 50 blows on each side with a kneading compactor at a foot pressure of 500 psi. This compaction effort is more effective than the normal Marshall and results in higher unit weight and lower voids. Also, the kneading action reorients particles to a greater extent, resulting in directional orientation of flats and rods. This orientation has different effects on Marshall and Hveem stabilities.

As the Marshall load is applied perpendicular to the compaction axis (parallel to the particle orientation), ever increasing degrees of orientation reduce the Marshall stability. The extreme example of 100% flat aggregate fully oriented could be compared to loading a deck of cards of edge. The Hveem stabilometer provides for loading along the compaction axis of the sample and measurement of the lateral force generated. In the deck of cards simile, this compares to loading the deck in a flat position and measuring the amount the size of cards increased. Thus, stability variation with shape can be anticipated.

Using spherical shaped particles with no friction would result in a lateral pressure equal to the vertical and low stability under either the Marshall or Hveem loading. The 100% regular shaped particles with friction would transmit part of the vertical load into lateral force. The lateral force will not equal the vertical, but will be sizeable. A sample of 100% flats all oriented perpendicular to the loading will generate very little lateral force, as flat on flat has little tendency to deform laterally. In a similar manner, rod shaped aggregate oriented by kneading compaction has a high stability.

Variation in unit weight cannot as readily be predicted. One hundred percent flats might be expected to have lower unit weight due to the ability of the pieces to span voids. This would in turn provide higher voids. Adding small quantities of either regular or rod aggregate to the 100% flats would increase voids and reduce unit weight. A single bead or pencil mixed into the deck of cards would cause substantial change in both voids and unit weight. As the flats are not truly flat, thick asphalt films permit some lateral extrusion and reduced stability. Increased quantities of regular and/or rod would eventually reach a point where voids formerly bridged by flats were filled with other shapes and the unit weight would increase and voids decrease.

Shape had the most effect on unit weight at 5.6% asphalt. This implies high internal friction at low aspahlt content resists compaction (reorientation). As the highest unit weight at 6.5% is the same as at 6.0% it can be expected that this effect has peaked and a further increase in A.C. will not cause increased unit weight.

These samples compacted by the kneading compactor do not show a great variation in unit weight. At any one asphalt content, the greatest difference was 2.9 lb/ c.f., and the range throughout 3.7 lb/c.f. It should be noted that these differences represent average differences and individual mixes differed more. This small difference indicates unit weight is not a sensitive control for asphalt mixes as related to aggregate shape variables. Shape had the most effect on voids at 6.0% asphalt content. As most voids are removed by 6.5% asphalt, further increased in asphalt cannot cause further appreciable reduction in voids.

Although the absolute value of voids ratio for all blends tends to be low as a result of kneading compaction, the relative values do show substantial differences in the character of the samples. For each asphalt level, the highest void ratio is more than twice the lowest. For all blends and asphalt, the highest void content is 10 times the lowest. The void ratio variation shows some inverse relation to unit weight. Shape had the most effect at the 6.5% level of asphalt content.

The effect of asphalt content on both voids and unit weight was similar at all blends. However, the effect of asphalt variation on stability was strongly affected by shape. Although increasing asphalt content lowered stability for all blends, the degree of change differed with blend. This effect is especially apparent when comparing a 50%-50% flat-regular blend to a 100 flat mix. Increasing the asphalt content form 5.6 to 6.5 reduced the stability of the former 30.7 stability units or 71% while the latter decreased only 7.8 or 23% while blends of 50 regular - 25 flats - 25 rods demonstrated the least loss in stability as the asphalt increased above 6.0%.

Conclusions

1. Effect of blend of shapes on density is not large. Thus, density is not an effective control of particle shape.

2. Voids decrease with increasing asphalt; higher voids always occurring in mixes with 30% or more flat particles.

3. In general, void ratio for blends of at least two shapes tends to be lower than for one shape alone.

4. Increases in asphalt above 6% cause large reductions in stability unless the aggregate is a blend of shapes approaching 50 regular - 25% flat and 25% rod.

5. Reducing asphalt content below 6% does not cause an increase in stability comparable in magnitude to the loss incurred when increasing asphalt content.

Recommendations

1. Shape of aggregate should be a consideration in mix design. Voids, for example, are usually specified as 3-5%. For durability, zero voids would be better, but some initial voids are needed to prevent bleeding caused by further compaction by traffic. Flat or rod shaped mixes preserve voids as seen by higher voids in this test work. Thus, initially acceptable voids should be related to shape.

2. Shape blends should be specified as 55% ± 15% reg. - 25% ± 20% flat - 25% ± 20% rod, Fig. 18. This would limit reduction in stability due to accidental/uncontrolled variation in asphalt content.

3. Tests should be attempted to evaluate the degree of particle-shape control possible through selection of type crusher and control of the crusher reduction factor.