

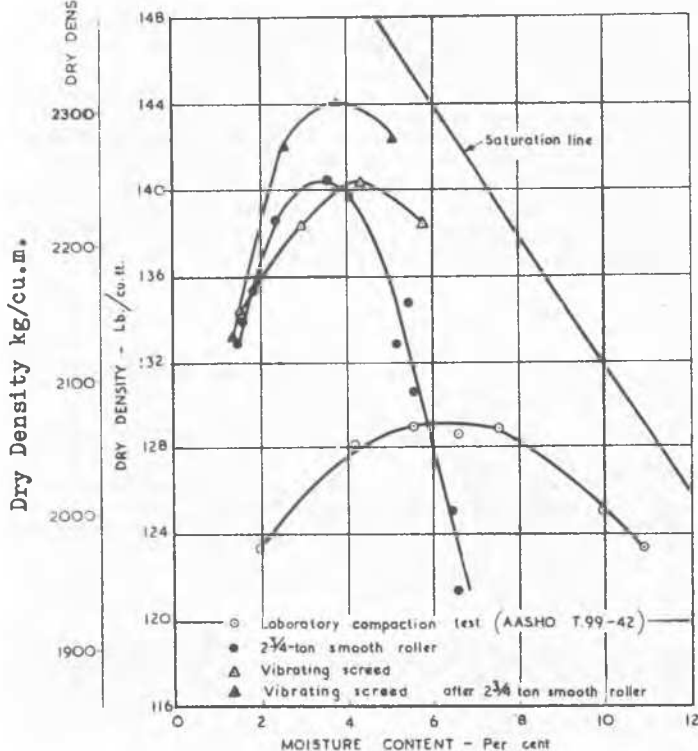
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Dry density-moisture content curves obtained by various methods of compaction for sand-gravel soil.

FIG. 21

21 shows the results obtained with the 2 $\frac{3}{4}$ -ton (2800 kg) roller and the vibrating screed independently and together. The results of a standard A.A.S.H.O. compaction test made on the soil are given for comparison.

The optimum moisture content of the sand-gravel when compacted by the plant was approximately 4%, and considerably less compaction was obtained when the moisture content was either slightly above or below this value. The best compaction was obtained when the subgrade was given four passes with the vibratory screed following eight passes with the smooth-wheel roller. When this amount of compaction was applied, a dry density of 144 lb./cu.ft.

(2300 kg/cu.m) was obtained at the optimum moisture content of 4%. These values compared with a maximum dry density of 129 lb./cu.ft. (2060 kg/cu.m) obtained at an optimum moisture content of 6% with the standard A.A.S.H.O. compaction test.

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ACKNOWLEDGEMENT.

The work described in this paper was carried out at the Road Research Laboratory of the Department of Scientific and Industrial Research as part of the programme of the Road Research Board. The paper is presented by permission of the Director of Road Research.

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COMPUTATION OF THE OPTIMUM MOISTURE CONTENT IN THE MOISTURE-DENSITY RELATIONSHIP OF SOILS

IX b 6

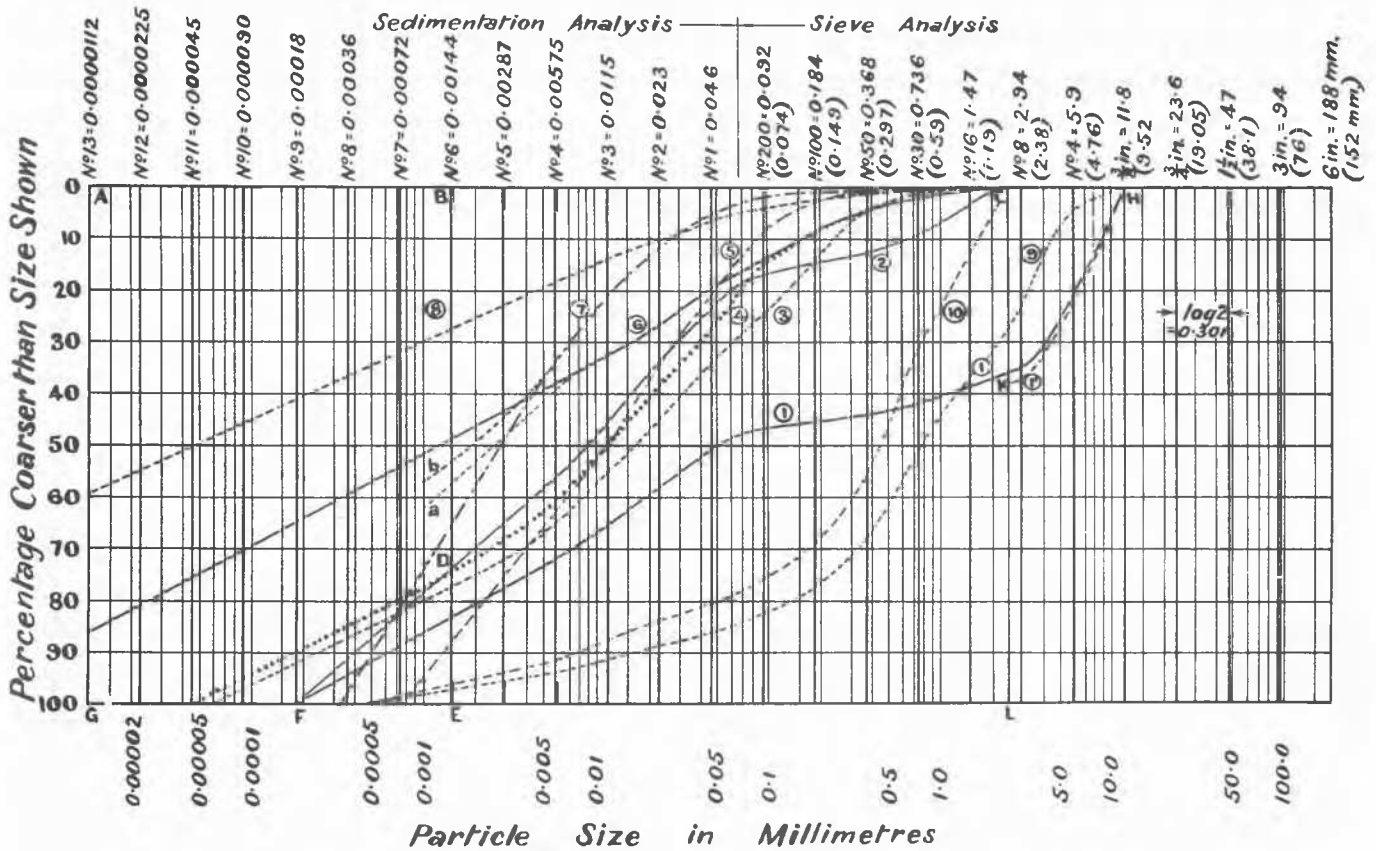
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(i) The compaction test determines the relationship between the moisture content of a soil and its dry density when compacted into a cylinder in a standard manner 1), which is equivalent to the compaction to which the soil will be subjected on the work site. It is not possible to satisfactorily compact into the standard cylinder soils containing particles having a maximum dimension greater than $\frac{3}{8}$ inch. Such par-

ticles are generally considered to be too large and a smaller limiting size is adopted, such as the 10-mesh sieve (2 mm. opening).

(ii) It is evident that, whatever size of particle is chosen as the limit in the test, there will be varying quantities of larger particles up to a maximum of about 4 in. for which allowance must be made in order to compute the optimum moisture content of the whole soil in



PARTICLE SIZE DISTRIBUTION CURVES

FIG. 1

TABLE I
OPTIMUM MOISTURE CONTENTS

Variation of the percentage moisture content, as computed, from the test value ±	Proportion of tests within the range as shown Per Cent.
± 0.5	44.4
± 1.0	72.2
± 1.5	90.6
± 1.8	97.2
± 2.0	98.3
± 2.3	100.0

the constructed work.

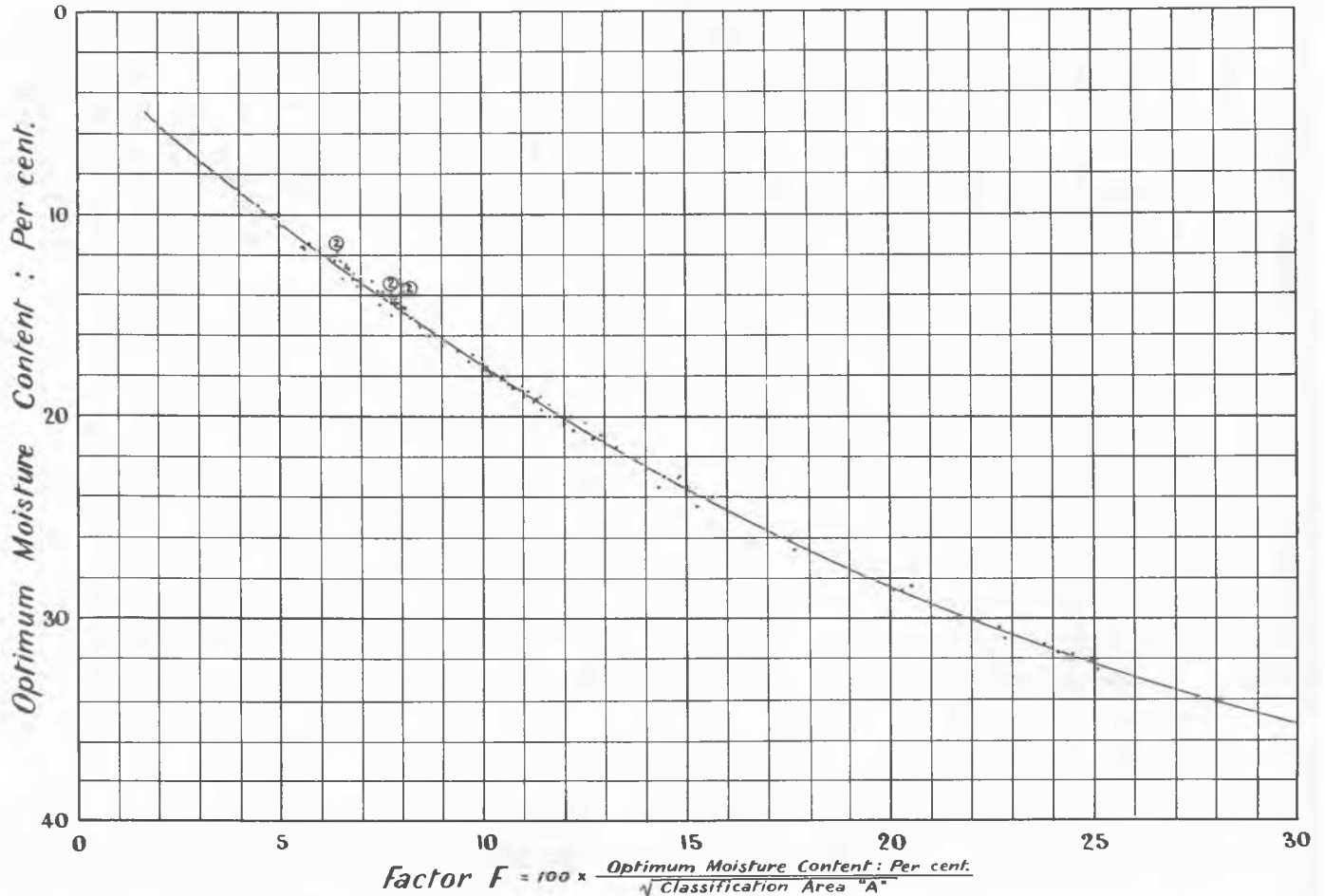
(iii) It, therefore, appeared to be very desirable that some means be found of evaluating the moisture requirement of a soil. This paper will describe a method whereby this information can be obtained and indicate the accuracy and utility of the resulting determination.

1. Use is made of the new classification of soils as described in a companion paper 2). In order to complete the data required for this classification the particle size distribution curve is continued, if necessary, below 0.001 mm. as a straight line; as shown in the curves of Figure 1. The results obtained, by the use

of data derived from such curves, in the computation of the optimum moisture contents will be shown to possess such good correlation with those given by tests; that the validity of the principle upon which they are based can be considered as being well substantiated.

2. Compaction tests have been made under 25 blows and 40 blows per 2-in. layer of a 5.5-lb tamper falling freely from a height of 18 inches. The data from 180 tests on 101 soils are shown in Figures 2 and 3. The mean curves through these points have been transferred to Figure 4.

3. The fact that the various clay minerals tend to form particles having their own character-



OPTIMUM MOISTURE CONTENT : 25 BLOWS PER 2-INCH LAYER

FIG. 2

istic range in size (3) enables us to make all due allowance for the known differences in the properties of the clay minerals without the necessity for identifying them both qualitatively and quantitatively. No allowance has been made for variations in the specific gravities of the soils, or the possible effects of organic matter and base exchange.

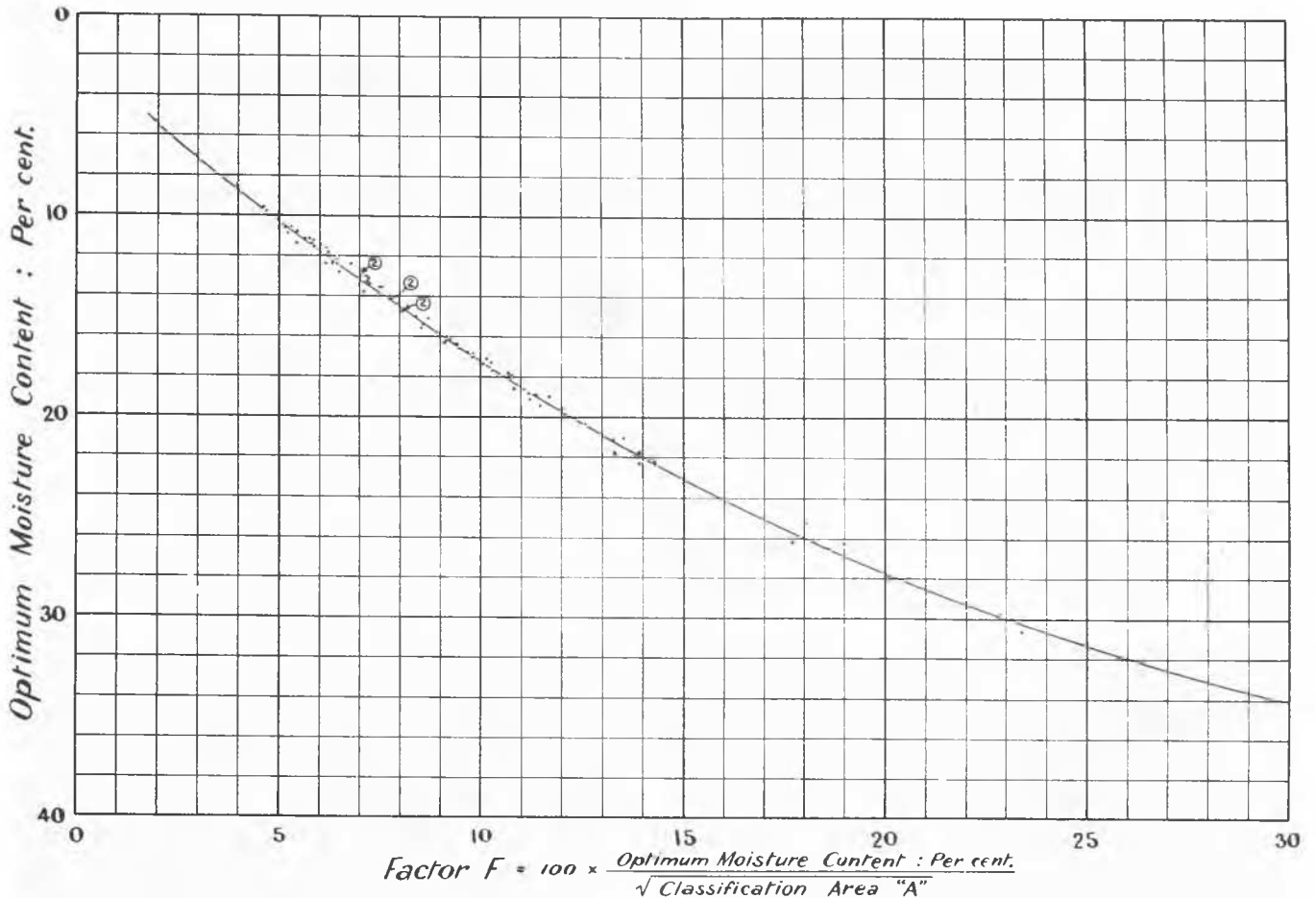
4. A comparison has been made of the computed and test values for the optimum moisture content in each of the 180 tests in Table I. The moisture contents ranged between 8.4 and 36.9 per cent., and the soil classification area A varied between 4.651 and 1.203. The fact that 91 per cent. of the values fall within a range of ± 1.5 , and 72 per cent. within ± 1.0 , of the moisture content, expressed as a percentage of the oven-dry weight, indicates that the computed moisture contents can serve a useful purpose. The results confirm the hypothesis upon which the soil classification rests: namely, a straight line relationship for the distribution of particles below 0.001 mm. in diameter. Sixty-four per cent. of the tests were made on mixtures of soil from two to eight samples. No allowance, except in one instance referred to later, has been made for any absorption of the sand or gravel portion of the soil.

5. Although it is now possible to compute the optimum moisture content of any soil whose particle size distribution curve is available, the principle use of this knowledge is the de-

termination of the optimum moisture and density of a mixture formed by the addition of coarser or finer material to a soil whose moisture-density curve has been obtained by test.

6. A series of compaction tests have been made on three soils to determine the effect of the addition of coarser material. The classifications of the soils and their optimum moisture contents, by computation and test, are given in Table II; while the moisture-density test curves are shown in Figure 5. It will be noted that the computed values agree within a small margin with the test figures. When the added material absorbs appreciable amounts of moisture, it becomes necessary to make the appropriate correction. The moisture-density curve No. 8", Figure 5, was obtained before making allowance for the 3.85 per cent. absorption of the particles retained on the 10-mesh sieve, and an adjustment in the weight of this portion of the mixture as represented by the partial grading curve No. 1' in Figure 1; where each of the porous particles have been replaced by a solid of the same volume but having the specific gravity of the nonporous portions of the original particles.

7. If the computed and test percentages for the optimum moisture of the original soil do not coincide, it is possible to estimate the effect of any additions of coarser material to much closer limits by recomputing a new moisture content on the basis of the known test re-



—OPTIMUM MOISTURE CONTENT : 40 BLOWS PER 2-INCH LAYER

FIG. 3

TABLE II

OPTIMUM MOISTURE CONTENTS OF SOIL SAMPLES WITH ADDED COARSER MATERIAL

Test No. (Fig. 5)	Soil No. (Fig. 1)	Soil Classification	Percentage coarser than size shown				Optimum moisture content under 40 blows per layer		
			No.4 Sieve 5.9 mm per cent.	No.10 Sieve 2.48 mm per cent.	No.30 Sieve 0.74 mm per cent.	No.50 Sieve 0.37 mm per cent.	By Test per cent.	Computed per cent.	Recomputed x) per cent.
1	2	3	4	5	6	7	8	9	10
2&3	10	2.48 mm./4.298	0.0	0.0	31.6	-	9.6	10.0	9.6
1	9	11.8 mm ./4.651	4.5	27.6	50.4	-	8.6	9.0	8.7
6 6	xa)	0.37 mm./3.183	0.0	0.0	0.0	0.0	14.9	15.6	14.9
5&7	b	0.74 mm./3.321	0.0	0.0	1.3	8.8	14.2	14.6	14.1
4	c	1.47 mm./3.844	0.0	0.0	23.1	39.0	11.3	11.6	11.2
9&10	2	1.47 mm./2.948	0.0	0.0	9.4	-	17.0	17.5	17.0
8'	1'	11.8 mm./4.018	22.0	37.1	43.1	-	11.2	11.0	10.9

x) Recomputed on the basis of the result of the first test in each series, see paragraph 7.

xa) Not shown. The curves are given on page 90 of reference 1).

TABLE III

RECOMPUTATION OF CLASSIFICATION AREA FOR SOIL IN SAMPLE NO. 9

Fraction 1	Percentage of Fraction in Soil ¹ Per Cent. x) 2	Classification Area of Fraction 3	Product of Columns 2 and 3 4
Minus No. 10 Sieve	72.4	4.430 xa)	3.207
No. 8 - No. 10	4.6	5.381	0.248
No. 4 - No. 8	18.5	5.568 } xb)	1.030
$\frac{3}{8}$ in. - No. 4	4.5	5.869	0.264
Total	100.0	-	4.749

x) From Figure 1.
 xa) As determined in paragraph 7.
 xb) From Table III of reference 2.

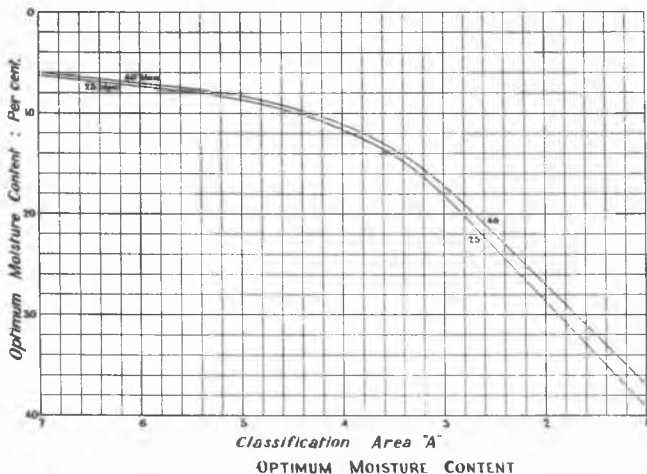


FIG. 4

sult. This has been done in column 10 of Table II, and represents the normal field procedure. The optimum moisture content of sample No. 10 by test No. 2 is 9.6 per cent. From Figure 4 for this moisture content, A = 4.430. Since the classification area for each fraction of a soil is proportional to the percentage of that particular fraction in the soil, there is no necessity to plot a new curve. The new area of the sample containing the added coarser material is computed as shown in Table III. The classification area of the mixture is 4.749 and, from Figure 4, the optimum moisture content for 40 blows per layer is 8.7 per cent. The other figures in column 10 of Table II were obtained in a similar manner.

8. Tests were made on soil No. 1' to determine the moisture contents of the original soil No.2 and the added coarser material, with the results shown in Table IV. In columns 1 and 2 of the lower half of Table IV are given approximate figures for the moisture contents of the whole soil corresponding to other values in the minus 10-mesh material. If soil No. 1' was mixed to a moisture content of 17.0 per cent. in the finer fraction in accordance with previous practice, the whole soil would be at 11.65

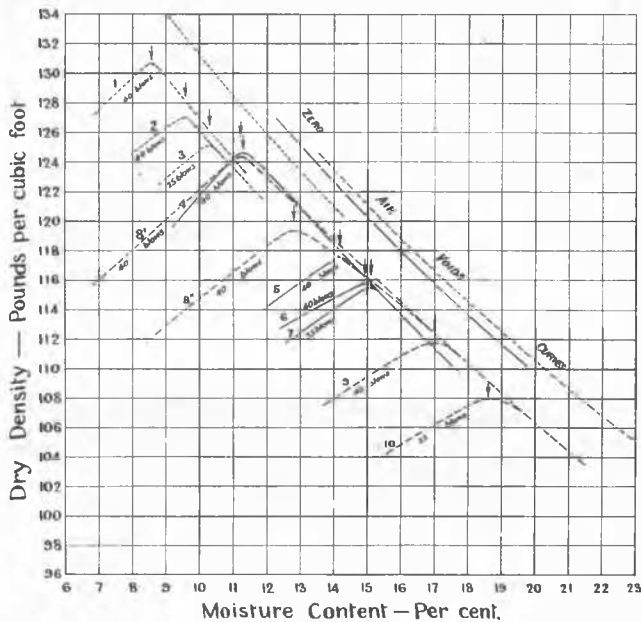


FIG. 5

per cent., or 0.45 per cent. wetter than the optimum.

9. The computation of the new optimum density when the test curve for the fine fraction is available can be effected by assuming that the difference between the moisture contents at the optimum density and saturation, w_a , for the fine fraction will be the same in the new mixture. We then have

$$W \left(\frac{w_s}{62.4} + \frac{w_a}{62.4} + \frac{1-p}{S_f \times 62.4} + \frac{p}{S_c \times 62.4} \right) = 1$$

where W = the dry density of the mixture in lb. per cu. ft.

w_s = the moisture content as per cent. of the dry soil of the mixture.

w_a = the equivalent moisture content, as

TABLE IV
MOISTURE CONTENTS OF SOIL NO. 1'

Moisture Content		
Whole Soil per cent 1	Fraction passing 10-mesh Sieve per cent. 2	Fraction coarser than 2.48 mm per cent. 3
8.61	13.68	0.50
10.08	15.25	1.78
10.47	15.69	2.09
11.05	16.34	2.56
11.2	Approx. 16.5	Approx. 2.70
Approx. 9.9	15.1	-
Approx. 11.65	17.0	-
Approx. 13.0	18.4	-

TABLE V
COMPUTED DRY DENSITY OF SOILS WITH ADDED COARSER MATERIAL

Test No. (Fig. 5)	Soil No. (Fig. 1)	Moisture Content		Added coarser material per cent. 5	Apparent Specific Gravity		Optimum dry density under 40 Blows per layer	
		w _s per cent. 3	w _a per cent. 4		S _f 6	S _c 7	By Test	By Computation
							lb. per cu. ft. 8	lb. per cu. ft. 9
1	2	-	2.0	-	2.66	-	127.0	-
2	10	-	2.0	-	2.66	-	127.0	-
1	9	8.7	2.0	27.6	2.66	2.66	130.7	129.2
6	a	-	2.1	-	2.70	-	115.8	-
5	b	14.1	2.1	8.8	2.70	2.70	117.5	117.2
4	c	11.2	2.1	39.0	2.70	2.70	124.6	124.0
9	2	-	2.4	-	2.74	-	111.7	-
8'	1'	10.9	2.4	37.1	2.74	2.73	124.3	125.2

per cent. of the dry soil, of the air voids in the compacted soil of the mixture.

- p = the percentage of the whole soil, comprising the added coarse fraction, larger than the particle size forming the limit of the fine fraction.
- S_f = the apparent specific gravity of the fine fraction comprising the original soil tested.
- S_c = the apparent specific gravity of the coarse fraction comprising the added material.

The results of the use of the above equation are given in Table V, using the data of columns, 5, 7 and 10 in Table II, and the moisture-density curves for the fine fractions shown in Figure 5.

10. Appreciation is expressed to Lewis R. East, Chairman, State Rivers and Water Supply

Commission, for permission to publish this paper; also the members of the staff of the Soil Mechanics Laboratory who made the tests which form the basis of this paper.

SUMMARY.

- (i) Using a new soil classification, graphs are provided whereby the optimum moisture content can be computed for any soil whose particle size distribution curve is available.
- (ii) Comparison of the computed and test values for the optimum moisture content shows that 72 per cent. of the results fall within ± 1.0 of the test figures.
- (iii) When coarser material is added to a finer soil, whose moisture-density relationship is known, an adjustment is made for the individual characteristics of the original soil; and the optimum moisture content for the mixture formed by the addition of a known quantity

of coarser material can be computed within very close limits.

(iv) The optimum dry density for such a mixture is then computed.

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IX b 7

SOIL STABILIZATION WITH SOFT AGGREGATES

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OBJECT.

The object of this paper is to bring to the notice of Soil Engineers of different countries, an original method of mechanical soil stabilization, fit for use in areas where gravel is not available within economic distance.

INTRODUCTION.

India is a vast country. There is immediate need to provide many thousands of miles of all-weather road in order to connect the thousands of agricultural villages with agricultural markets. Neither can the country afford to provide such large mileages of the expensive higher type of pavement, nor does the small intensity of traffic on these rural roads, warrant such heavy expenditure per mile of road. In search of a solution of this stupendous problem of a cheap all-weather road, the writer travelled through Great Britain, France, Belgium, Italy, Switzerland, Germany, Czechoslovakia, Holland, Denmark, Norway and Sweden in 1936 and 1937 and studied with the local Soil Scientists and Soil Engineers all that was being done in the field of Soil Stabilization. Even chemical stabilization of soil was ruled out on the score of cost. It was decided that Gravel Stabilization was all that India could afford.

The snag however was that gravel is not sufficiently universally available in India to allow of its use in more than a few restricted areas. The only substitute that is cheap as well as universally available is aggregate broken from burnt brick.

THE RESEARCH PROBLEM.

Experiments were carried out by the conventional gravel stabilization methods, after substituting graded brick aggregate for gravel. As was only to be expected, the brick aggregate, being comparatively soft, got its sharp corners rounded off by rubbing against its neighbours, during the vibration set up in the body of the road crust, by fast moving traffic. The effect was accentuated by the slow moving bullock cart with its high local intensity. The result was the rapid breaking up of the interlock of the coarse aggregate and consequent disintegration of the road

crust. It was noticed however that the brick aggregate was reasonably strong against surface abrasion under the bullock cart and motor traffic. The research problem to be solved was therefore to provide a safeguard against the crushing of the adjoining sharp corners of the brick aggregate, through rubbing against one another due to the vibration set up in the road crust by traffic.

LABORATORY RESEARCH.

Laboratory research was started in the writer's private laboratory in the Punjab on return to India in 1938. All attempts at sufficiently improving the hardness of the brick aggregate through chemical and other treatments having failed, attention was diverted towards providing physical protection to the individual particles of the aggregate itself within the body of the crust. The quantity of graded soil in the soil-aggregate mixture, was so adjusted, that in addition to filling the voids in the aggregate, the soil also provided a thin coating round each particle. This thin coating of soil round each particle, not only acted as mortar for holding together the particles of the coarse aggregate but also prevented the adjoining bits of aggregate from rubbing against each other under traffic vibration. It had the additional advantage of acting as a shock absorber, against traffic shocks, thus doubly protecting the coarse aggregate.

It was found that the requirements of this type of soil-aggregate mixture are reasonably satisfied, if the proportion of soil and coarse aggregate is 4 parts of aggregate to 8 parts of soil, making 10 parts of mixture.

In a mixture of this kind, there being no interlocking of the coarse aggregate, the soil mortar naturally plays the most important part and consequently careful attention has to be paid to the design of soil mixtures, keeping in view the climatic conditions and traffic requirements of the locality. In the design of soil mixtures, the writer follows the American System.

SMALL SCALE FIELD EXPERIMENTS.

A few small lengths of road totalling about five miles were constructed by this meth-