Redesign of Bituminous Binder and Leveling Courses

EGONS TONS

September 1969

Sponsored by

Michigan Department of State Highways

THE UNIVERSITY OF MICHIGAN 1817

Department of Civil Engineering

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Department of Civil Engineering
University of Michigan
Ann Arbor, Michigan 48104

Synopsis

The work involved analysis, redesign, and laboratory testing of bituminous mixes used in Michigan for binder and leveling courses. By using a "uniform grading" approach it was anticipated to improve mix properties.

Altogether, two different stones with 9 gradations and varying asphalt contents were evaluated for stability and work to cause cracking in tension. In addition, segregation tendencies and ease of handling of the mixes were noted.

Two of the new gradations using combinations of 9A with 25A stone and 9A with 31A stone as coarse aggregates showed better performance in the laboratory evaluation when contrasted with the present mixes. Field testing of one or both of these mixes is suggested.

Acknowledgement

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The author wishes to acknowledge the assistance given by the Michigan Department of State Highways Testing and Research Division in providing the background experience of these type mixtures and for participating in the organizing of the Laboratory Research Study of this investigation; also for providing the Laboratory personnel to perform the details of this work and for supplying the necessary materials and equipment required in the performance of this investigation.

Thanks are also due to Daniel Jahnke, Theodore Hanlon, and Laurence Haskell, Michigan Department of State Highways Laboratory Technicians who helped prepare the mixes and perform the testing for this project. Mr. A. S. Mongia, a graduate student, assisted in compiling and analyzing data.

Introduction

Bituminous mixture designs for Binder Course or Leveling Course, as used by the Michigan Department of State Highways, are basically a skip grading type. These mixes have served quite well from the standpoint of stability and durability, however they have exhibited some cracking and raveling, and have had a tendency to segregate under certain conditions of handling. It was felt that a redesign of the mixes with emphasis towards "uniform gradation" may be beneficial.

Purpose and Scope

The purpose of this study was to attempt to improve the present leveling and binder mixes so that:

(1) The mixes are less susceptible to segregation than at present

(2) Easier to place and roll

(3) Result in denser, more stable, and more crack and ravel resistant layers than obtained at present

In order to make the changes in mix design practical, economical and immediately applicable to field use, the existing gradations of stone, namely 9A, 25A, and 31A were blended with each other and used with 3 NS sand.

Altogether nine different mixes and blends were made and evaluated in the laboratory. The time limit for completion of this work was 3 months.

Experimental Approach

The main emphasis in the numerical evaluation and comparison of mixes was placed on values obtained in Marshall and Split Cylinder (tension) tests.

In the Marshall test[1] cylindrical specimens 4 inches in diameter and 2½ inches in height were made and tested to establish the optimum asphalt content for a given mix and traffic frequency. Stability, density, voids and deformation characteristics are measured in this test.

The Marshall stability test was selected because of its simplicity and also availability of data for comparisons with previous research work. Basically the standard procedure was followed, except that two specimens per point were used instead of the usual three.

While the Marshall test was used to evaluate the stability of the mixes, the Split Cylinder test[2] was an attempt to check the tensile strength or cracking resistance

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[1] See Manual Series No. 2, The Asphalt Institute, May 1963, p. 19.

[2] Breen, J. J. and Stephens, J. E., "Split Cylinder Test Applied to Bituminous Mixtures at Low Temperatures," ASTM Journal of Materials, March 1966, p. 66.

at low temperatures. The specimens were prepared by the Marshall method, cured, cooled to 0° F, then placed sideways in a compression machine and loaded at a constant rate until the specimens split. A continuous stress-strain curve was obtained, from which both maximum strength and work to failure could be measured.

In addition to the measurements, observations were made marking the mix uniformity, segregation tendencies, handling, and effects of water on the mixtures.

Choosing of Materials

The type of aggregates chosen were those used most frequently in Michigan. Two types were selected: (a) Natural crushed aggregate and (b) crushed dolomite. The properties of these are summarized in Table 1.

Natural sand from one source was used for all mixes. The filler was limestone dust.

The asphalt used was 85-100 penetration, also from one source (see Table 1).

Choosing of Gradations

This investigation included 9 blends of aggregates. Three of the blends were made using the median gradation of MDSH standard specifications aggregate for 9A, 25A and

31A.[3] These mixes were designated as 1, 2 and 3 respectively and the actual grading curves are given in Figures 1, 2 and 3. Each of the figures also includes maximum density uniform grading curves with power of 0.45.[4]

It is apparent that a large number of blends could be prepared and tested using the three types of mixtures. Due to limited time only six compositions in addition to the three standard mixes were chosen. The guide lines for the choice were as follows:

(1) From a practical standpoint, it was assumed that only two standard gradations could be combined in the plant. This resulted in trial combinations of 9A + 25A, 9A + 31A, and 25A + 31A gradings.

(2) It was assumed that blends approaching maximum density gradation would give mixes with better cracking and raveling resistance, less segregation and easier handling. By using graphical methods mixes 5, 7 and 9 were obtained.[5] These mixes required higher relative proportions of fine aggregate when compared to standard 9A and 25A mixes.

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[3] See "Standard Specifications for Road and Bridge Construction," MDSH, article 4.12.02, p. 209, 1967.

[4] Percent passing $= 100 \left(\frac{\text{sieve in question}}{\text{max size of aggregate}} \right)^{0.45}$

[5] See Table 2 and Figures 4, 5, and 6.

(3) Mixes 4, 6 and 8 were chosen with the thought of having the stone content around 65 percent (high) by the weight of the mix for economy purposes. The gradation of these is also given in Table 2 and Figures 4, 5, and 6. Mixes 4 and 6 are quite close to maximum density grading if power of 0.5 is used.

Laboratory Work -- Marshall Tests

The first part of laboratory work involved preparation and testing of Marshall size specimens, namely 4 inches diameter and about 2½ inches high bituminous concrete cylinders. The procedure was as follows:

(1) First, the optimum asphalt contents for each of the nine mixes using natural coarse aggregate was estimated.

(2) The basic determination of the optimum asphalt content for the mixes with natural stone involved mixing and testing 9 x 2 x 5 = 90 specimens. Additional specimens were made where the estimated asphalt content was not sufficiently close to the optimum obtained in the experiment.

(3) Each of the 90 specimens was assigned a number and mixed and tested according to a random drawing procedure.

(4) The weight of the total dry aggregate was kept constant.

(5) The aggregate and the 85-100 penetration asphalt were heated to 300° F and each specimen was mixed individually by hand.

(6) The compaction was accomplished by a mechanical Marshall compactor, applying 40 blows on each side of the specimen. This is equivalent to 50 blows applied manually.

(7) The rest of the procedure was identical to that of Marshall.

(8) In addition to the 9 mixes tested using natural coarse aggregate, about 30 specimens of mixes 1, 4, and 6 were also made and evaluated substituting crushed dolomite for the coarse aggregate, other ingredients being the same.

(9) The data from the Marshall tests are summarized in Tables 12 to 20 and Figures 7 to 19.

Laboratory Work -- Tension Tests

The preparation of specimens for the Split Cylinder test was identical to that described in the Marshall procedure. Instead of placing the specimens at 140° F and afterwards testing for stability and flow, the specimens for the Split Cylinder test were stored at 0° F for three hours before testing. They were then taken out of the cold storage, placed on their side between two parallel, flat steel plates (cooled to 0° F) and loaded at a rate of 6000 pounds per minute. A load-deformation curve was obtained for each specimen from which was calculated the work in inch-pounds to split each specimen.

The tension tests were run only for the three strongest mixes, namely 1, 4 and 6, both with the natural and the crushed dolomite aggregate. The optimum asphalt contents (see Table 20) were used for the mixes and five replicates were made for each. This permitted statistical comparisons between the mixes. The actual data are tabulated in Table 21 and graphical comparisons are made in Figure 20.

In addition to evaluation by the Marshall and the Split Cylinder test, the segregation tendencies and other effects on the mixes were compared by visual observation (see Figures 21 and 22).

Results and Discussion

Marshall Tests

One of the factors emphasized in the Marshall results is the stability or "strength." The optimum asphalt content, however, was determined by averaging the asphalt contents at maximum stability, maximum unit weight and 3 percent voids in the mix. If such a procedure is used, the optimum asphalt contents are as given in Table 20. At these asphalt contents the strongest or most stable mixes containing the natural rock aggregate are

4, 5, 6 and 7. Mix 1 (conventional 9A binder course mix) also shows relatively good stability, while Mix 9 is low in this respect. Mixes 2, 3, and 8 and 9 have a relatively high void content. Since Mixes 4 and 5 are combinations of stone 9A and 25A and Mixes 6 and 7 are composed of 9A and 31A, it is possible to say that Mixes 4 and 6 are the best according to the Marshall criterion. In other words, in these series of tests two mixtures containing a portion of 9A binder course stone have been obtained which show an improvement over Mix 1 or the present standard binder course mix when natural coarse aggregate is used. Mixes 8 and 9, having a mixture of 25A and 31A stone, do not show superiority over the present standard leveling course mix here designated as Mix 2. More work is needed in this area.

The general trends in the Marshall test values using the crushed dolomite aggregate were similar to those with the natural aggregate, except for Mix 1, which showed a slightly different optimum asphalt content for the two cases. Another difference was evident in the amount of residual voids in the mixes after compaction. The dolomite mixes showed slightly lower void contents when compared with similar mixes containing natural stone. The maximum stability value for Mix 1 was lower than that of Mix 6 but higher than that for Mix 4. The peak Marshall stability attained for each mix is shown graphically in Figure 19.

Split Cylinder Tests

Only the three "strongest" mixes found by the Marshall test were evaluated in the Split Cylinder test; namely, Mixes 1, 4, and 6. The comparisons were made in the amount of work (force times distance) needed to "crush" each specimen. This could be measured from the x-y plots obtained during the test showing pounds of load and inches of deformation. Since the thickness (heights) of the specimens were not always constant, the work (in inch-pounds) measured for each specimen was divided by the thickness to obtain work per inch of thickness. The values for each mix and specimen are tabulated in Table 21 and graphically shown in Figure 20. Mix 6 expecially shows an improvement over Mix 1. Statistical comparisons also show that the differences are significant.

Table 22 gives an additional comparison between the mixes on the basis of maximum load on the specimen (at the time of failure). Mix 6 again is ahead.

It must be pointed out that the asphalt contents for the five specimens of each mix used in the Split Cylinder tests were those of the Marshall optimum. Therefore Mix 1 had a slightly lower asphalt content than mixes 4 and 6. This, of course, cannot be avoided since Mix 1 would probably be unstable if say 5.1 percent of asphalt would be used in the mix in the field.

Other Improvements

In addition to strength measurements, observations were made to see what other benefits could be derived if Mix 6 or 4 were used in binder courses, instead of Mix 1. The following observations were made:

(1) It is known from experience and research that uniformly graded mixes are subject to less segregation than skip graded mixes. Also placement and compaction is usually improved. Since Mix 1 is skip graded and Mixes 4 and 6 are closer to uniformly graded, an improvement is expected.

(2) While mixing and making each specimen, it was observed that Mix 1 was more difficult to place in the mold and harder to obtain a uniform looking specimen than Mixes 4 and 6. Photographic evidence of this phenomenon is given in Figure 21 for three specimens of Mix 1 compared to three specimens of Mix 6. All are identical specimens in each class.

(3) Due to compaction and the Split Cylinder test afterwards, a number of aggregate pieces were crushed in the specimen as shown in Figure 22. Less crushing took place with Mix 6 as compared to Mix 1.

(4) When specimens of Mix 1 and 6 after the Split Tension test were immersed and kept in water for about 14 days, more "stripping" of asphalt from stone was observed with Mix 1 than Mix 6.

Conclusions

Because the Marshall and the Split Cylinder tests are laboratory tests, only field performance can give the final answer whether true improvements have been achieved. From the laboratory work done so far the following is apparent:

(1) Mixes 4 and 6 are as stable or better than Mix 1, the presently used binder course mix in Michigan.

(2) Mixes 4 and 6 are superior to Mix 1 as far as their resistance to cracking at low temperatures is concerned.

(3) Mixes 4 and 6, when compared to Mix 1:

(a) Look more uniform in appearance

(b) Show less segregation when handled and placed in molds. It is expected that this may be so also in the field.

(c) Less crushing of rock particles during compaction was observed with Mixes 6 and 4.

(d) Moisture effects and stripping of asphalt from rock surfaces may be reduced for Mixes 6 and 4 since they have fewer large rocks with large areas exposed to water action.

Suggestions

It is suggested that:

(1) Further laboratory studies be done with the leveling course mix.

(2) Mix 6 and possibly Mix 4 should be applied to field use. The recommended grading limits and composition are outlined in Table 23.

TABLES

TABLE 1

PROPERTIES OF AGGREGATES AND ASPHALT USED

Property	Natural Stone	Dolomite Stone	3NS Sand	Limestone Filler	Asphalt
Specific Gravity	2.740	2.834	2.690	2.760	1.024
Penetration	--	--	--	--	99
Viscosity, S.F. 275° F	--	--	--	--	154.9
Ductility, 25° C	--	--	--	--	110^{+}

TABLE 2

PERCENT OF STONE, SAND AND FILLER
IN EACH MIX, BY DRY WEIGHT OF AGGREGATE

Mix	Stone 9A	Stone 25A	Stone 31A	3NS Sand	Limestone Filler	Total
1	68.4	0	0	31.1	.5	100.0
2	0	68.4	0	31.1	.5	100.0
3	0	0	68.4	31.1	.5	100.0
4	34.2	34.2	0	31.1	.5	100.0
5	30.0	30.0	0	39.5	.5	100.0
6	45.6	0	22.8	31.1	.5	100.0
7	40.0	0	20.0	39.5	.5	100.0
8	0	45.6	22.8	31.1	.5	100.0
9	0	33.4	16.7	49.4	.5	100.0

TABLE 3

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 1

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone 9A	Sand 3NS	Filler
1 - 3/4	20.4	--	--
3/4 - 1/2	26.2	--	--
1/2 - 3/8	13.1	--	--
3/8 - 4	5.2	0.7	--
4 - 8	3.5	3.9	--
8 - 16	--	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 4

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 2

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone 25A	Sand 3NS	Filler
1 - 3/4	--	--	--
3/4 - 1/2	1.7	--	--
1/2 - 3/8	15.3	--	--
3/8 - 4	37.8	0.7	--
4 - 8	9.5	3.9	--
8 - 16	4.1	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 5

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 3

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone 31A	Sand 3NS	Filler
1 - 3/4	--	--	--
3/4 - 1/2	--	--	--
1/2 - 3/8	1.7	--	--
3/8 - 4	32.5	0.7	--
4 - 8	25.7	3.9	--
8 - 16	8.5	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 6

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 4

Size, Inches	Percent of Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	10.2	--	--
3/4 - 1/2	14.0	--	--
1/2 - 3/8	14.2	--	--
3/8 - 4	21.4	0.7	--
4 - 8	6.5	3.9	--
8 - 16	2.1	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 7

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 5

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	8.9	--	--
3/4 - 1/2	12.3	--	--
1/2 - 3/8	12.5	--	--
3/8 - 4	18.8	1.1	--
4 - 8	5.7	4.9	--
8 - 16	1.8	9.0	--
16 - 30	--	7.9	--
30 - 50	--	7.9	--
50 - 100	--	6.9	--
100 - 200	--	0.9	
- 200	--	0.9	0.5
Totals	60.0	39.5	0.5

TABLE 8

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 6

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	13.6	--	--
3/4 - 1/2	17.9	--	--
1/2 - 3/8	19.7	--	--
3/8 - 4	12.0	0.7	--
4 - 8	5.2	3.9	--
8 - 16	--	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 9

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 7

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	11.8	--	--
3/4 - 1/2	15.3	--	--
1/2 - 3/8	8.4	--	--
3/8 - 4	12.5	1.1	--
4 - 8	9.6	4.9	--
8 - 16	2.4	9.0	--
16 - 30	--	7.9	--
30 - 50	--	7.9	--
50 - 100	--	6.9	--
100 - 200	--	0.9	--
- 200	--	0.9	0.5
Totals	60.0	39.5	0.5

TABLE 10

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 8

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	--	--	--
3/4 - 1/2	1.1	--	--
1/2 - 3/8	10.0	--	--
3/8 - 4	35.4	0.7	--
4 - 8	16.1	3.9	--
8 - 16	5.8	7.0	--
16 - 30	--	6.2	--
30 - 50	--	6.3	--
50 - 100	--	5.4	--
100 - 200	--	0.9	--
- 200	--	0.7	0.5
Totals	68.4	31.1	0.5

TABLE 11

PROPORTIONS OF AGGREGATES FOR EACH SPECIMEN
MIX 9

Size, Inches	Percent by Weight of Dry Aggregate		
	Stone	Sand	Filler
1 - 3/4	--	--	--
3/4 - 1/2	0.7	--	--
1/2 - 3/8	7.3	--	--
3/8 - 4	26.1	1.3	--
4 - 8	11.6	6.2	--
8 - 16	4.3	11.0	--
16 - 30	--	9.9	--
30 - 50	--	9.9	--
50 - 100	--	8.6	--
100 - 200	--	1.3	--
- 200	--	1.3	0.5
Totals	50.0	49.5	0.5

TABLE 12

MARSHALL STABILITY FOR EACH SPECIMEN, POUNDS, NATURAL COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	980	1540 1440	1470 1440	1290 1230	1180 1140	1050 1290	1090 1090	1240 1290	
2			1080 830	1080 1000	1080 1080	1320 1270	1270 1080	900	
3			880 880	960 540	880 740	770 790	1040 700	960 960	700 700
4			1090	1230	1380 1040	1290 1230 1180	1730 1470	1280 1560	1180 1130
5			1040 960		1180 960	1380 1290	1290 1650	1470 1130	1180 1230
6		730 730	1290 1180	1180 1090	1140 1470	1290 1440	1440 1400	1470 1800	1560 1290
7				780 960	1090 960	1180 1430	1380 1380	1000 860	
8				1000 880	790 880	1080 1180	1080 1080	830 1080	
9			830 750		830 1000	1080 1000	1000 1000	1080 1000	1000 920

TABLE 13
AIR VOIDS FOR EACH SPECIMEN, PERCENT BY VOLUME,
NATURAL COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	6.9 8.0	6.0 5.6	5.5 6.9	6.4 4.9	4.1 3.8	3.1 3.4	3.3 3.1	2.4 2.8	
2			9.1 10.1	8.7 8.4	7.8 8.0	6.2 8.0	7.4 6.9	6.2 8.1	
3			11.8 12.3	12.1 12.1	11.0 11.2	10.5 10.0	9.8 10.1	8.7 8.3	8.5 8.5
4			7.1	6.8	5.9 5.9	5.1 5.0 5.1	3.6 3.9	3.6 4.1	2.7 2.7
5			6.8 7.0		5.4 6.1	4.1 4.5	3.5 3.7	3.6 4.1	2.7 3.3
6		7.2 6.9	6.3 6.3	4.9 5.6	5.2 4.3	4.7 4.2	3.3 3.2	2.5 3.0 3.4	2.4 2.1 3.3
7				7.1 6.6	5.9 6.1	3.9 4.6	3.5 4.4	3.5 3.5	
8				8.9 10.5	9.0 9.6	9.1 8.5	9.4 7.7	8.1 8.3	
9			10.9 9.1		8.5 7.9	7.4 7.9	6.9 7.4	6.2 8.3	5.5 5.2

TABLE 14

UNIT WEIGHT FOR EACH SPECIMEN, POUNDS PER CUBIC FOOT, NATURAL COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	151.5	151.5 152.5	151.0 152.0	149.0 151.4	151.9 152.0	152.8 152.0	151.5 152.0	152.0 151.5	
2			145.0 144.0	145.0 146.0	145.9 145.4	147.9 145.0	145.1 146.0	146.0	
3			141.0 140.5	140.0 139.9	141.0 140.6	141.1 142.0	141.5 141.0	142.3 143.0	141.5 141.5
4			148.5	148.5	149.0 149.0	149.5 150.0 149.6	151.0 151.0	150.2 149.8	150.4 150.2
5			149.0 148.5		149.8 148.2	150.2 151.0	151.5 151.0	150.0 149.8	150.2 149.5
6		149.8 150.2	149.9 150.0	151.5 150.3	150.0 151.5	150.2 151.0	151.8 152.0	151.0 151.0 152.0	151.0 149.2 151.2
7				148.0 148.5	149.0 148.5	151.5 150.1	151.1 150.0	150.2 150.1	
8				145.0 142.9	143.7 142.8	143.5 144.0	144.0 145.0	143.4 146.5	
9			144.0 145.0		144.5 145.8	145.9 145.2	146.0 145.4	146.1 146.5	146.3 146.7

TABLE 15

MARSHALL FLOW FOR EACH SPECIMEN, 1/100 INCHES, NATURAL COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	6	11 7	8 10	10 11	10 11	10 10	10 8	11 11	
2			11 9	10 10	11 9	12 10	10 11	16	
3			11 10	10 8	11 11	10 11	10 10	10 10	15 10
4			8	9	10 11	10 10 8	13 13	11 10	11 11
5			10 7		10 10	11 11	11 12	11 10	11 12
6		9 11	9 9	10 10	10 8	10 10	11 11	11 8 13	12 11 10
7				8 9	8 10	11 10	11 13	11 11	
8				10 10	10 9	12 9	12 10	11 10	
9			10 9		10 11	11 10	10 8	11 10	10 11

TABLE 16

MARSHALL STABILITY FOR EACH SPECIMEN, POUNDS,
CRUSHED LIMESTONE COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	980 420	900 860	1190 980	1400 900	1510 1610	1350 1540	1510 1400		
4					1440 1050	1140 1440	1540 1350	1350 1350	
6					1420 1400	1350 1710	1610 1800	1100 1400	980 1350

TABLE 17

AIR VOIDS FOR EACH SPECIMEN, PERCENT BY VOLUME,
CRUSHED LIMESTONE COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	6.3 6.8	5.6 5.6	4.5 4.5	3.5 3.6	2.3 2.3	2.6 2.6	2.2 2.2		
4					3.3 4.0	3.6 2.7	2.4 2.4	1.8 2.0	
6					2.9 2.2	2.6 2.6	2.4 2.4 1.9	1.5 1.4	1.2 1.7

TABLE 18

UNIT WEIGHT FOR EACH SPECIMEN, POUNDS PER CUBIC FOOT, CRUSHED LIMESTONE COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	156.0 155.0	155.1 155.8	156.0 155.9	156.8 156.0	157.8 157.8	156.6 156.8	156.8		
4					156.2 155.0	155.1 156.7	156.2 156.3	156.0 156.0	
6					156.8 158.0	156.6 156.8	156.0 156.6 157.0	156.0 157.0	156.0 155.2

TABLE 19

MARSHALL FLOW FOR EACH SPECIMEN, 1/100 INCHES, CRUSHED LIMESTONE COARSE AGGREGATE

Mix No.	Asphalt Content -- Percent of Dry Aggregate Weight								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
1	8 9	11 8	10 9	10 9	10 11	10 10	10 11		
4					10 11	10 10	8 12	12 10	
6					10 10	11 10	11 12 11	9 15	10 14

TABLE 20

OPTIMUM ASPHALT CONTENTS FOR
THE MIXES BY MARSHALL METHOD

A. Natural Aggregate Mixes

	Max. Stability	Max. Density	3% Voids	Opt. A.C.	Stability at Opt.
Mix 1	3.5	4.8	5.2	4.5	1260
Mix 2	4.8	4.8	--	(4.8)	(1280)
Mix 3	5.5	5.5	--	(5.5)	(960)
Mix 4	5.2	5.2	5.7	5.4	1540
Mix 5	5.2	5.2	5.9	5.4	1350
Mix 6	5.5	5.2	5.4	5.4	1580
Mix 7	5.2	4.9	--	(5.1)	(1370)
Mix 8	5.0	5.5	--	(5.3)	(1050)
Mix 9	5.3	5.9	--	(5.6)	(1020)

B. Crushed Limestone Mixes

	Max. Stability	Max. Density	3% Voids	Opt. A.C.	Stability at Opt.
Mix 1	4.5	4.5	4.8	4.6	1540
Mix 4	5.2	5.2	4.8	5.1	1440
Mix 6	5.2	5.2	4.5	5.0	1620

TABLE 21

SPLIT CYLINDER TEST DATA
WORK IN INCH-POUNDS PER INCH
OF SPECIMEN WIDTH (HEIGHT), REQUIRED
TO SPLIT THE SPECIMEN AT 0°F

		Natural Aggregate	Crushed Dolomite
Mix 1			
	Spec 1	870	600
	2	820	930
	3	910	1070
	4	790	680
	5	610	720
Average, Mix 1		800	800
Mix 4			
	Spec 1	1110	870
	2	950	1010
	3	1110	890
	4	1090	1210
	5	1020	860
Average, Mix 4		1060	970
Mix 6			
	Spec 1	1040	1000
	2	1070	810
	3	1370	1350
	4	1430	960
	5	1320	1170
Average, Mix 6		1250	1060

TABLE 22

SPLIT CYLINDER TEST DATA
PEAK STRENGTH, POUNDS PER INCH OF
SPECIMEN WIDTH (HEIGHT)

		Natural Aggregate	Crushed Dolomite
Mix 1			
	Spec 1	2460	2720
	2	2580	2680
	3	2540	3060
	4	2500	2920
	5	2470	2550
Average, Mix 1		2510	2790
Mix 4			
	Spec 1	2700	3200
	2	2540	3370
	3	2600	3090
	4	2650	3210
	5	2370	3460
Average, Mix 4		2570	3270
Mix 6			
	Spec 1	2740	2610
	2	2650	3450
	3	2970	2600
	4	2840	3450
	5	2460	2960
Average, Mix 6		2730	3010

TABLE 23

SUGGESTED COMPOSITION OF MIXES FOR FIELD USE

Sieve Size	Percent Passing	
	Mix 4	Mix 6
1 in	100.0	100.0
3/4 in	86 - 93	82 - 91
1/2 in		
3/8 in	52 - 71	53 - 76
# 4	34 - 46	38 - 51
# 8	24 - 34	24 - 36
# 16	16 - 24	16 - 24
# 30	10 - 18	10 - 18
# 50	5 - 10	5 - 10
# 100	0 - 4	0 - 4
# 200	0 - 2	0 - 2
Percent Asphalt by wt. of mix	4 - 6	4 - 6

FIGURES

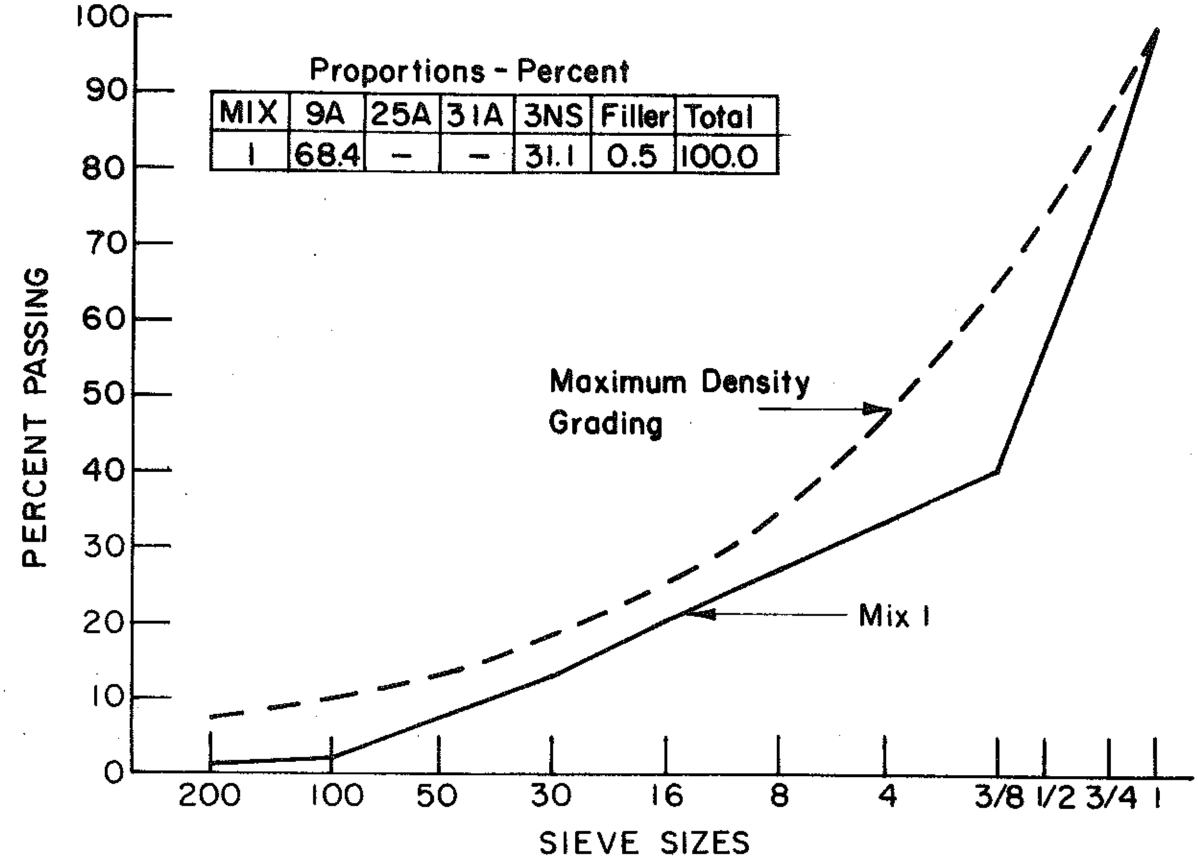


Figure 1 Aggregate Grading for Mix 1

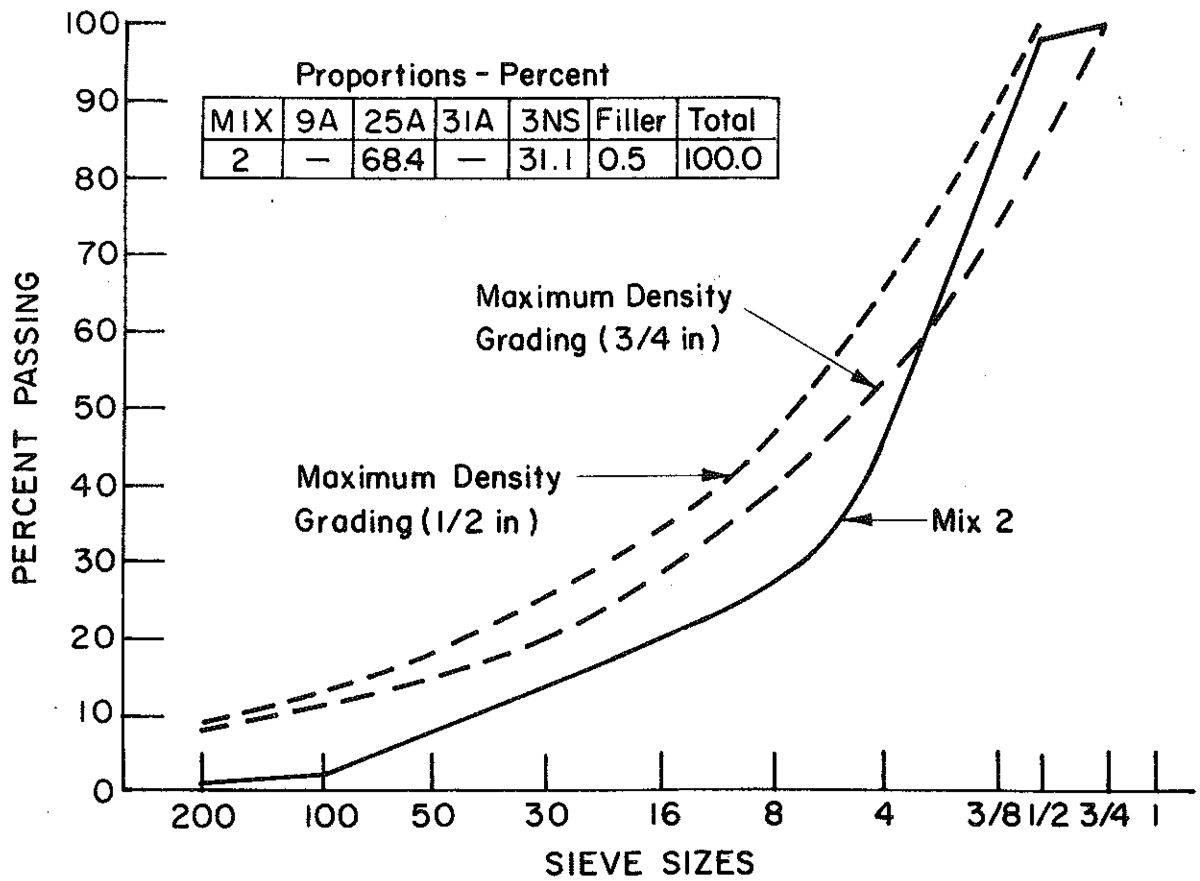


Figure 2 Aggregate Grading for Mix 2

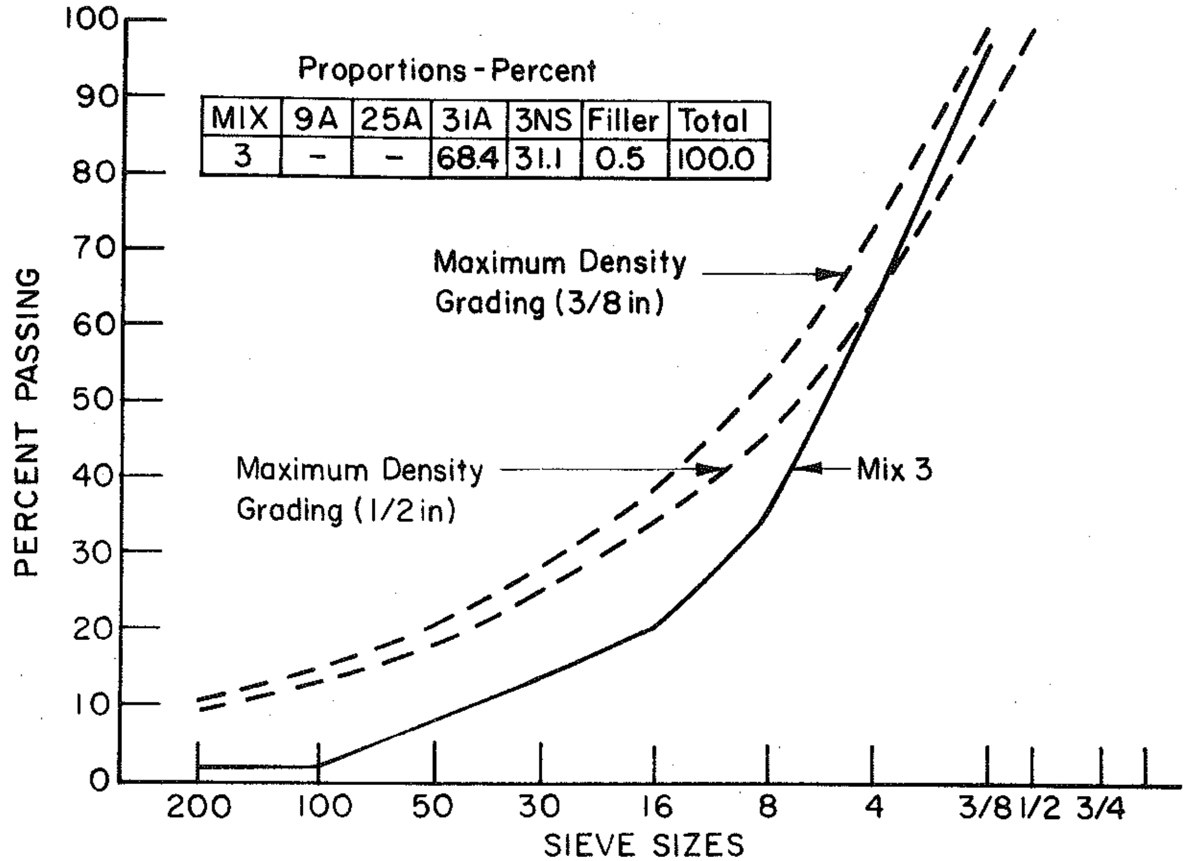


Figure 3 Aggregate Grading for Mix 3

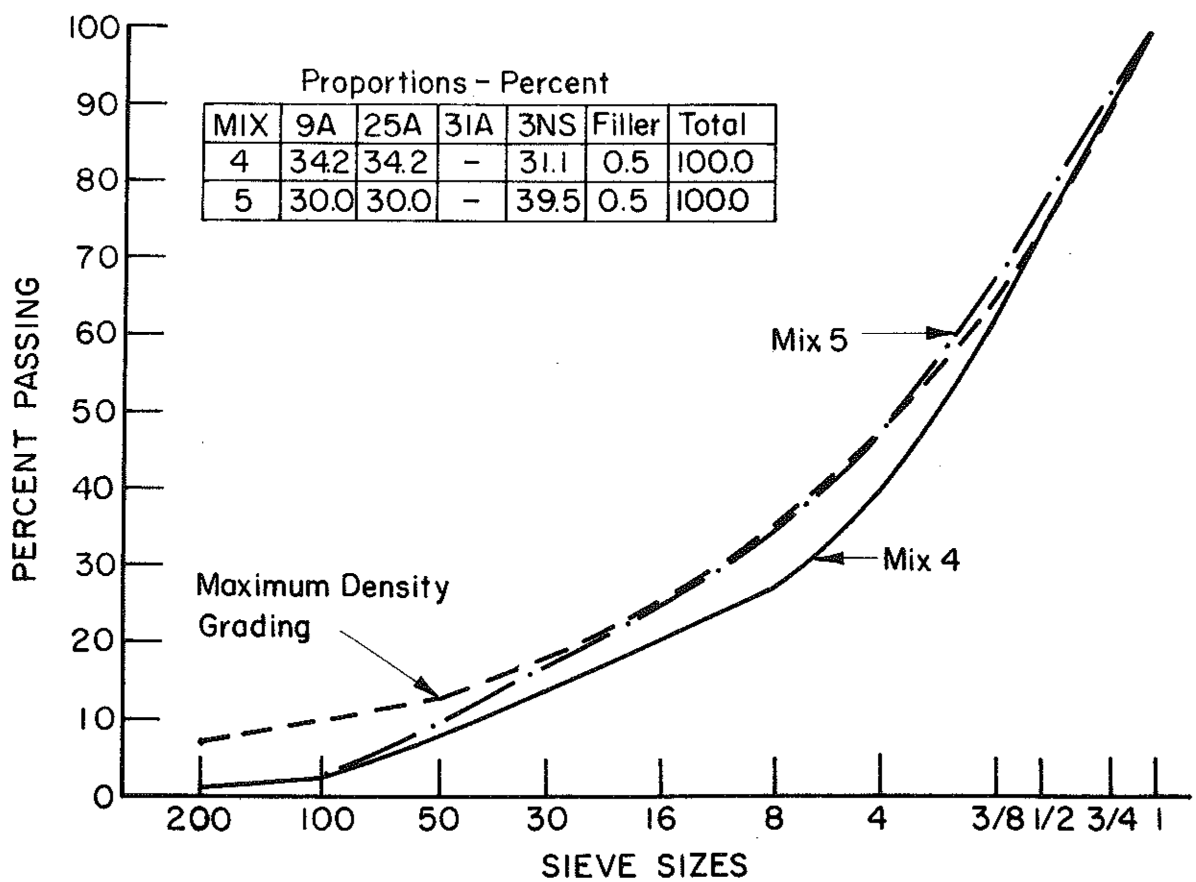


Figure 4 Aggregate Grading for Mix 4 and 5

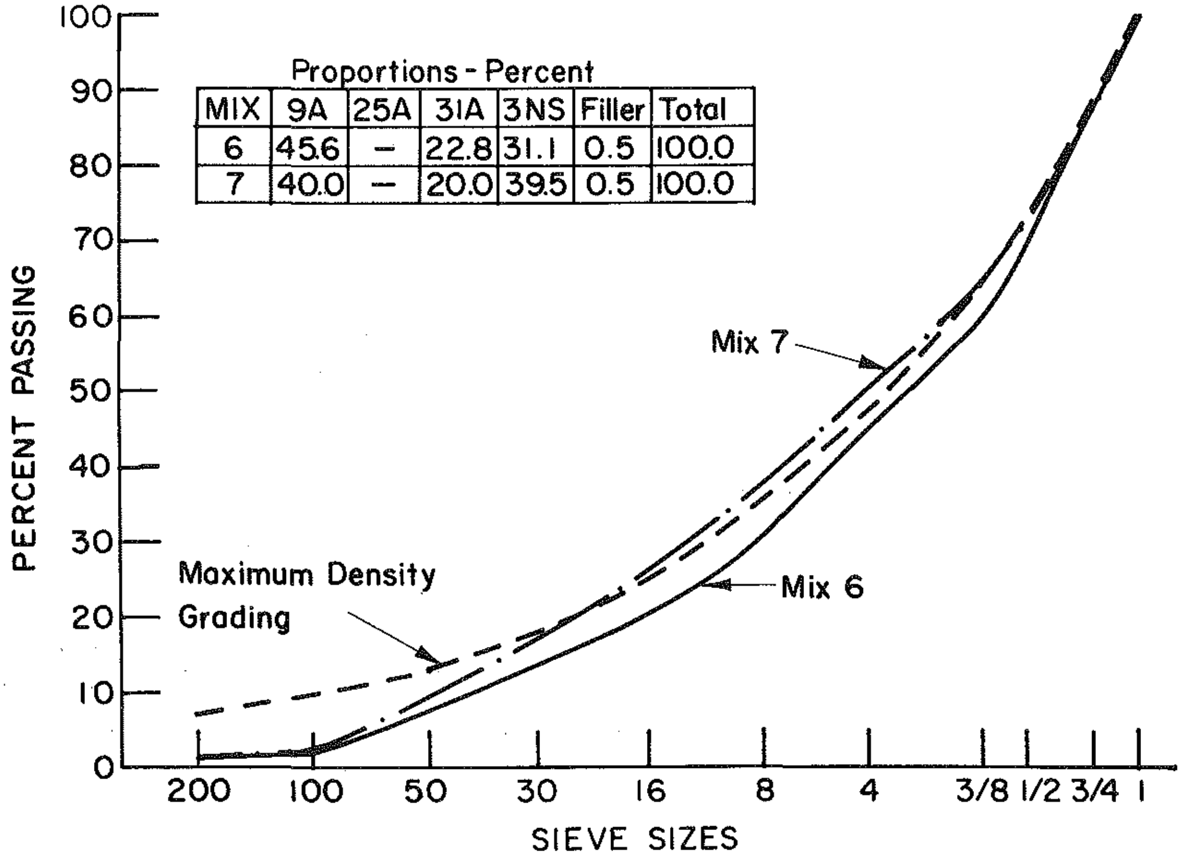


Figure 5 Aggregate Grading for Mix 6 and 7

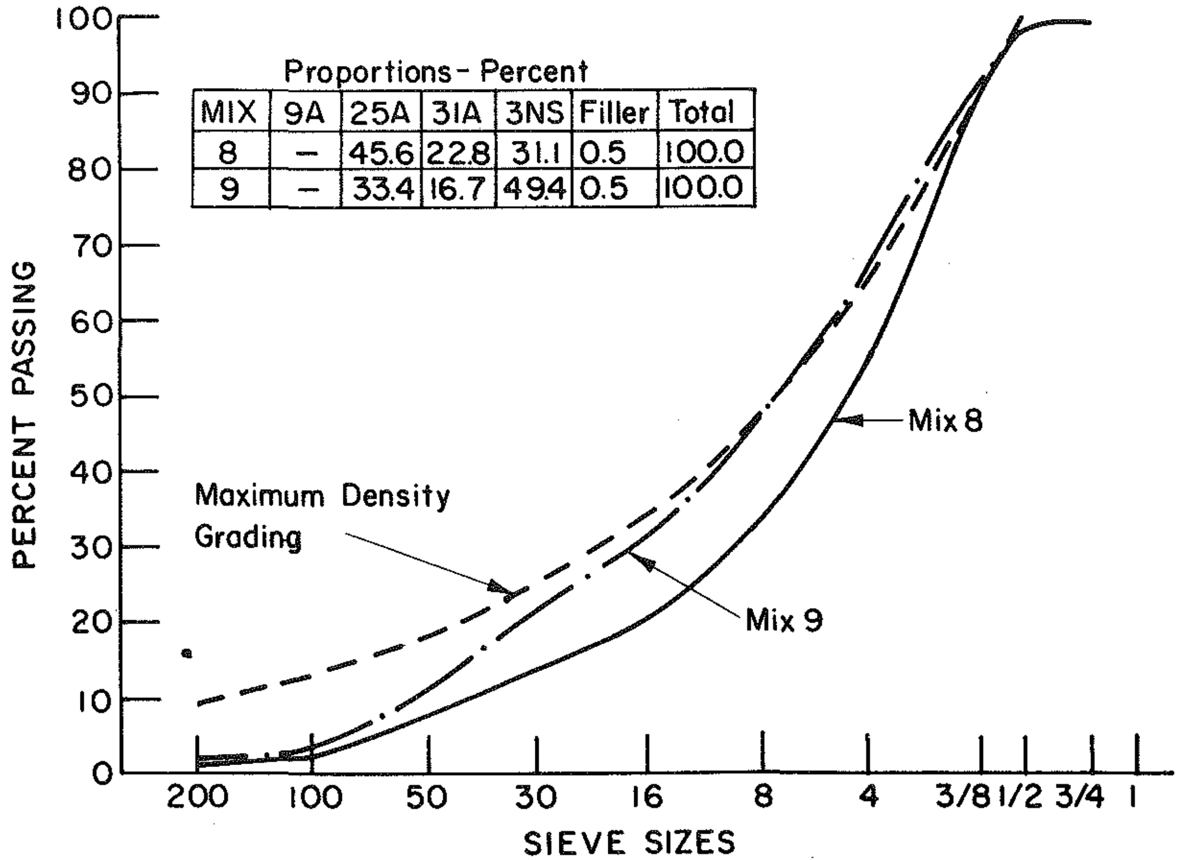
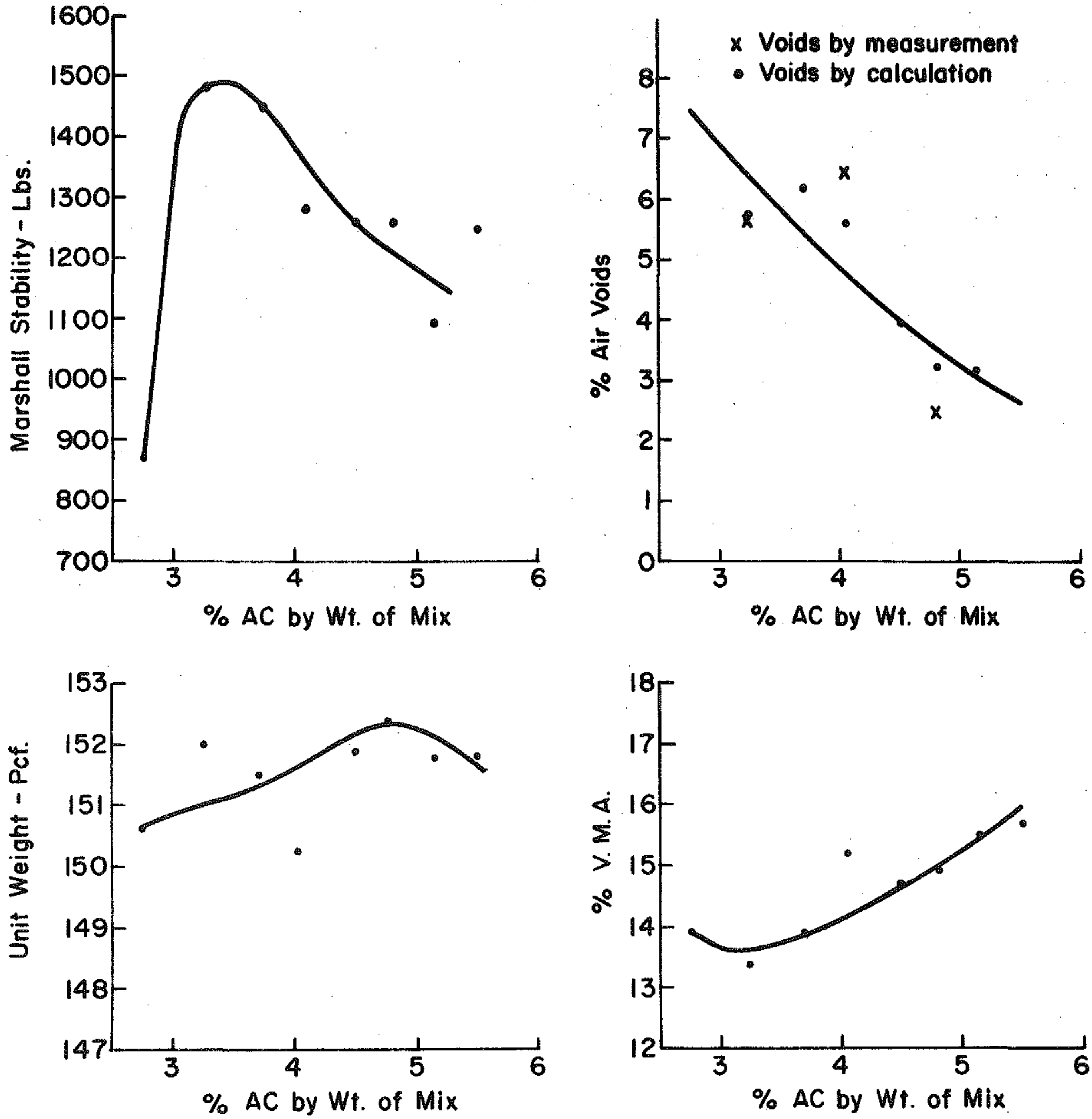
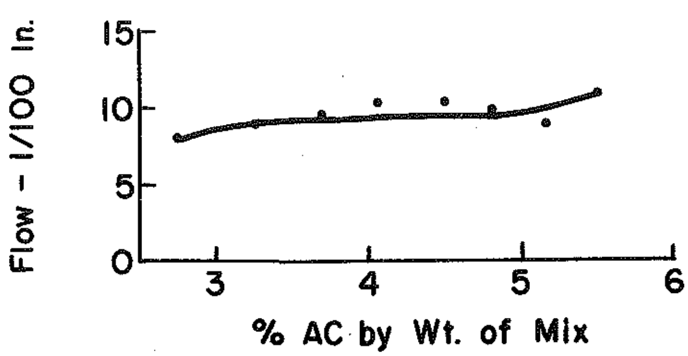


Figure 6 Aggregate Grading for Mix 8 and 9



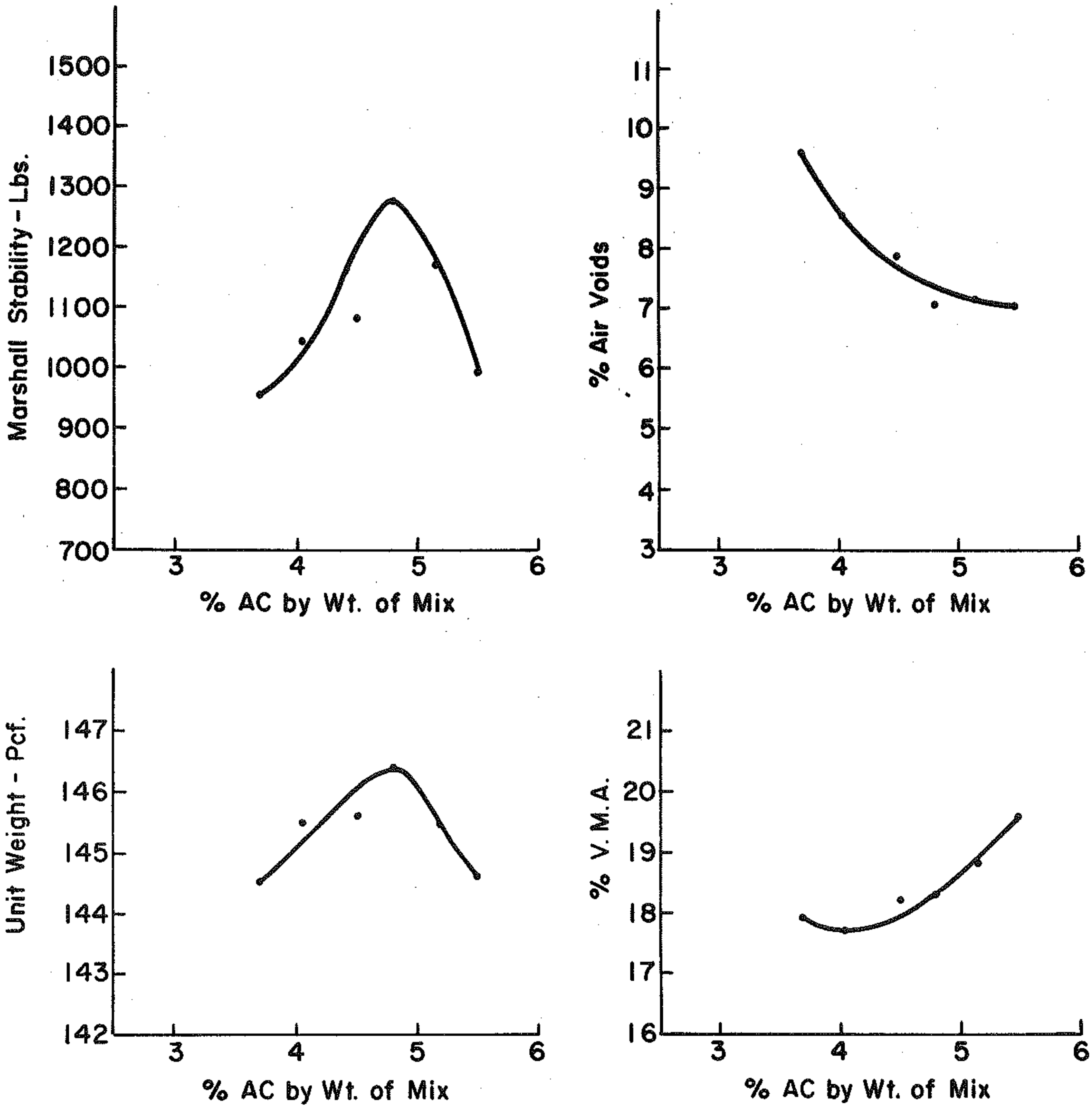


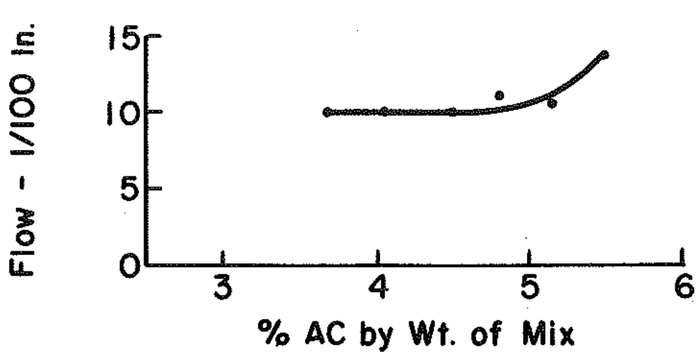
Mix I

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
68·4	–	–	31·1	0·5	100·0

Figure 7 Marshall Data for Mix 1 with Natural Coarse Aggregate



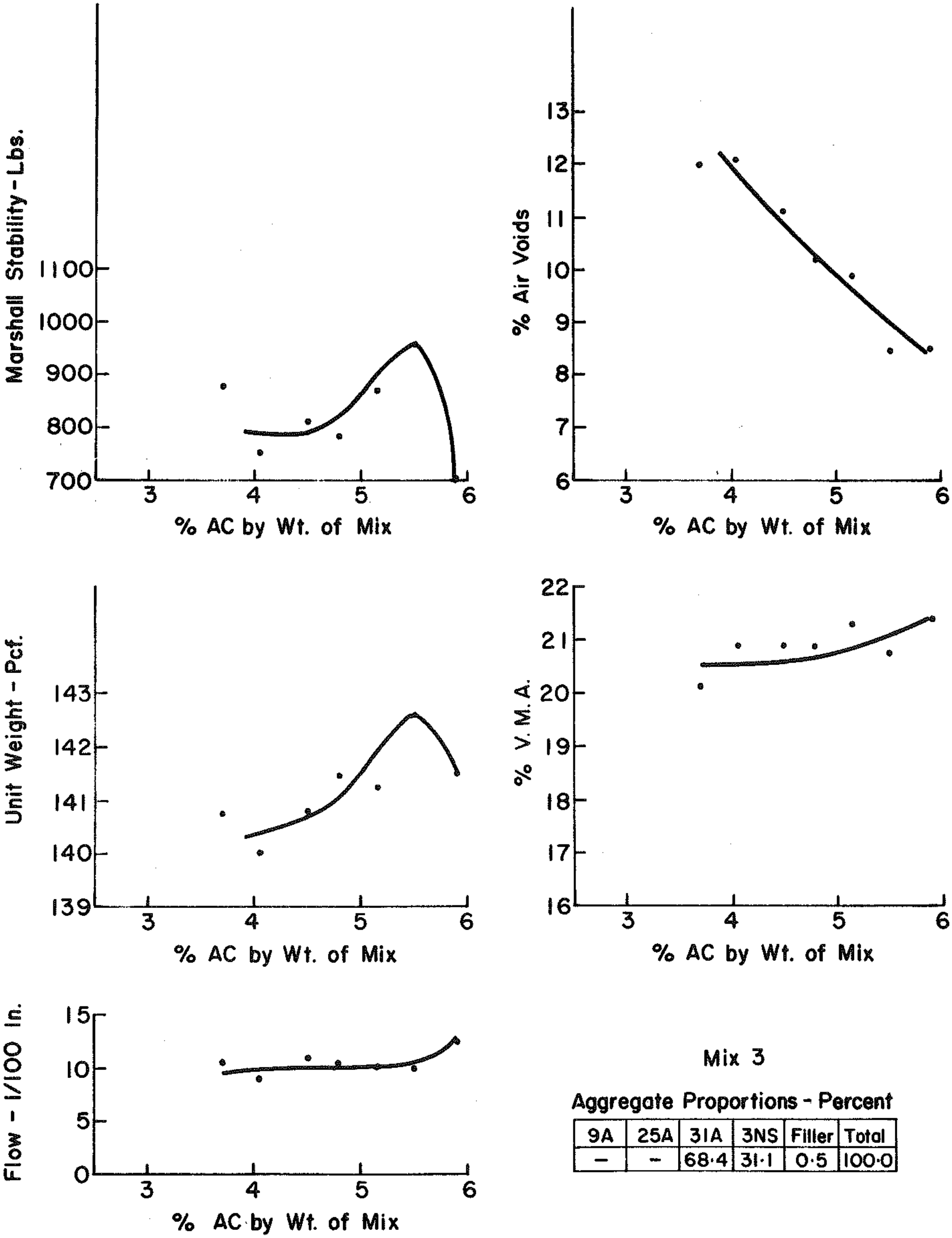


Mix 2

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
-	68·4	-	31·1	0·5	100·0

Figure 8 Marshall Data for Mix 2 with Natural Coarse Aggregate

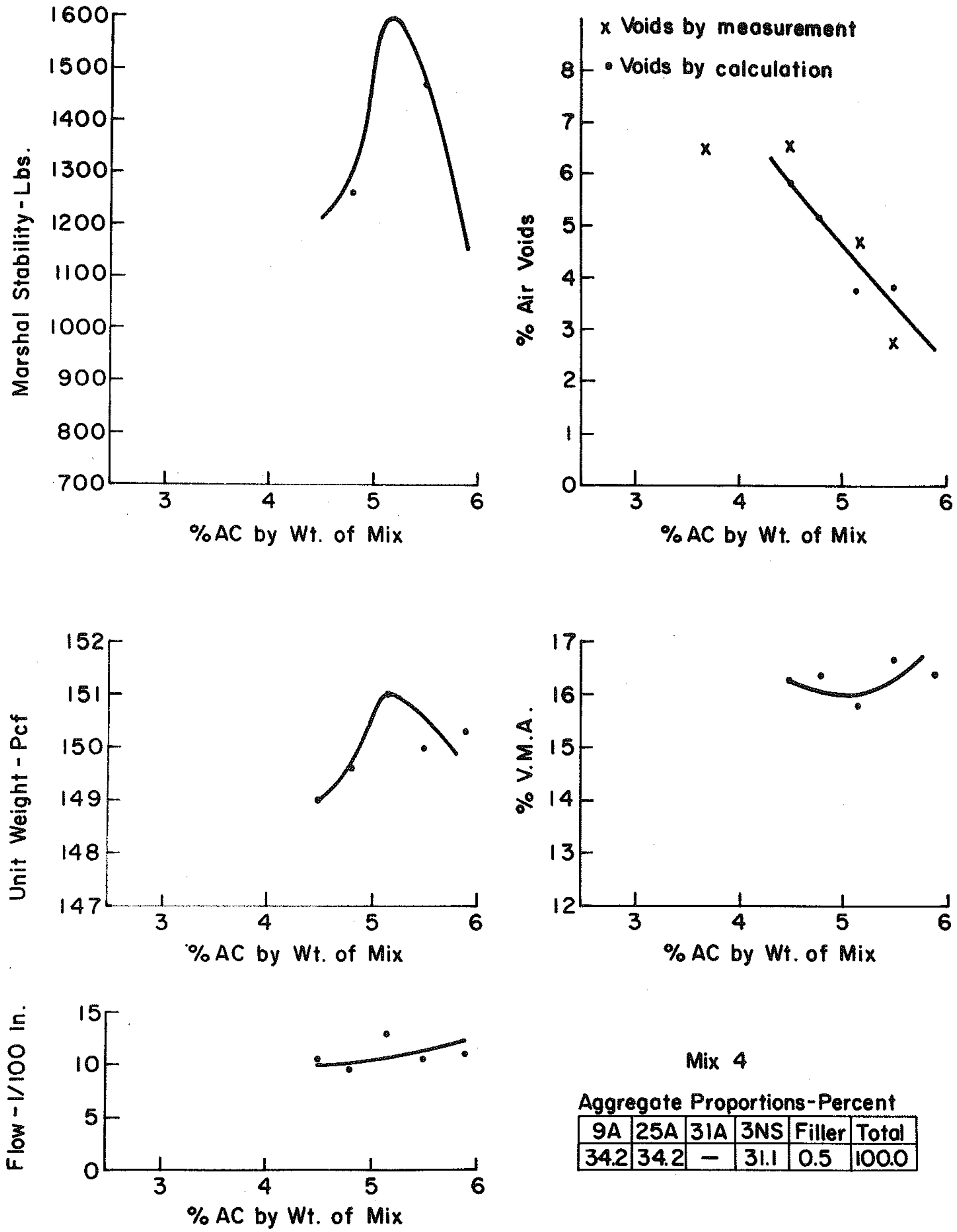


Mix 3

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
–	–	68·4	31·1	0·5	100·0

Figure 9 Marshall Data for Mix 3 with Natural Coarse Aggregate

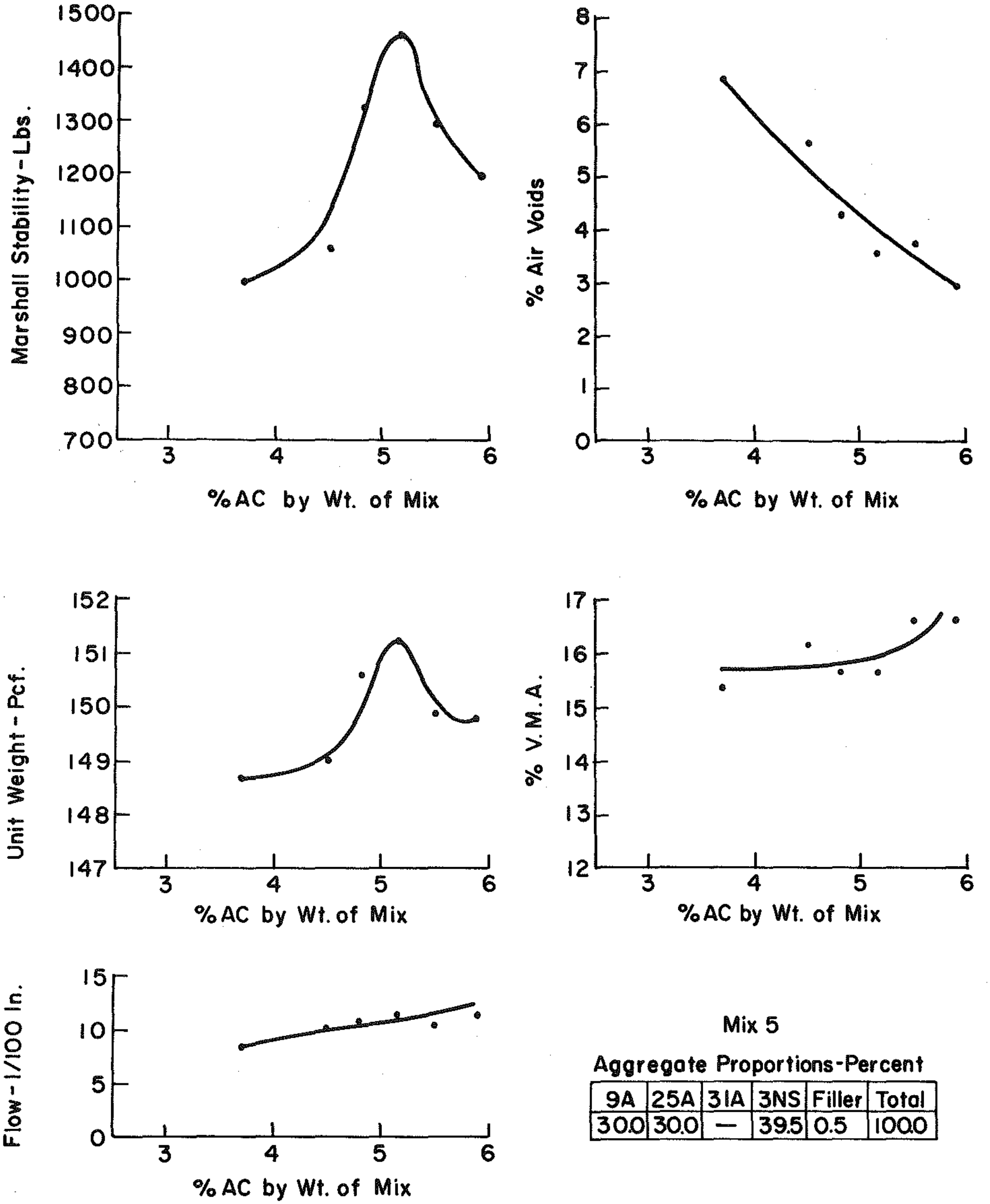


Mix 4

Aggregate Proportions-Percent

9A	25A	31A	3NS	Filler	Total
34.2	34.2	–	31.1	0.5	100.0

Figure 10 Marshall Data for Mix 4 with Natural Coarse Aggregate

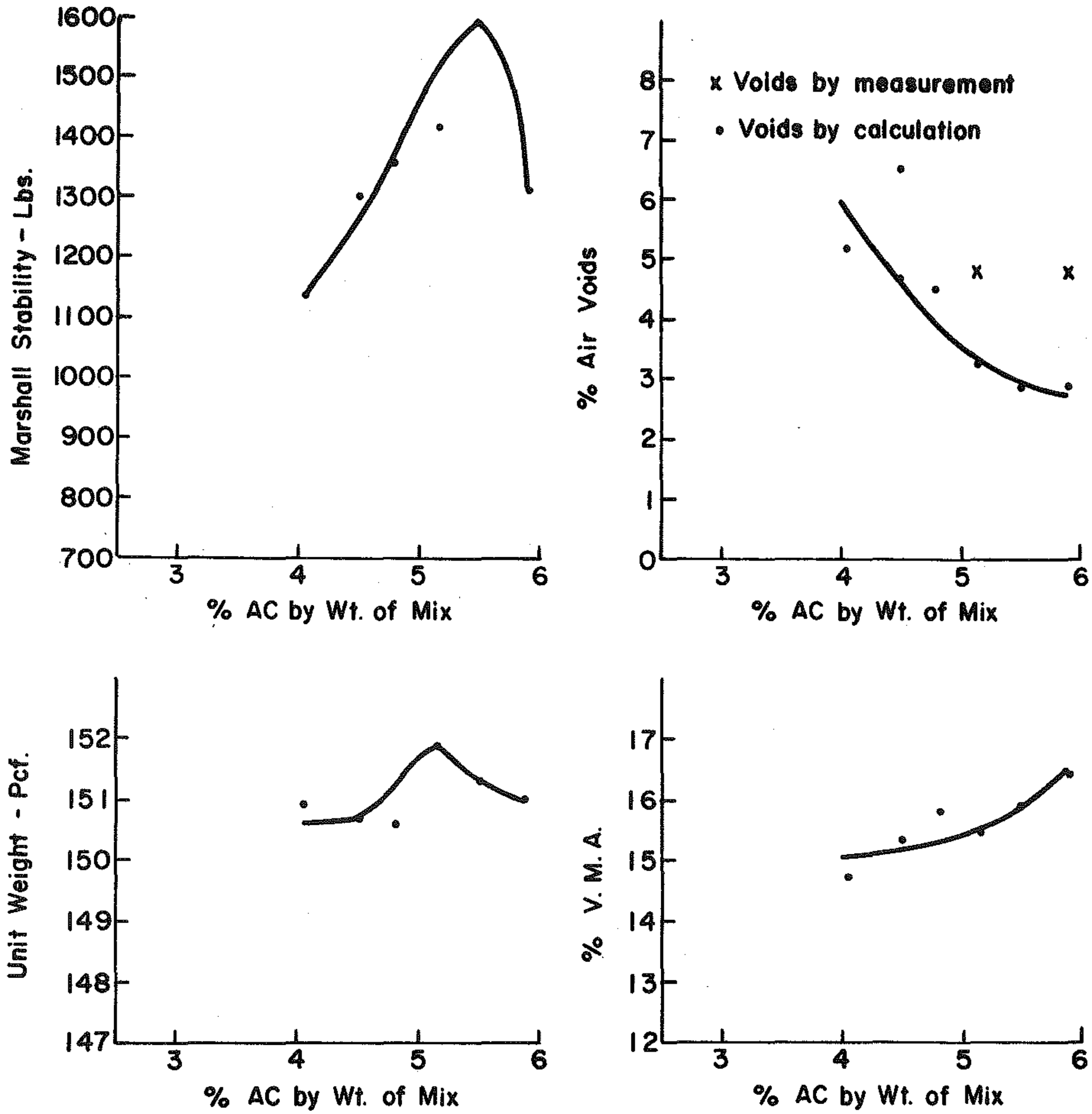


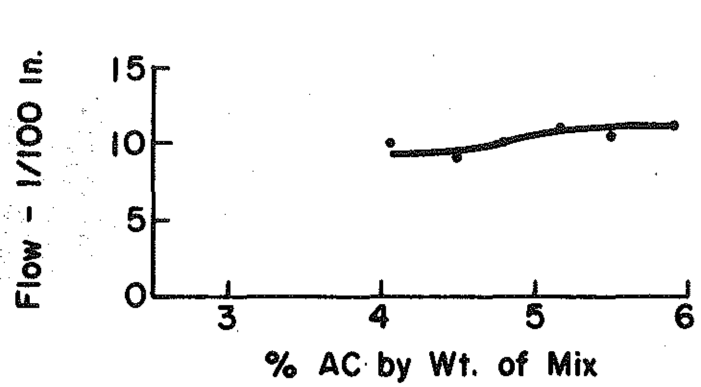
Mix 5

Aggregate Proportions-Percent

9A	25A	31A	3NS	Filler	Total
30.0	30.0	—	39.5	0.5	100.0

Figure 11 Marshall Data for Mix 5 with Natural Coarse Aggregate



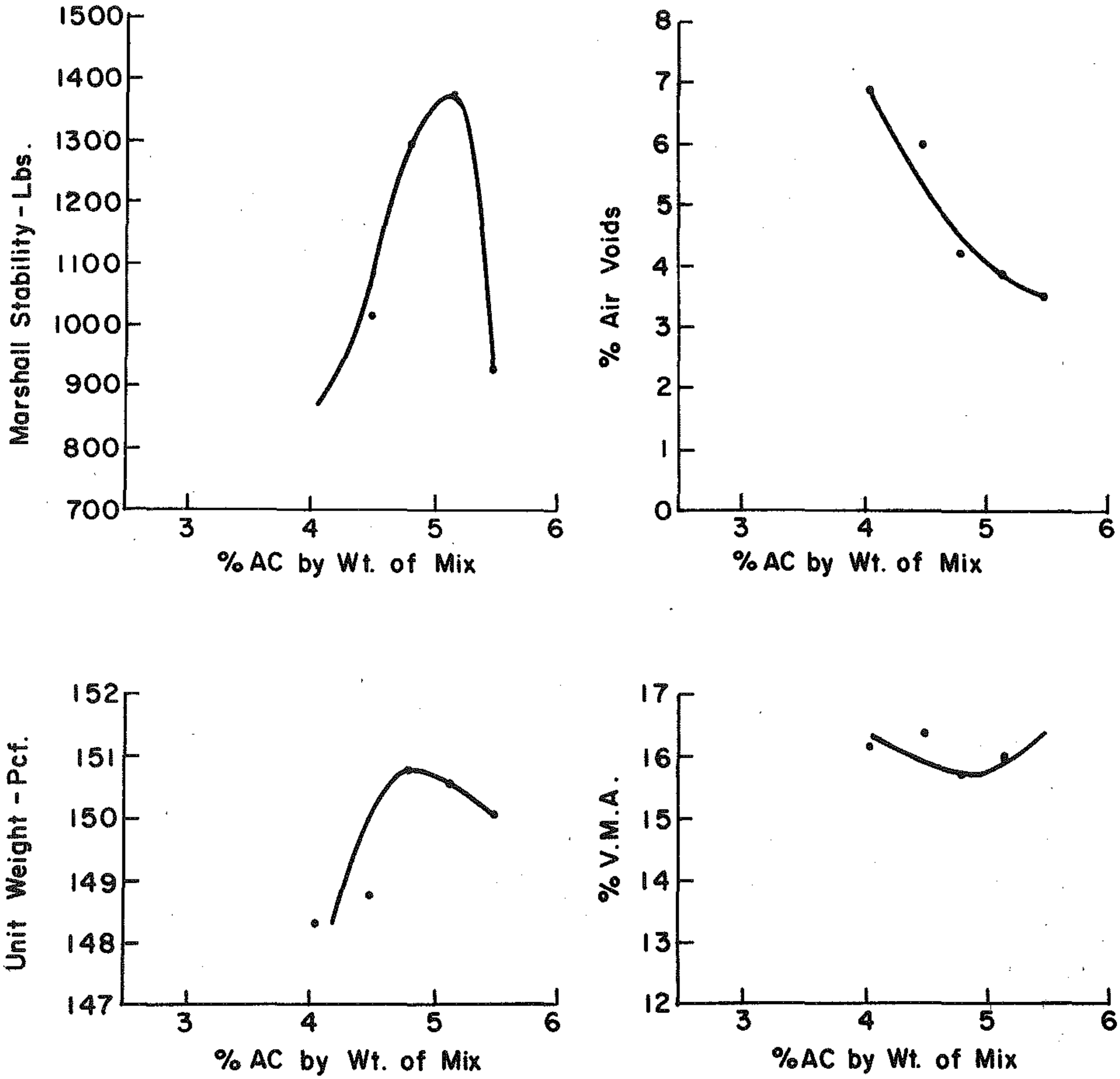


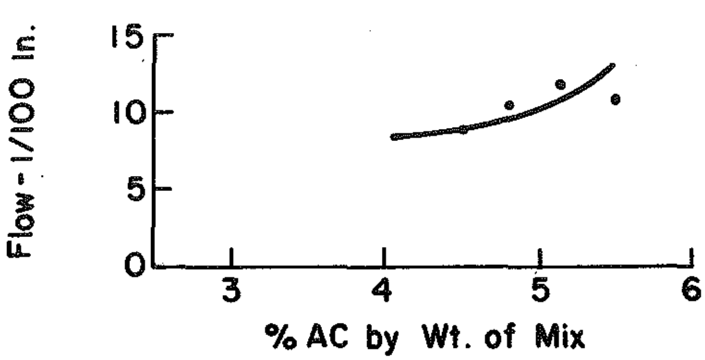
Mix 6

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
45·6	–	22·8	31·1	0·5	100·0

Figure 12 Marshall Data for Mix 6 with Natural Coarse Aggregate



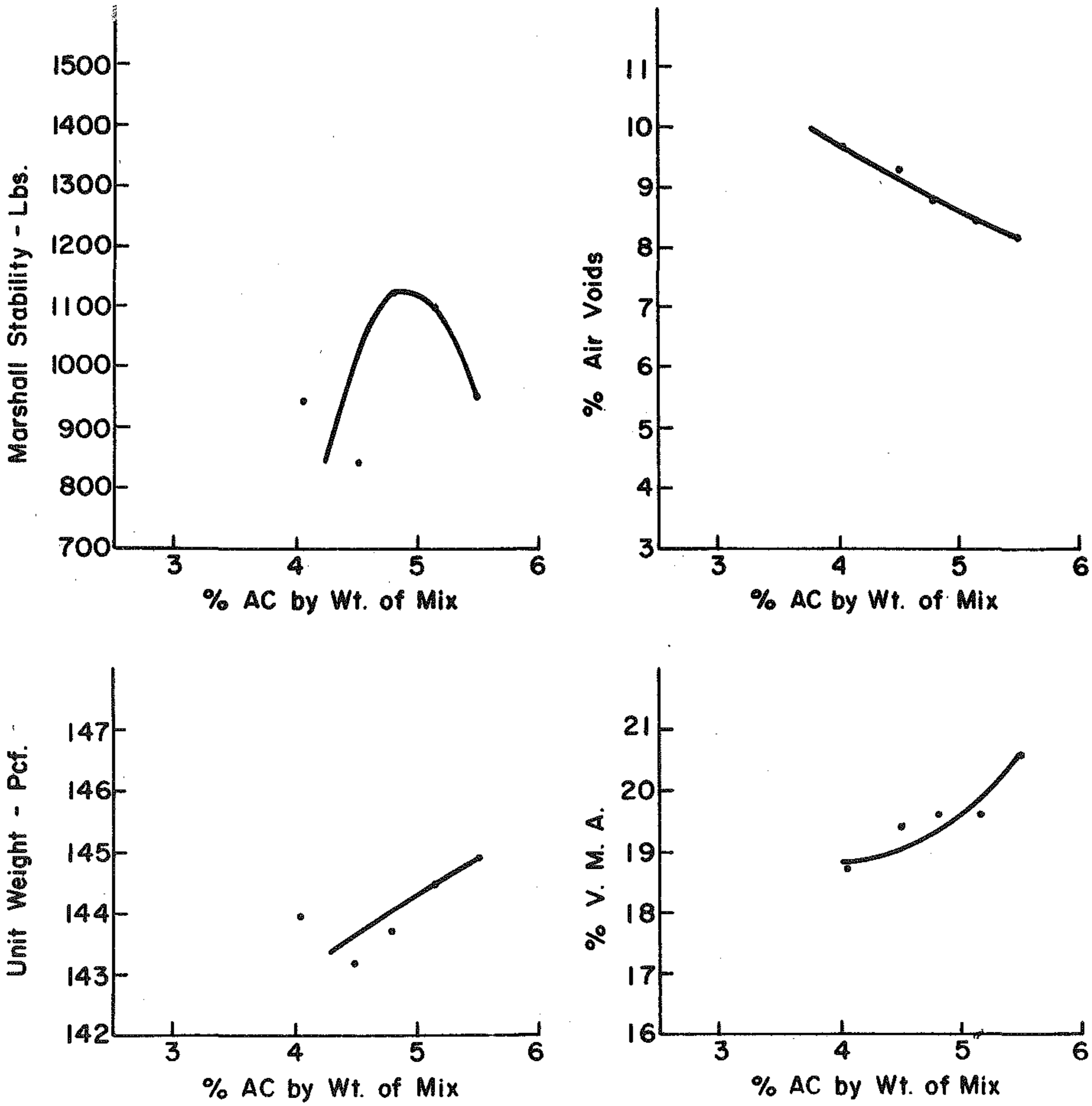


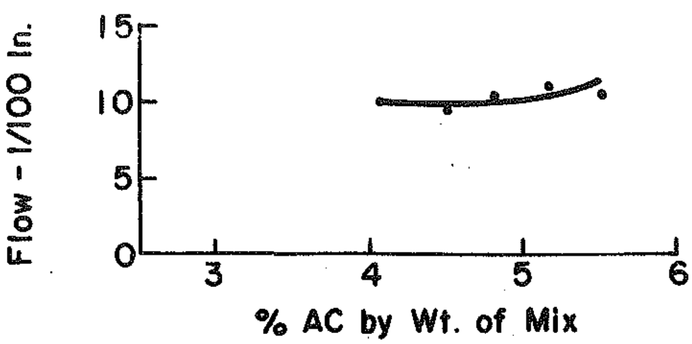
Mix 7

Aggregate Proportions-Percent

9A	25A	31A	3NS	Filler	Total
40.0	–	20.0	39.5	0.5	100.0

Figure 13 Marshall Data for Mix 7 with Natural Coarse Aggregate



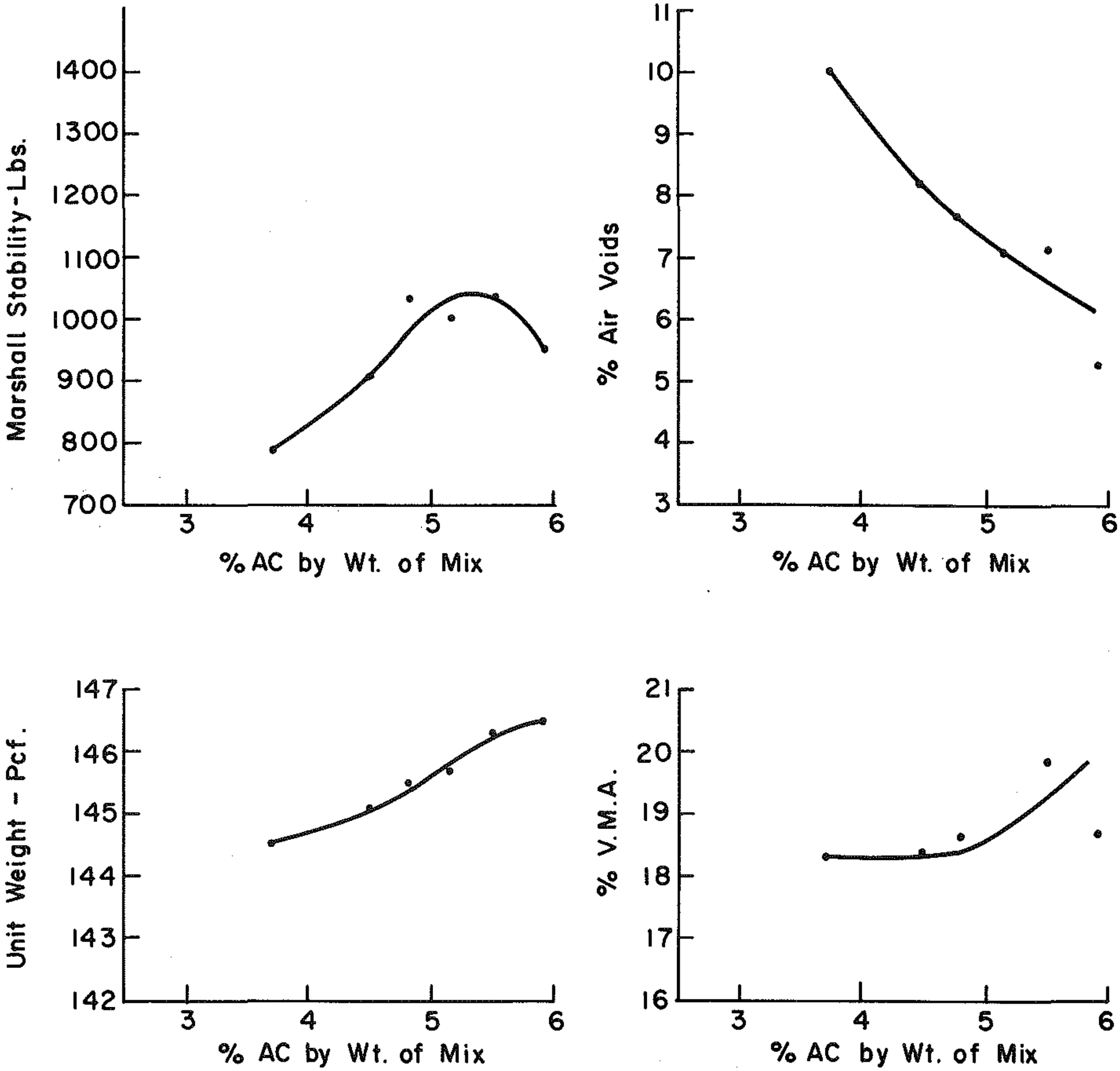


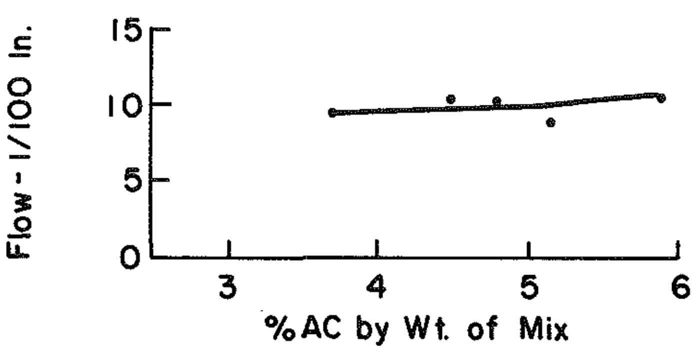
Mix 8

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
–	45·6	22·8	31·1	0·5	100·0

Figure 14 Marshall Data for Mix 8 with Natural Coarse Aggregate



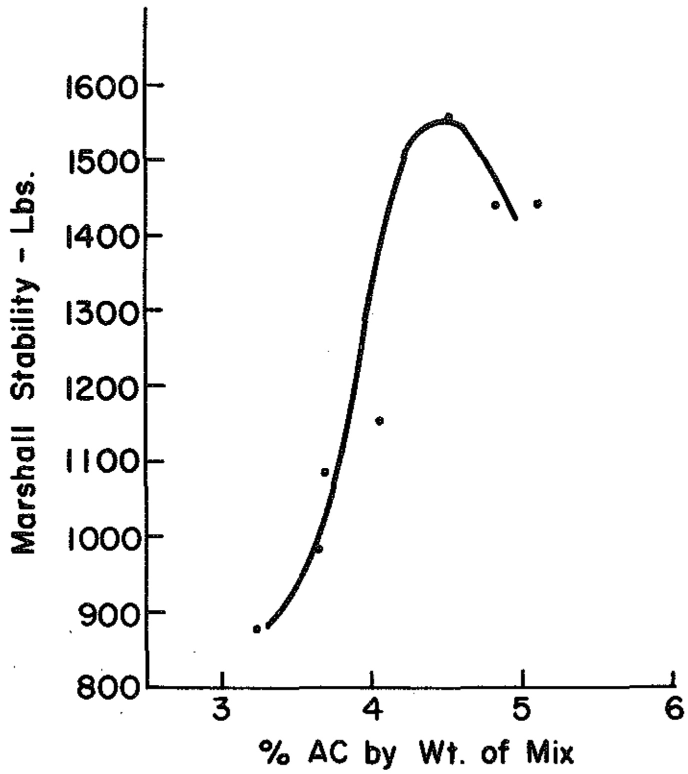


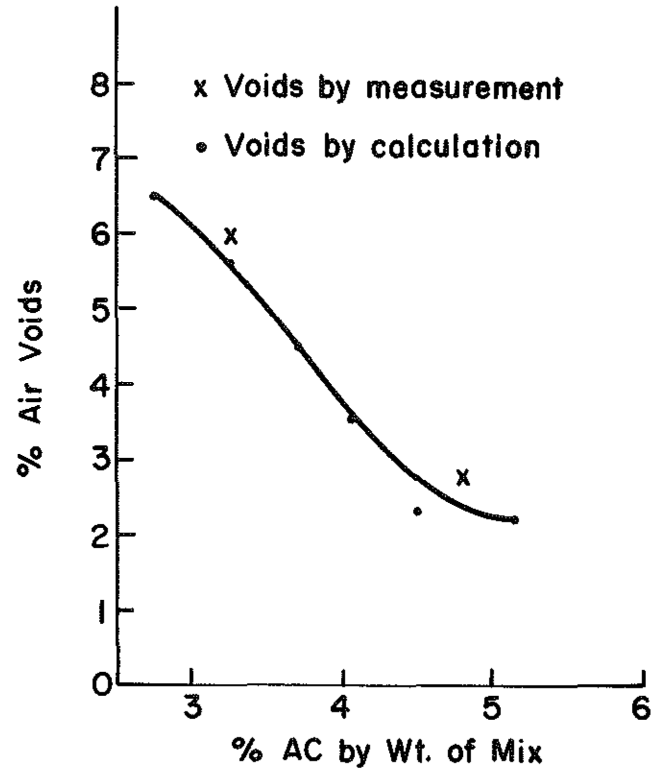
Mix 9

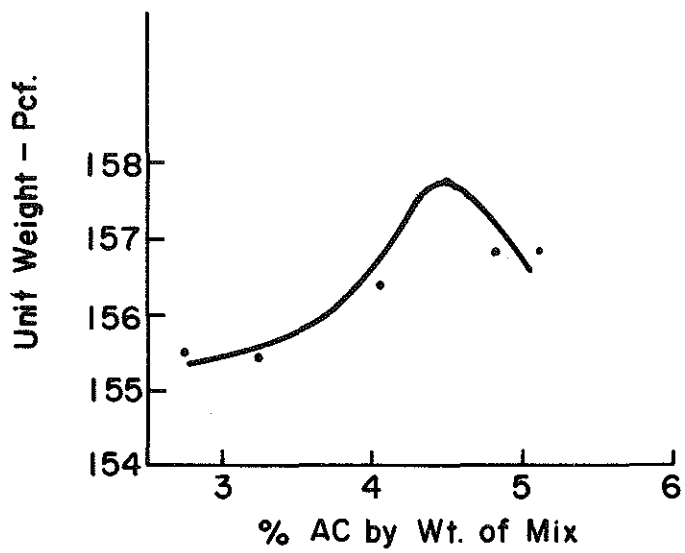
Aggregate Proportions-Percent

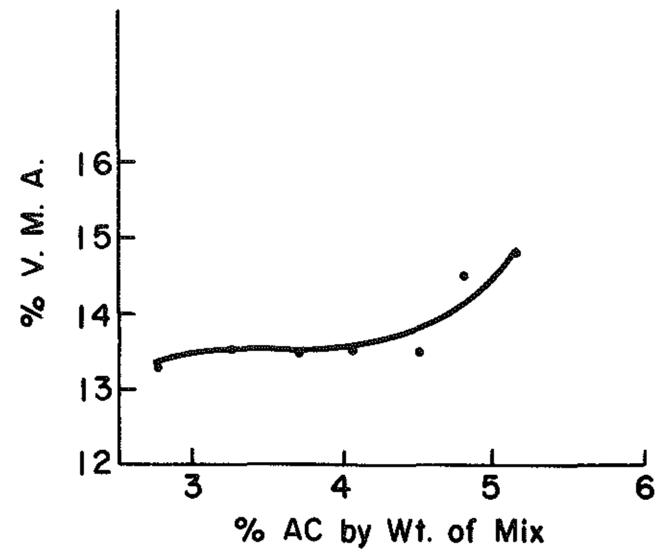
9A	25A	31A	3NS	Filler	Total
–	33.4	16.7	49.4	0.5	100.0

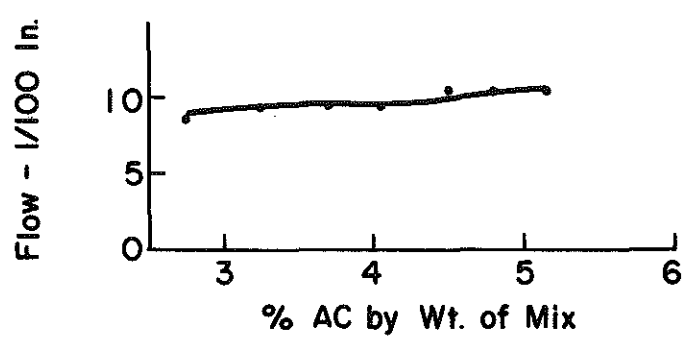
Figure 15 Marshall Data for Mix 9 with Natural Coarse Aggregate









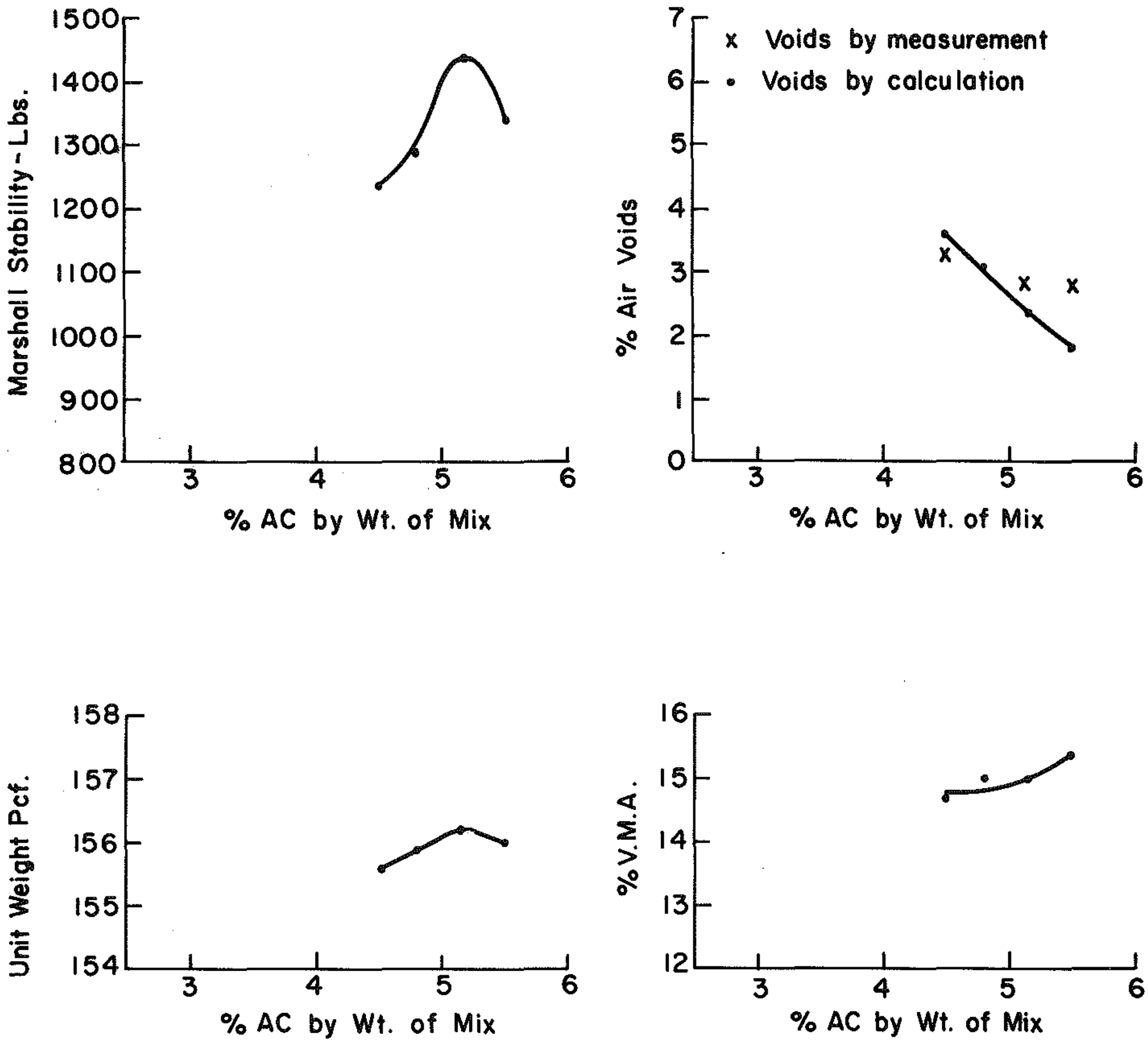


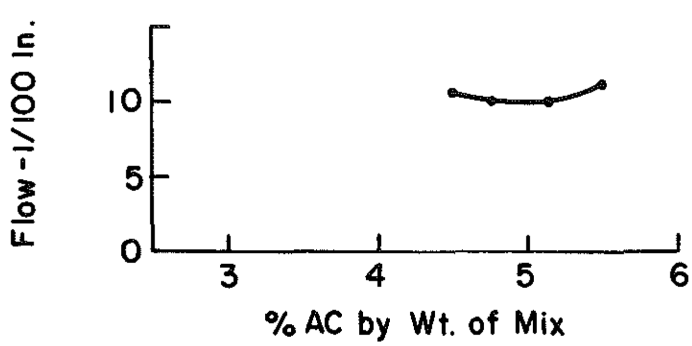
Mix 1

Aggregate Proportions - Percent

9A	25A	31A	3NS	Filler	Total
68·4	-	-	31·1	0·5	100·0

Figure 16 Marshall Data for Mix 1 with Crushed Dolomite Coarse Aggregate



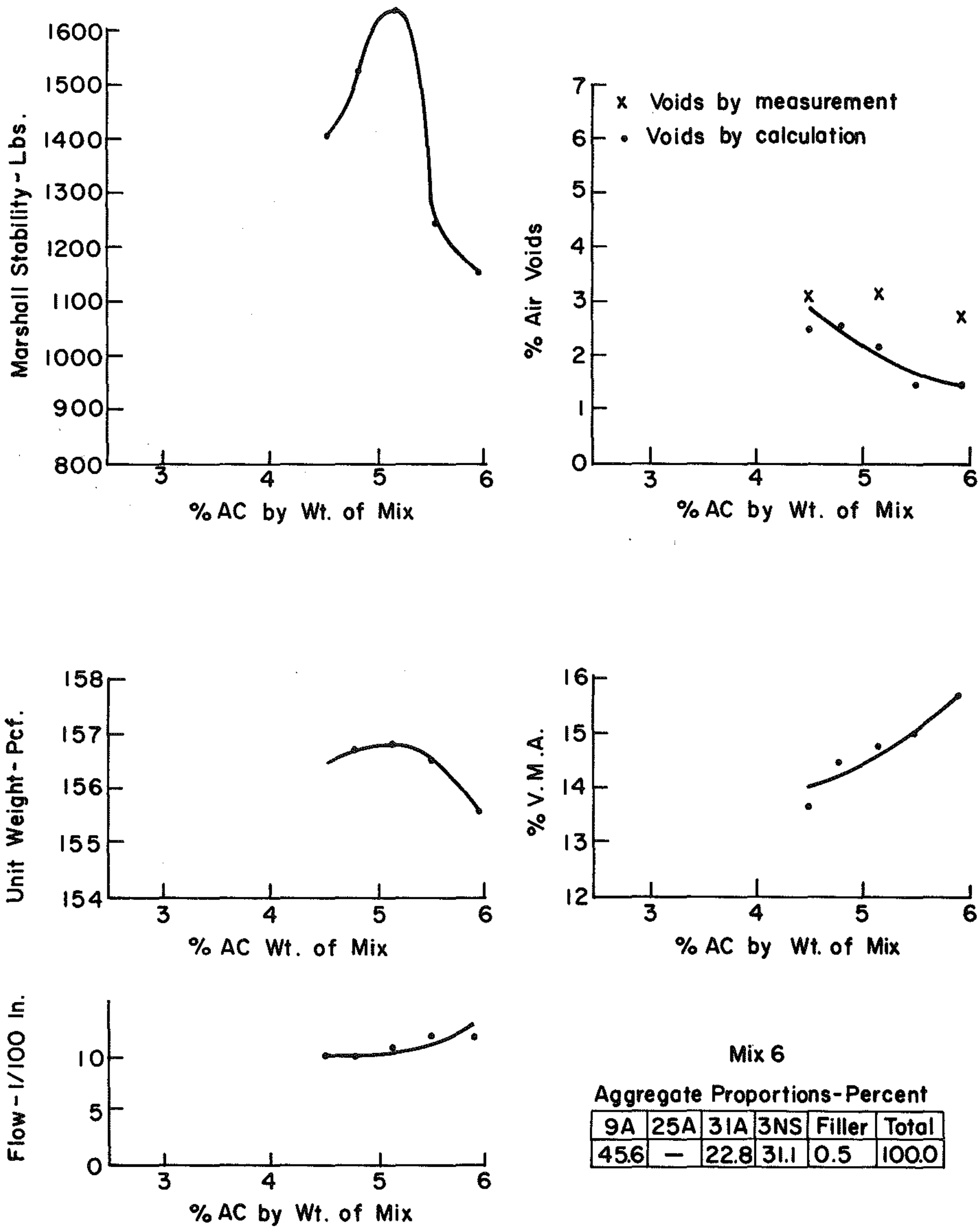


Mix 4

Aggregate Proportions-Percent

9A	25A	31A	3NS	Filler	Total
34.2	34.2	—	31.1	0.5	100.0

Figure 17 Marshall Data for Mix 4 with Crushed Dolomite Coarse Aggregate



Mix 6

Aggregate Proportions-Percent

9A	25A	31A	3NS	Filler	Total
45.6	—	22.8	31.1	0.5	100.0

Figure 18 Marshall Data for Mix 6 with Crushed Dolomite Coarse Aggregate

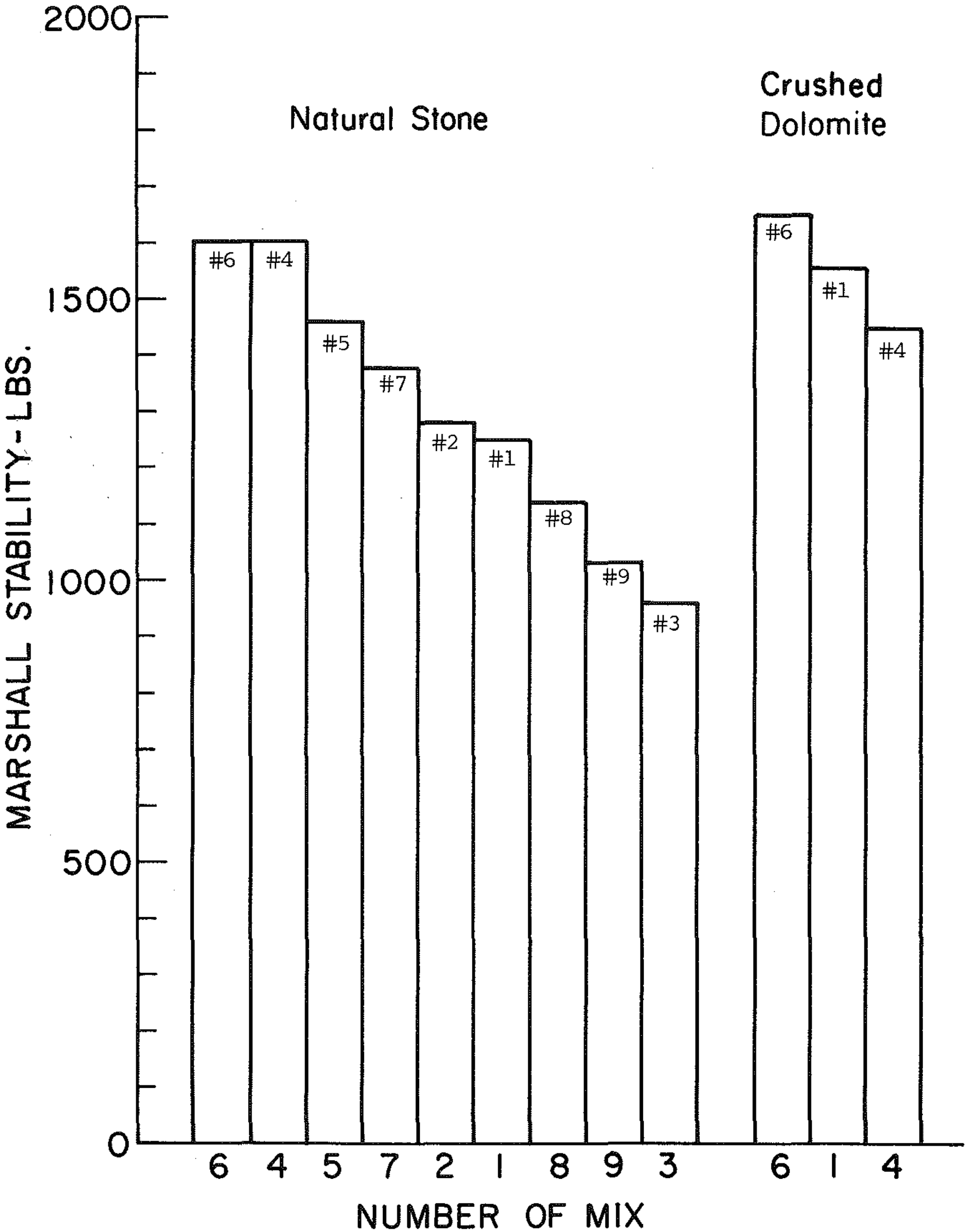


Figure 19 Peak Marshall Stability Attained for Each Mix at Asphalt Content Above 4.5%

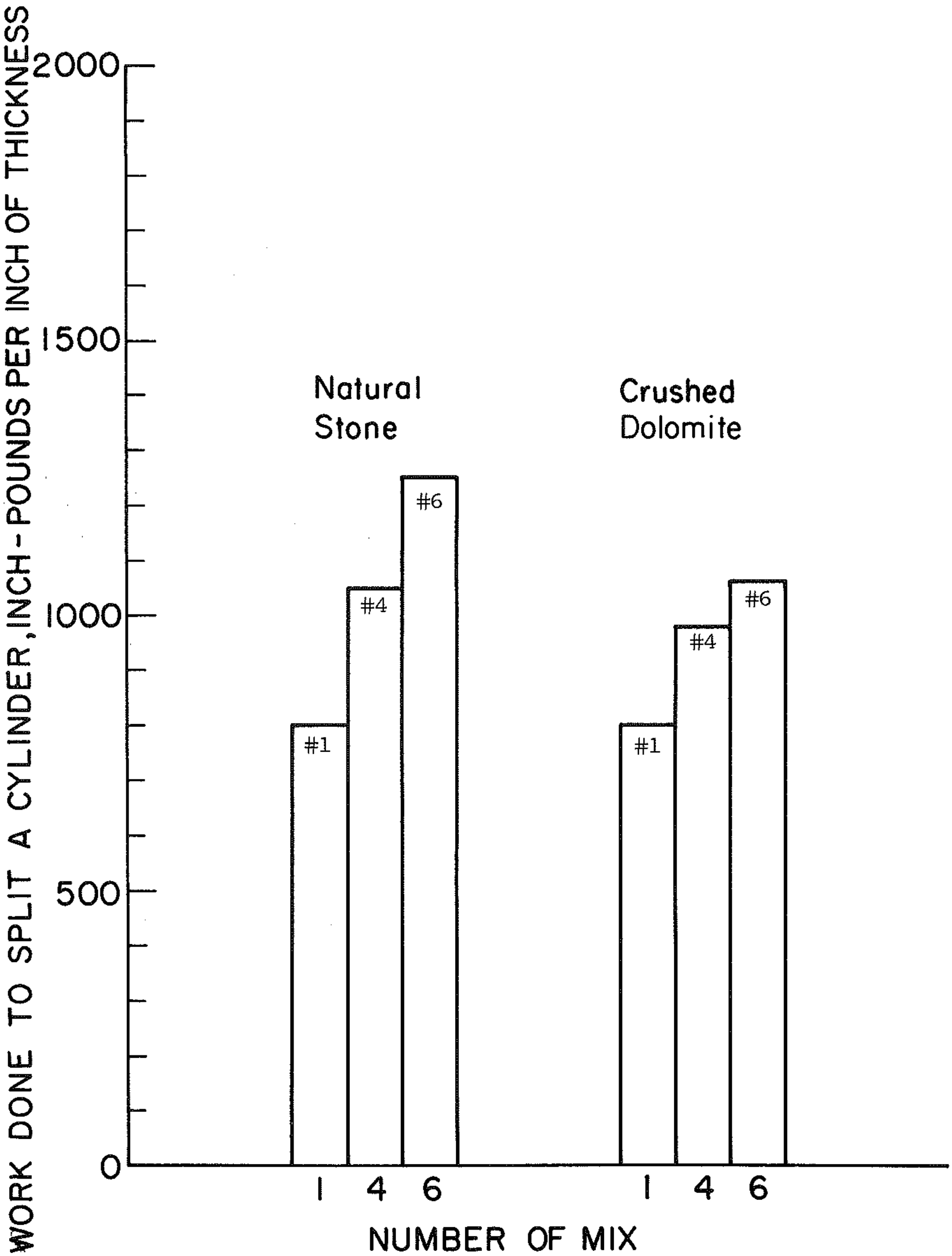


Figure 20 Comparisons of Work Necessary to Split Cylinders Made Out of Various Mixes

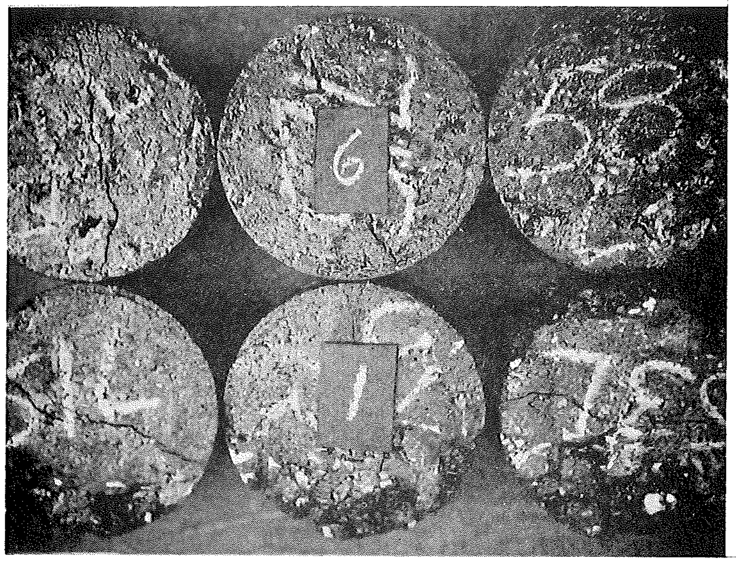


Figure 21 Mix 6 (top 3 specimens) shows less segregation than Mix 1 during placement and compaction

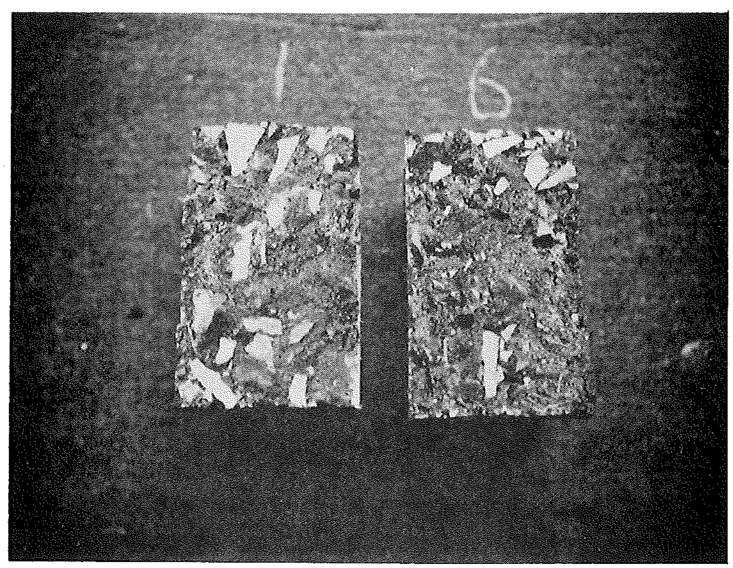


Figure 22 Broken surfaces of Mix 1 show more crushed and degraded particles than in Mix 6