FINDING THE MAXIMUM PRACTICABLE DENSITY OF COARSE AGGREGATE THROUGH SCIENTIFIC GRADING

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In the November, 1923 issue of the Crushed Stone Journal; the United States Bureau of Public Roads made an annoucement in which they declared, that the results of their research and tests, show that it is possible by applying the theories developed by the experiments; to produce concrete of much greater uniformity and increased strength. Chief Thos. H. Mac Donald, laid the following principles by which these results may be obtained.

1. The abandonment of volumetric proportioning of aggregates and the adoption of proportioning by weights as standard practice. Inundation will be recognized as a permissible alternate method for fine aggregate, but weighing is preferred.

2. Maintenance of the lowest water-cement ratio which, with the particular type, grading and proportions of aggregate used, and the methods of finishing employed, will produce a workable, dense and uniform concrete.

3. The scientific grading of coarse aggregate by combination of separated sizes in each batch in the porportions which will produce the maximum practicable density.

4. The abandonment of the hand finishing methods in favor of machine finishing.

The principle which is of very vital interest to all producers of either gravel or crushed stone; is No.3.

One of the many reasons for the laiding down of this principle was that segregation of sizes of aggregates occurs in storage piles which have been built up as a cone by dropping material in the center. The larger particles roll to the bottom of the cone and the smaller ledge somewhere between the top and the botton with the smallest at the top. The worst cases of seggregation are found in piles built up by conveying machinery which discharges in one spot only. If, in addition, material is removed by a loader that works around the edge of the pile, the core and the top of the pile may become almost entirely fine material and the base all large rock. A sieve analysis from such a pile 20 feet high gave the following results: (This sieve analysis was made by the Portland Cement Association)

Sieve Size Iniches	Per cent Passing Sample taken from Center of Pile	¾ ths. of Distance to outer edge of Pile	Outer edge of Pile
2½"	100	100	100
2	94	34	30
1	56	30	0
¼	17	1	0

It is nearly impossible to make good concrete with segregated materials. When the coarse rock is going into the mixer the concrete is harsh; when the center of a segregated pile is being used there is too much fine material. The result is porous concrete in the first case and weak, scaly concrete in the second. Segregated materials can be done away with by the application of Principle NO.3.

For the application of this principle the producer must ship his gravel, not according to a given gradation extending from the smallest to the largest size as is present-day practice, but, on the other hand, the gravel must be separated and shipped in several different sizes, such, as illustration, as ¼ to ¾ in., ¾ to 1½ in., and 1½ to 2½ in. These separate sizes will then be combined at a centeral proportioning plant and the proper quantities of each batch of concrete made. This method of proportioning is intended to produce concrete of greater uniformity and because of the uniformly low voids thus produced in the gravel, an increased amount of gravel and a decreased amount of mortar is rendered possible, with no sacrifice in strength.

There is no lost of strength but rather an increase according to the principles of proper proportioning, given by George A. Hool, Consulting engineer, Professor of Structural Engineering of the University of Wisconsin. He states, " For given materials (including water) and assuming workable mixtures only, the following factors govern the theory of proper proportioning, namely

1. Strength of concrete is determined by the ratio of the volume of mixing water to the volume of cement, called water-cement ratio. Strength increases as the water-cement ratio decreases.

2. For the same workability, the strength of concrete is increased by using coarser aggregate, since coarser aggregate requires less water and reduces the water-cement ratio.

3. For water-tight work, the size as well as the percentage of voids is important; therefore, careful attention should be given to the grading of the aggregates.

4. The quanity of cement and the size and grading of the aggregate affect the strength of the concrete only in so far as they affect the quanity of mixing water needed.

5. For a given mix, the strength of concrete is increased by increasing cement content, or decreasing the water content.

The fact that the Bureau of Public Roads is encouraging these new methods for concrete proportioning will undoubtedly result in their very wide adoption and as time goes on, gravel producers will be called upon to ship gravel in two or more, separated sizes to be combined in their proper proportions at the site of the work. The development of a desire for more uniform concrete has been quite apparent and the present action on the part of the Bureau of Public Roads was foreseen by the Bureau of Engineering of the Crushed Stone Association as a strong possibility more than a year ago. Consequently, work was immediately started in their laboratories and the information gain was given to the crushed stone producers.

Therefore the gravel producer is naturally interested in knowing what affect this new method of concrete proportioning will have on his production problems. Principle No.3 states that the coarse aggregate is to be combined in each batch in those proportions which will produce the maximum practicable density. This, in general, means the combinations of the various sizes of gravel in such a way that the smallest percentage of voids will result. The purpose of this thesis is, therefore, to determine what combinations of sizes will give the lowest percentage of voids and also what variation may be made in the proportions of the different sizes without increasing the voids appreciably over the minimum.

Method of Procedure

For the purpose of this investigation gravel of a rather good quality was used. It was screened into eight different sizes as follows; 1/8 - 1/4 in., 1/4 - 3/8 in., 3/8 - 1/2 in., 1/2 - 3/4 in., 3/4 - 1 in., 1 - 1½ in., 1½ - 2½ in.

The 1/8 - 1/4 in., 1/4 - 3/8 in., 3/8 - 1/2 in., and 1/2 - 3/4 in. sizes were then combined in accordance with a straight line gradation. A straight line on a mechanical analyses diagram indicates a uniform grading size. The mechanical analysis of this combination is shown as curve No. 66 in Fig. 1 . This required 20% of 1/8 to 1/4in., 20% of 1/4 to 3/8 in., 20% of 3/8 to 1/2 in. and 40% of 1/2 to 3/4 in. sizes.

Similarly the 3/4 to 1 in. and the 1 to 1½ in. sizes were combined in the proportions of 33 1/3 per cent of the 3/4 to 1 in. and 66 2/3 per cent of the 1 to 1½ sizes, this straight line gradation is shown in curve No. 11 in Fig. 1.

The 1½ to 2 in. and 2 to 2½ in. sizes were combined in equal proportions to produce a straight line gradation shown in curve No. 1. in Fig. 1. These three sizes, each having a straight line mechanical analysis curve were then combined in 66 different proportions having mechanical anayses all shown in Fig. 1. It will be noted that these mechanical analyses curves cover the entire field of possible combinations for these three different sizes. These combinations are also shown in the triaxial diagram of Fig. 2. As this diagram is very convenient for showing the effects resulting from the combinations of three sizes of gravel in different proportions it will be well to explain it briefly.

Each point on the diagram represents a given combination of the three different sizes of materials and the percentage of each size is represented by the perpendicular distance between the point on the diagram and the side of the triangle which serves as the base line for the size under consideration. Thus, point No. 42 in Fig. 2 represents a material made up of 40 per cent of 1/8 to 3/4 in., 30 per cent of 3/4 to 1½ in., 30 per cent of 1½ to 2½ in. size. Similarly, point No. 11 represents 100 per cent of 3/4 to 1½ in. and 0 per cent of the other sizes.

From this diagram it can be seen again that all the possible combinations of the three batches are covered. The 1/8 in. size was chosen as the smallest size used in this investigation because standard coarse aggregate specifications permit not more than 5 per cent of the aggregate to pass a sieve having opening 0.185 in. square, and by extending the minimum size down to 1/8 in., the permissible amount passing the 1/4 in. screen will approximately be obtained.

The procedure in testing was to weigh out 90 pounds of the combined sizes which were then thoroughly mixed. This mixture was shoveled into a standard American Society for Testing Materials one-half cubic foot measure. The tests were made in two ways, first, by loose measurement and, second, by the standard A.S.T.M. rodded method. When the loose measurement tests were made, the material was shoveled into the measure and struck off. The rodding test calls for filling the measure one-third full, rodding 25 times with a 5/8 in. by 24 in. bullet-pointed metal rod. This process was repeated three times and the container was leveled off and weighed. The weight per one-half cubic foot determination was repeated twice for each method of fillinf the measure and the average was obtained for each method. When one determination did not agree with the other within one-half pound, a third determination was made, and the average taken. In only two cases was this necessary. The percentage of the voids was calculated as follows.

$$\text{Percentage of voids} = 100\left(1 - \frac{\text{wt. per } \tfrac{1}{2} \text{ cu. ft.}}{\text{sp.gr. x } 31.17778} \right)$$

A sample of the gravel was obtained by the quartering method from the 1 to 1½ in. size. Then the specific gravity of each stone was found by weighing each one out of water and in water, the difference of the two weights gave the loss of weight in water. Then dividing the weight of the stone out of water by the loss of weight in water gave the specifice gravity of that piece of gravel. The average of all was taken as the specific gravity of the gravel used. In Table 1 the weight per half cubic foot and the percentage of voids are shown for both loose and rodded condition. The results given in this table for voids are plotted in Figs. 3 and 4 on triaxial diagrams.

The lines are contour lines of equal voids. The specific gravity of the gravel used in this investigation was 2.79.

Dicussion of Results

Referring first to Fig. 3 which represents the voids for the material in a loose condition in the half cubic foot measure, it is evident that the lowest percentage of voids is obtained with grading No. 39. This material is composed of 40 per cent 1/3 to 3/4 in. size, 0 per cent of 3/4 to 1½ in. size and 60 per cent of 1½ to 2½ in. size. Ther are no intermediate sizes in the mix. The percentage of voids for this grading was 32.5. It can be seen that as more and more intermediate size is added to the mixture there is a general tendency toward an increase in the percentage of voids.

Obviously if every producer were required to furnish gravel graded to have the very minimum of voids on a loose measurement No. 39 or namely- 1/3 to 3/4 in., 40 per cent; 3/4 to 1½ in., 0 per cent ; 1½ to 2½ in., 60 per cent, there would be the necessity of disposing of all of the 3/4 to 1½ in. size for some other use than for road concrete. This would be a wasteful procedure and would make the production of gravel more expensive. On the other hand if a low percentage of voids, a few per cent more than the minimum is permissible and it obviously would have to be permissible to make the general scheme practical and workable, the field is opened up to a reasonable range of sizes. This point is well illustrated in Fig. 5 in which are plotted the mechanical analyses of mixtures having within 2 per cent higher voids than the minimum. These mixtures are as follows:

1/3 - 3/4 in.	3/4 - 1½ in.	1½ - 2½ in.
30	0	70
40	0 - 30	60 - 30 %
50	0 - 10	50 - 40 %
60	0 - 30	40 - 10 %
70	0 - 20	30 - 10 %

If the lowest practicable percentage of voids on a "rodded" basis is required and the word "practicable" is interpreted to mean within 2.5 per cent of the minimum possible percentage of voids, a range of gradations which will satisfy the requirements is shown in graphical form as Fig. 6. This possible range of mixtures is seen to be as follows.

1/3 - 3/4 in.	3/4 - 1½ in/	1½ - 2½ in.
40	0-- 20	60 - 40 %
60	0 - 20	40 - 20 %

The closer to the absolute minimum percentage of voids required by the specifications, the more restricted is the range of combinations of sizes, but the diagrams in Figs. 3 and 5 or 4 and 6 will show the available combinations necessary to produce any desired percentage of voids.

In the preceding discussion it should not be inferred that the lowest percentage of voids referred to is the absolute minimum that can be obtained but is merely the minimum which was obtained with the three sizes of gravel used, each of which had a straight line gradation. No doubt a still lower percentage of voids could be produced by special gradation of the three sizes used but this would be a rather difficult procedure from the operating standpoint and the slight decrease in voids which might thus be obtained would probably not warrant the extra cost involved.

Table 1

Weights Per Half Cubic Foot and Percentages of Voids of Gravel (Specific Gravity - 2.79) Graded as Shown in Figures 1 and 2

	Loose			Rodded		
Grading	Wt. per	Per cent		Wt. per	Per cent	
No.	Cu. Ft.	Solids	Voids	Cu. Ft.	Solids	Voids
1	48.8	56.2	43.8	52.06	59.8	40.2
2	47.75	55.0	45.0	53.5	61.5	38.5
3	49.3	56.56	43.44	54.25	62.4	37.6
4	50.25	57.7	42.3	53.74	61.8	38.2
5	48.8	56.2	43.8	54.26	62.4	37.6
6	51.06	58.7	41.3	55.36	67.4	32.6
7	50.91	58.5	41.5	54.37	62.5	37.5
8	50.1	57.5	42.5	54.17	62.3	37.7
9	49.65	57.1	42.9	54.7	62.9	37.1
10	48.29	55.5	44.5	53.76	61.8	38.2
11	48.41	55.6	44.4	53.34	61.2	38.8
12	50.3	57.8	42.2	55.19	63.5	36.5
13	52.51	60.4	39.6	56.49	65.0	35.0
14	52.52	60.4	39.6	55.7	64.1	35.9
15	52.76	60.6	39.4	56.92	65.5	34.5
16	53.42	61.5	38.5	56.84	65.4	34.6
17	52.35	60.2	39.8	56.29	64.6	35.4
18	52.07	59.8	40.2	56.76	65.2	34.8
19	51.09	58.7	41.3	55.19	63.5	36.5
20.	51.51	59.3	40.7	55.05	63.2	36.8
21	50.8	58.6	41.4	55.0	63.2	36.8
22	54,3	62.4	37.6	56.74	65.2	34.8
23	53.51	61.6	38.4	57.73	66.4	33.6
24	54.12	62.2	37.8	58.23	67.0	33.0
25	54.9	63.1	36.9	57.87	66.5	33.5
26	53.11	61.1	38.9	58.04	66.6	33.4
27	52.63	60.5	39.5	57.76	66.4	33.6
28	52.51	60.4	39.6	57.65	66.2	33.8
29	52.18	60.0	40.0	57.62	66.2	33.8
30	51.58	59.3	40.7	57.66	66.2	33.8
31	57.18	65.7	34.3	60.23	69.2	30.8
32	54.7	62.9	37.1	60.58	69.6	30.4
33	54.35	62.5	37.5	59.91	68.9	31.1
34	54.77	63.0	37.0	59.56	68.6	31.4
35	54.84	63.1	36.9	60.55	69.6	30.4

Table 1 continued

	Loose			Rodded		
Grading	Wt. per	Per cent		Wt. per	Per cent	
No.	Cu. Ft.	Solids	Voids	Cu. Ft.	Solids	Voids
36	54.13	62.2	37.8	58.83	67.3	32.7
37	54.23	62.3	37.7	58.61	67.4	32.6
38	54.18	62.3	37.7	58.32	67.3	32.7
39	58.66	67.5	32.5	61.65	70.9	29.1
40	57.25	65.8	34.2	61.63	70.9	29.1
41	56.64	65.6	34.4	61.25	70.4	29.6
42	56.98	65.5	34.5	59.41	68.4	31.6
43	55.92	64.8	35.2	59.94	69.0	31.0
44	55.72	64.0	36.0	59.68	68.6	31.4
45	54.53	62.8	37.2	58.97	67.9	32.1
46	58.55	67.3	32.3	60.8	70.0	30.0
47	58.6	67.3	32.6	60.66	69.7	30.3
48	56.83	65.4	34.6	60.78	69.8	30.2
49	55.71	64.0	36.0	59.95	69.0	31.0
50	55.96	64.8	35.2	60.39	69.5	30.5
51	55.51	63.9	36.1	59.29	68.2	31.8
52	57.0	65.6	34.4	63.27	72.7	27.3
53	58.1	66.8	33.2	62.92	72.4	27.6
54	57.74	66.5	33.5	61.32	70.5	29.5
55	57.47	66.0	34.0	60.38	69.6	30.4
56	56.29	64.6	35.4	59.81	68.8	31.2
57	58.56	67.3	32.7	60.3	70.0.	30.0
58	58.27	67.0	33.0	60.24	69.2	30.8
59	57.37	65.9	34.1	59.42	68.4	31.6
60	55.4	63.7	36.3	59.77	68.7	31.3
61	55.38	63.7	36.3	60.39	70.1	29.9
62	56.2	34.5	65.5	59.7	68.6	31.4
63	54.74	63.0	37.0	58.19	66.9	33.1
64	54.15	62.2	37.8	58.37	67.0	33.0
65	54.63	62.8	37.2	56.91	65.5	34.5
66	52.71	60.6	39.4	56.84	65.4	34.6

Mechanical analysis of aggregates used in

the calculation of percentage of voids.

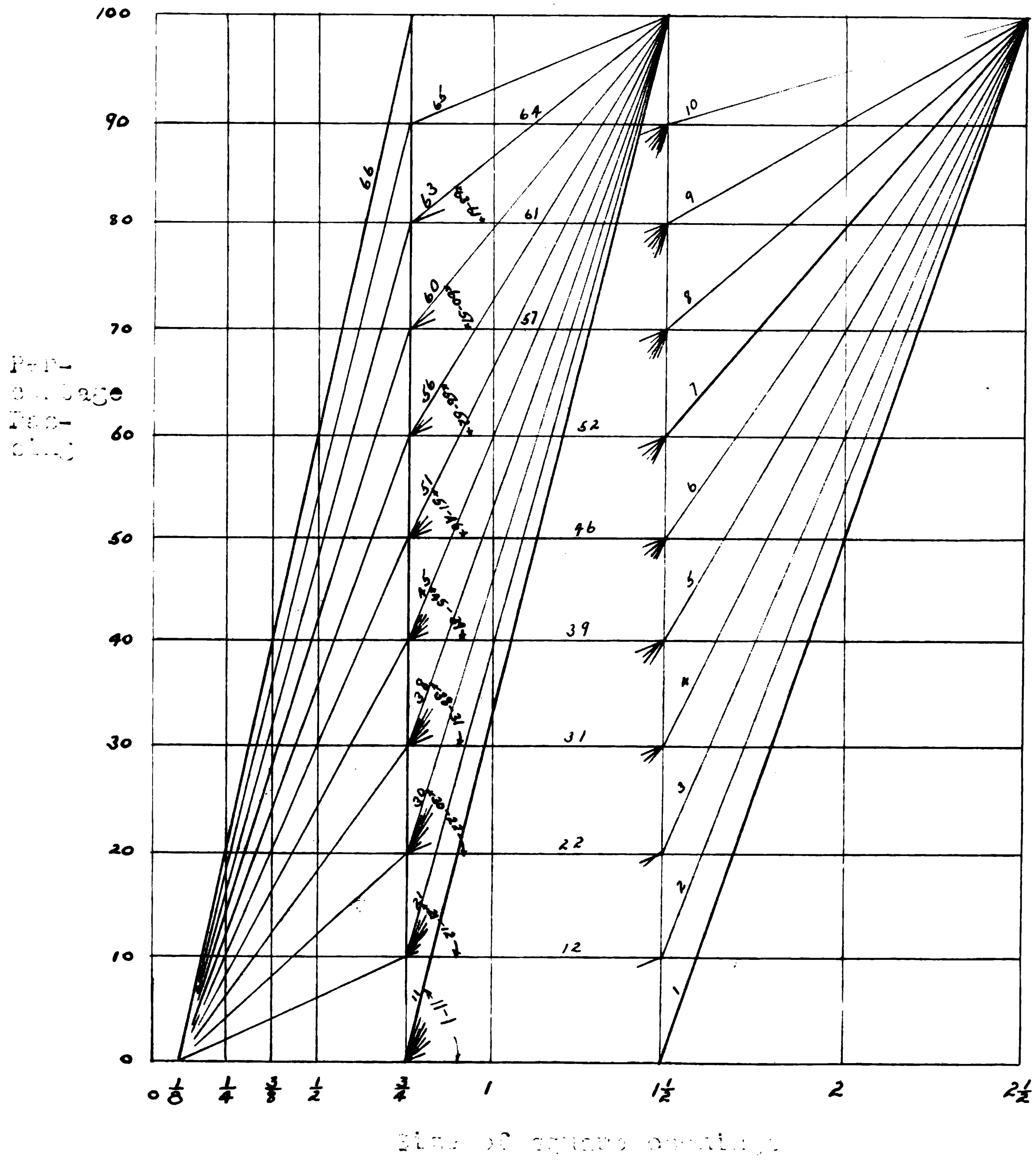

Fig. 1

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[illegible]

[illegible]
Point No. 42 represents

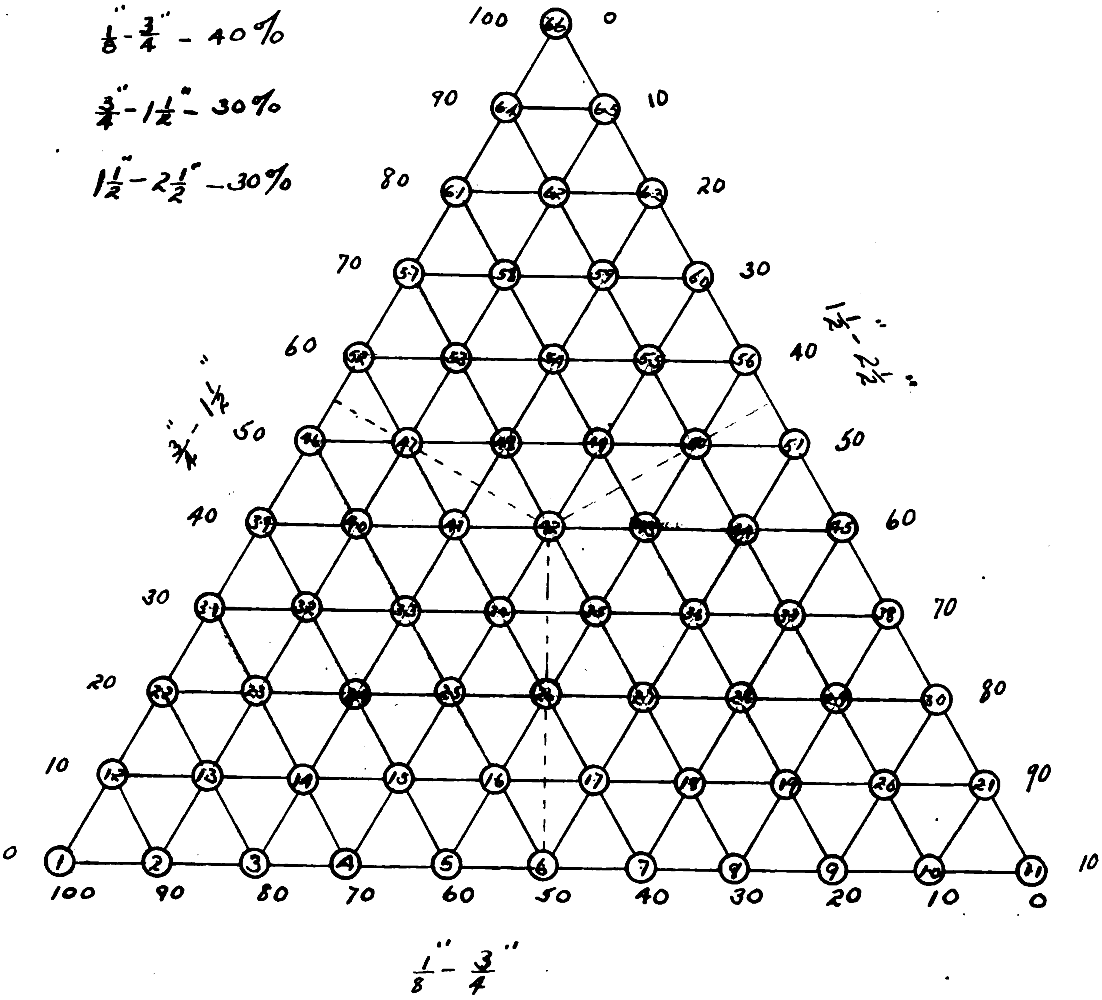

Fig. 6

Percentage of voids in gravel. Loose measurement in A.S.T.M. standard one-half cubic foot measure.

Example of use of diagram.
Point A represents the following gradation.
(square opening)

$\frac{1}{8}'' - \frac{3}{4}''$ - 20%

$\frac{3}{4}'' - 1\frac{1}{2}''$ - 20 %

$1\frac{1}{2}'' - 2\frac{1}{2}''$ - 60%

voids - 37.8 %

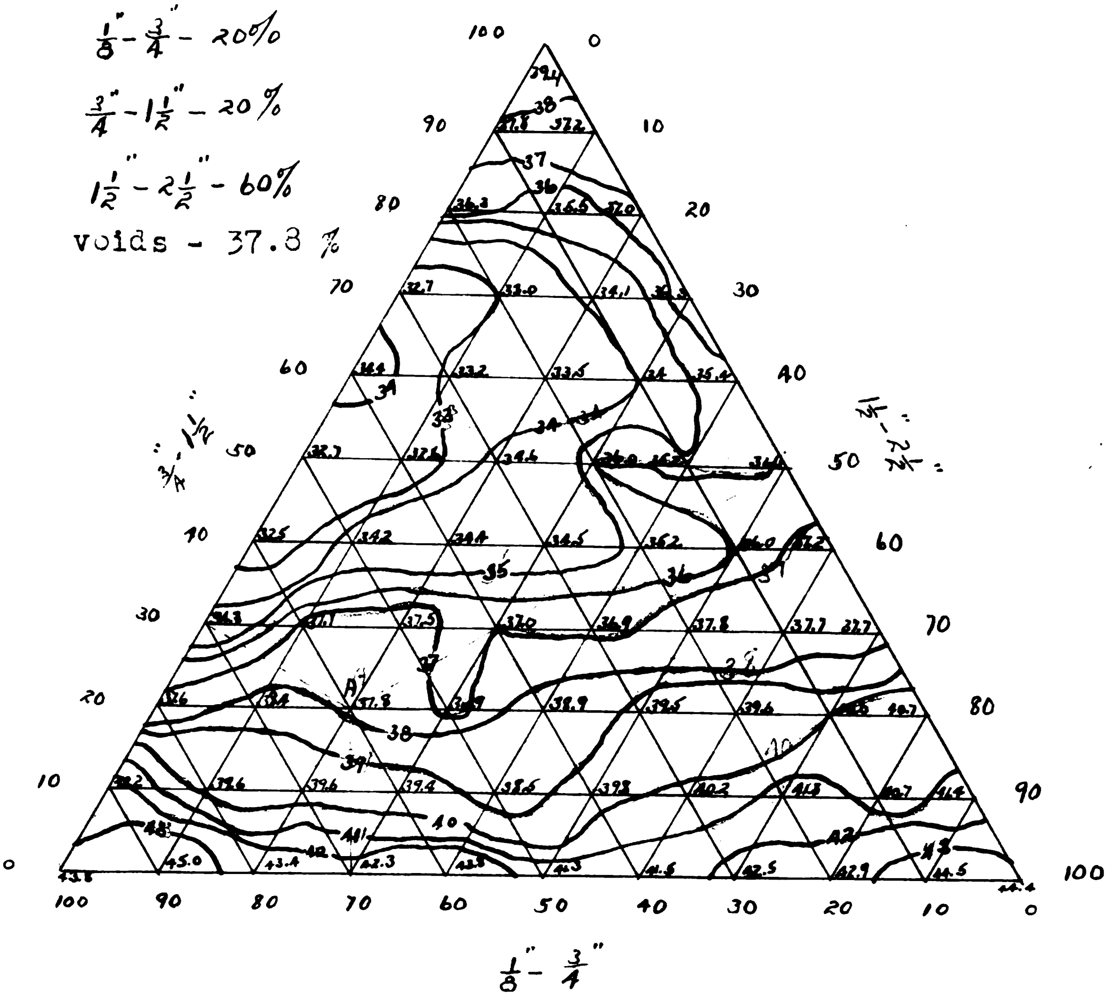

Fig. -3-

Percentage of voids in gravel rodded in A.S.T.M. standard one-half cubic foot measure.

Example of use of diagram.
Point A represents

$\frac{1}{8}$" - $\frac{3}{4}$" - 20 %

$\frac{3}{4}$" - 1$\frac{1}{2}$" - 20 %

1$\frac{1}{2}$" - 2$\frac{1}{2}$" - 60 %

voids - 33.0 %

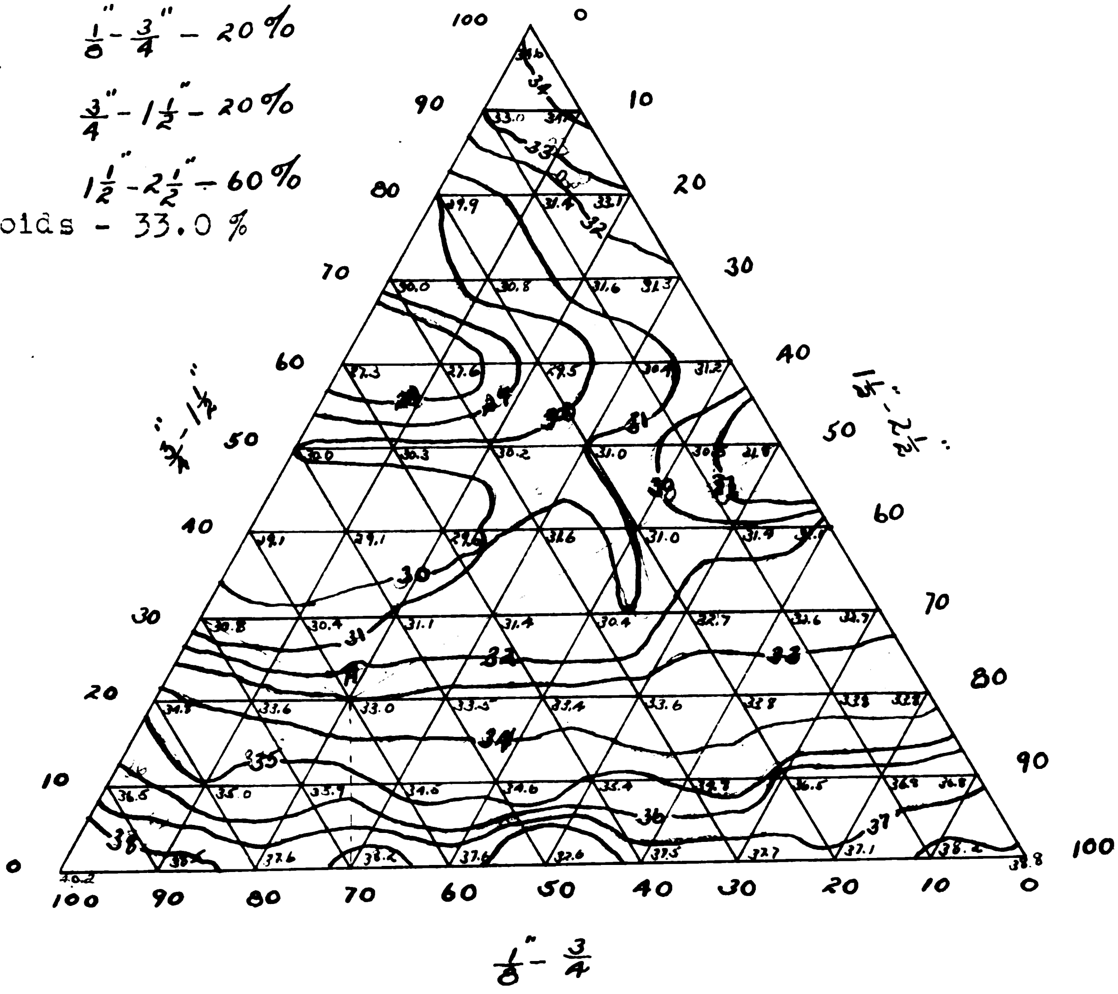

Fig 4

Mechanical analyses of gravel having low percentage of voids, loose measurement.
Voids are within 2 per cent of the lowest possible with the three sizes 1/3 to 3/4 in., 3/4 to 1½ in., 1½ to 2½ in., used in various combinations.

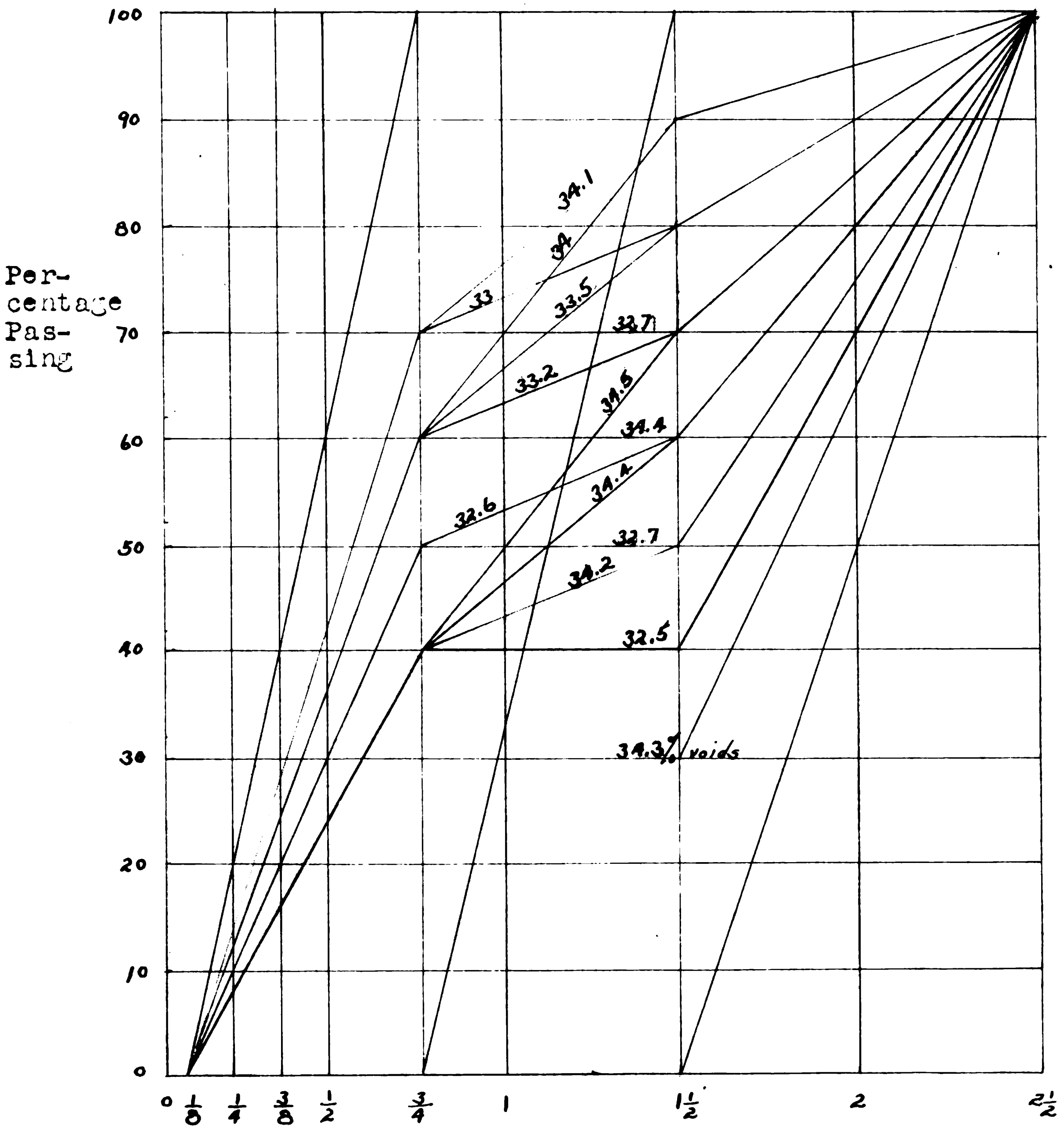

Fig. 5

Mechanical anaylses of gravel, having low percentage of voids, standard A.S.T.M. rodded measurement.
Voids are within 2 ½ per cent of the lowest possible, with the three sizes 1/8 to 3/4 in., 3/4 to 1½ in., 1½ to 2½ in., used in various combinations.

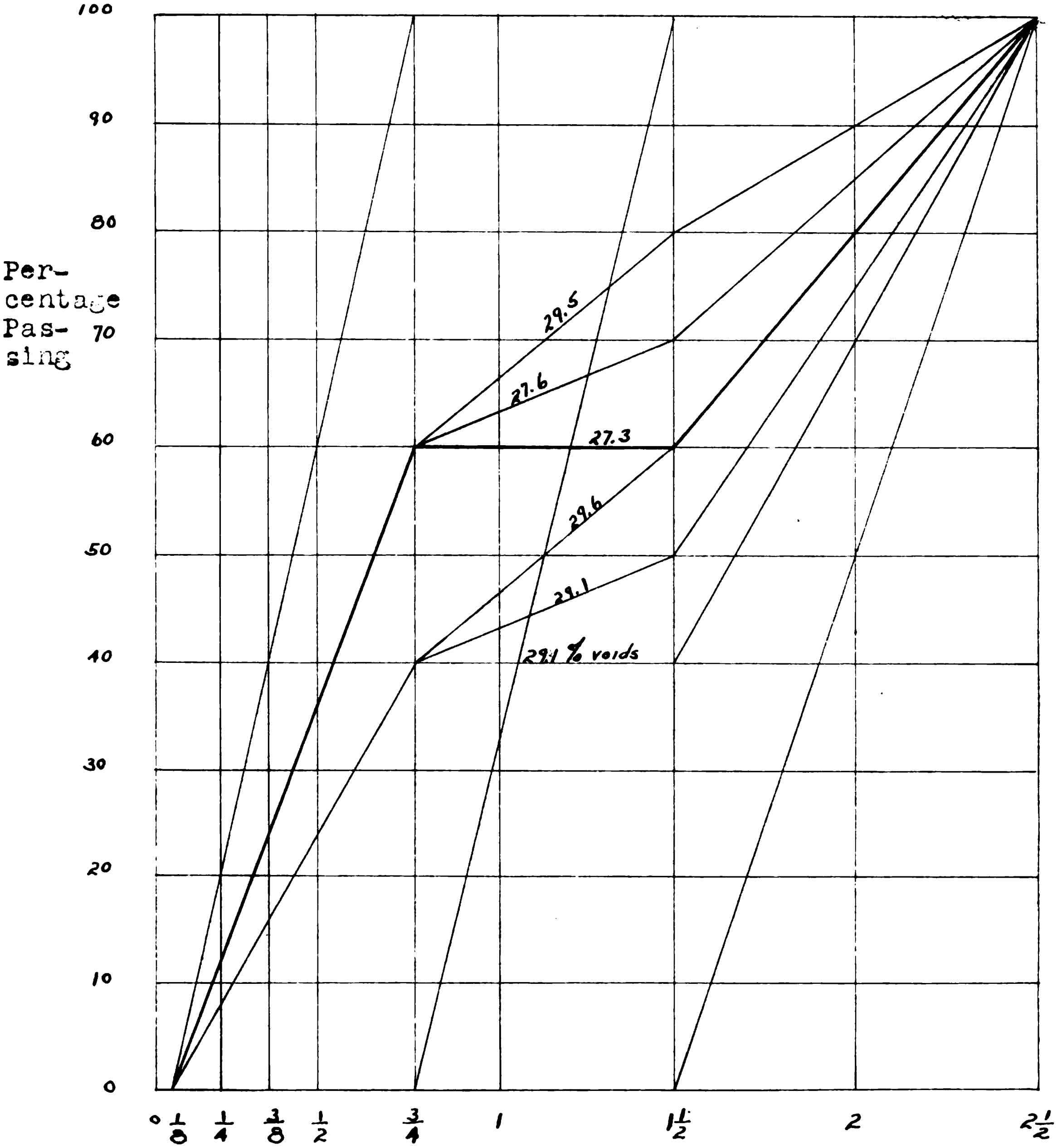

Fig. 6