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CONSOLIDATION OF GRANULAR
SOILS BY VIBRATION

Thesis for the Degree of B. S.
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Robert Mundie McGinnis
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THESIS

CONSOLIDATION OF GRANULAR
SOILS BY VIBRATION

By

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Candidate for the Degree
of Bachelor of Science

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INTRODUCTION

The consolidation of structural backfills has been a prime problem to the engineer since ancient times, but until recent years most consolidation was done by allowing the soil to consolidate over a long period of time due to natural rainfall seepage. Obviously, most present day construction cannot be held up for long periods; therefore, ways were found to do the job quickly by means of rollers or by running over the backfill with heavy machinery. However, in many cases there is insufficient space to permit rolling. Hand or pneumatic tampers have been used although they are slow devices for any extensive amount of backfill. This has led to the development of other means of compaction.

It has long been known that vibration influenced compaction but, until recently, little work has been done along this line. At the present time vibrational compaction machines are being developed and used with very good results. Besides consolidating soil at a much faster rate than by use of hand tampers, the machines consolidate a much thicker layer of soil and the effects of the vibration on each layer continues consolidation of the lower layers so that very high densities are attained.

At the present, little is known about the factors governing consolidation by vibration and the optimum conditions to give the best results. It is known that the speed of vibration has a definite effect, the best results being given by frequencies of 60 to 70 V.P.S. Increasing the weight of the machine has the effect of increasing the depth and also the rate of compaction. Various types of vibrating surfaces are being tested at the present time.

The purpose of this study is to determine the effect of the moisture content of granular soils on their compaction by vibration and to find an optimum moisture content to obtain the fastest and most dense consolidation. This information should aid in producing more efficient results in the field, and since this objective was followed, types of granular materials likely to be found in the field were used. Most of the testing was done on 2NS sand and 6A gravel, although tests were also run on pea gravel and blast furnace slag (3). The test procedure followed in this work was developed by the Michigan State Highway Department laboratory at the University of Michigan with slight variations as were considered feasible for testing the materials used.

Vibration is merely a means of rearranging soil particles in a much more dense condition than in loose backfill. This is done in vibration by setting the individual soil grains in motion enough to overcome the internal friction. The resistance to displacement is due first to sliding of grain on grain and second to the interlocking of grains (1). The interlocking becomes more important as the material becomes denser, and this is especially true of natural or 2NS sand since the grains are angular in shape. When the grains are set in motion by means of vibration, accompanied by a compressive force or weight, the particles have a tendency to fill the large voids in the loose backfill and to rearrange themselves in a dense mass. This will be especially true of a graded material since the small particles work into the voids between the large particles. However, in this case excessive vibration has been found to cause the fine particles to sift downward through the coarse particles, resulting in a less dense consolidation at the top of the soil layer. The actual time to achieve

consolidation by vibration is very short. Several time-consolidation tests are contained in this report to give an indication of the time of compaction.

In this thesis careful laboratory technique has been used with the purpose of obtaining as accurate data as possible so that the results may add to our present knowledge of soils and especially to the problem of consolidation of granular soils by vibration.

CONCLUSIONS

1. At near zero moisture content compaction by vibration is almost instantaneous.
2. From zero moisture content to between 4 and 5% moisture the rate of compaction by vibration decreases in sands.
3. From between 4 to 5% moisture to the saturation point the rate of compaction increases for 2NS sand.
4. The optimum moisture contents for compaction of 2NS sand by vibration is at or near zero per cent moisture and at the saturation point.
5. Prolonged vibration will have the effect of producing densities approaching those obtained by vibration at the optimum moisture contents.
6. Moisture content has no effect on compaction of pea gravel by vibration.
7. A large cylinder of at least 12 inches inside diameter is recommended for testing 6A gravel.
8. Slag will not compact to a high density unless a high percentage of fines particles is present.

DESCRIPTION OF TESTS

The apparatus used in the vibration tests is a vibrometer located in the concrete laboratory in the Engineering Building. This machine consists of a table set on springs. Attached to the bottom of the table is the vibrator, motor driven by a 3/4 H.P. electric motor at 1425 R.P.M. On top of the table is a disk set up on legs to hold the sample cylinder. A piston machined to fit the cylinder subjects the sample to a 30 pound load. The inside diameter of the cylinder is 8.125 in. and the length 10 in. (See Figure 1 and photographs.)

The tests were run in the following manner:

1. An air dry soil sample was first weighed. (4,000 g. of 2NS sand; 4,000 g. pea gravel; 7,000 g. 6A gravel; 5,000 g. slag, except test No. 3 which is 3400 g.)
2. Sample was put in 8 inch cylinder on vibrometer and leveled.
3. Thirty pound piston was inserted in cylinder and turned 180° to insure an even bearing.
4. Sample was vibrated for two one-minute periods and then for as many two-minute periods as were necessary to show no further consolidation for a four-minute time of vibration. A measurement of the protruding piston was made for each period.
5. Piston was removed and a portion of the sample was weighed and then dried in an oven for 24 hours, cooled to room temperature and then reweighed.
6. Soil sample was removed from cylinder and put in a pail. A small amount of water was sprinkled over the soil and then the soil was mixed until a homogeneous moisture content was obtained.

7. Moist sample was reweighed and procedure repeated.
8. Moisture content of samples was gradually increased to cover range from air dry to complete saturation.



Fig. I
Front view Vibrometer showing piston and
cylindar disassembled.

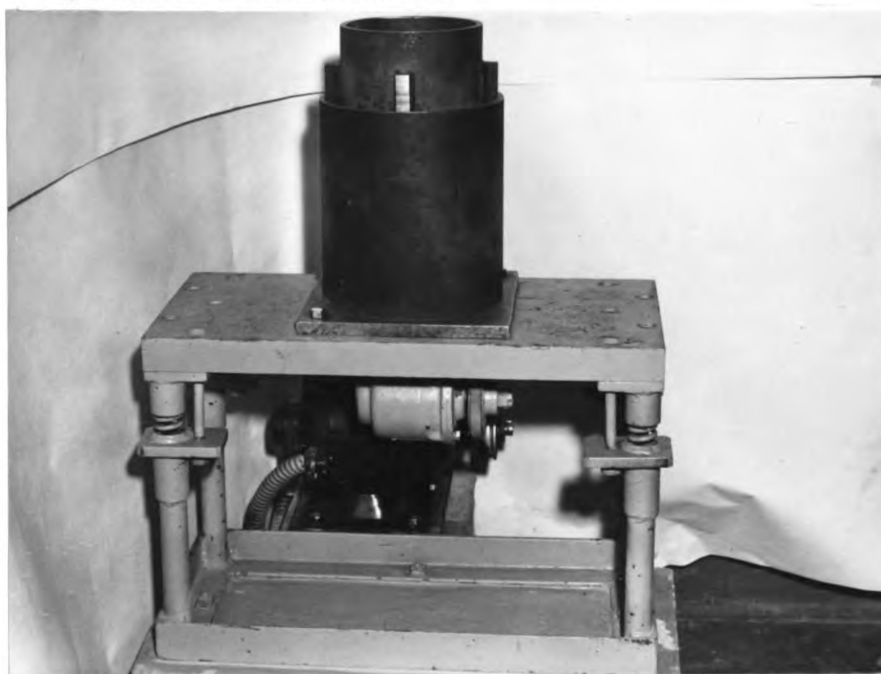


Fig. 2
Front view Vibrometer showing piston and
cylindar in test position.



Fig. 3

Side view of Vibrometer

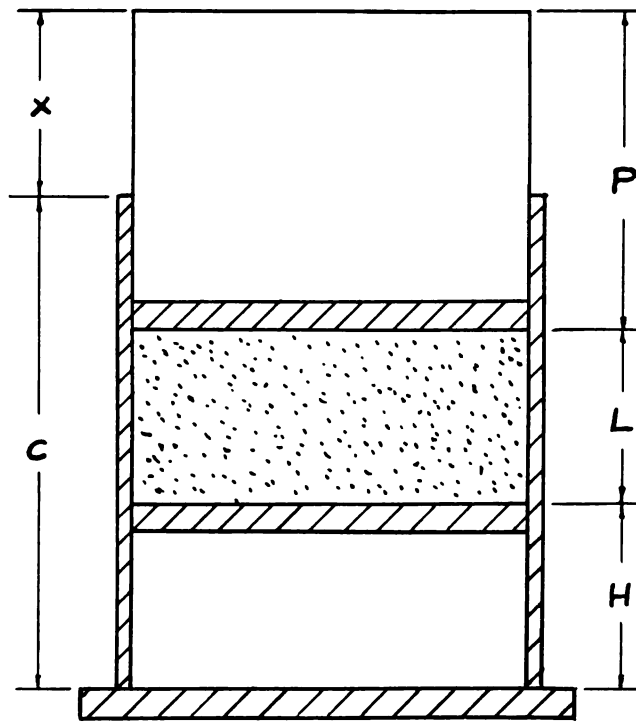
COMPUTATIONS

The consolidation range, moisture content, and dry densities were computed for each test in the following manner with sample computations from test No. 1, Table III (2).

Consolidation Range

Loose volume:		<u>Sample Comp.</u>
Length of sample	= L_1	3.10 in.
Volume of sample	= V	2630 cc.
Weight of sample	= W	4102 g.
Dry weight of sample	= W_o	3983 g.
Per cent moisture	= M	2.98%
Dry bulk specific gravity	= $\frac{W_o}{V} = G_o$	1.52
Apparent specific gravity	= G_a	2.98
Per cent voids	$100(1 - \frac{G_o}{G_a}) = 0$	49.2%
Compacted volume:		
Length of sample	= L_2	2.55 in.
Volume of sample	= V_c	2160 cc.
Dry bulk specific gravity	= $\frac{W_o}{V_c} = G_o$	1.85
Per cent voids	$100(1 - \frac{G_o}{G_a}) = 0_c$	38.0%
Consolidation range	= $0 - 0_c$	11.2%

The length of the soil sample in the cylinder is computed as follows:



C = cylinder length = 10 in.

X = reading of protruding piston

P = piston length = 6.5 in.

L = depth of soil in cylinder

H = cylinder holder = 3.75 in.

$$C + X = P + L + H$$

$$L = (C + X) - (P + H)$$

$$L = 10 + x - 6.5 - 3.75$$

$$L = X - .25 \text{ in.}$$

Note: In the case of the 6A gravel a 7,000 g. sample was used and it was necessary to put a 7/8 in. block under the cylinder. This would make the cylinder (c) equal to 10.875, changing the equation to:

$$L = 10.875 + X - 6.5 - 3.75$$

$$L = X + .625$$

Moisture Content

$$M = \frac{W - W_o}{W_o} \times 100\%$$

where M = moisture content in per cent of dry weight

W = weight of wet soil obtained by subtracting the weight of the container from the weight of the wet soil and the container.

W_o = weight of dry soil obtained by subtracting the weight of the container from the weight of the dry soil and the container.

Sample computation:

$$M = \frac{4102 \text{ g} - 3983 \text{ g}}{3983 \text{ g}} \times 100 = 2.98\%$$

Dry Density

$$D = \frac{W}{V_c(M + 100)} \times 100 \text{ \#/cu. ft.}$$

where D = dry density for compacted volume

W = wet weight of sample.

V_c = compacted volume of sample.

M = moisture content in per cent of dry weight.

Sample computation:

$$W = \frac{4102 \text{ g}}{453.6} = 9.05 \text{ lb.} \quad V_c = \frac{2160 \text{ cc.}}{16.39 \times 1728} = .0763 \text{ cu. ft.}$$

$$D = \frac{9.05}{.0763(2.98 + 100)} = 115.1 \text{ \#/cu. ft.}$$

On the 2NS sand and the 6A gravel sieve analysis tests were run and on the 2NS sand, pea gravel, slag and 6A gravel specific gravity determinations were made. Following is an outline of these tests (4).

Sieve Analysis: This test is for the determination of particle size and gradation of a soil.

The samples are dried to a constant weight and placed on a nest of sieves using such sieves as are necessary to determine compliance with the specifications for the material under test.⁽³⁾ The sieves are then vibrated and jarred by a mechanical vibrator for twenty minutes. The weights of soil retained on each sieve are then found.

The results are reported as total percentages passing each sieve or total percentages retained on each sieve.

Specific Gravity: Dry bulk specific gravity (G_o) is found by use of the following:

$$G_o = \frac{W_o}{V}$$

where G_o = dry bulk specific gravity.

W_o = weight of dry sample.

V = volume of sample, does not take into account the permeable voids.

Sample computation:

$$G_o = \frac{3283}{2630} = 1.52$$

Apparent specific gravity (G_a) is found by use of the formula:

$$G_a = \frac{W_o}{V_s}$$

where G_a = apparent specific gravity.

V_s = volume of soil particles including permeable voids.

W_o = weight dry sample.

The volume V_s is found for fine aggregates by surface drying and weighing the sample and placing it in a 500 cc volumetric flask. Water is then poured into the flask nearly up to the 500 cc mark and the flask is rotated between the hands to remove all air bubbles in the sample. The flask is allowed to stand for one hour in water at 20° C. Water is then

added up to the 500 cc mark and the weight recorded. Considering the weight or volume of water added to the flask as V, then V_s will equal $(500 - V)$.

In the case of coarse aggregate a specific gravity overflow can is used. This is filled to overflowing and all excess water is allowed to run out the spout. A container is then put under the spout and the sample is slowly poured into the can. After all the water has been caught in the container the weight of this water is found and is equal to V_s .

Sample computation:

Refer to Table II, Sample 1.

$$G_a = \frac{412.9}{138.4} = 2.98$$

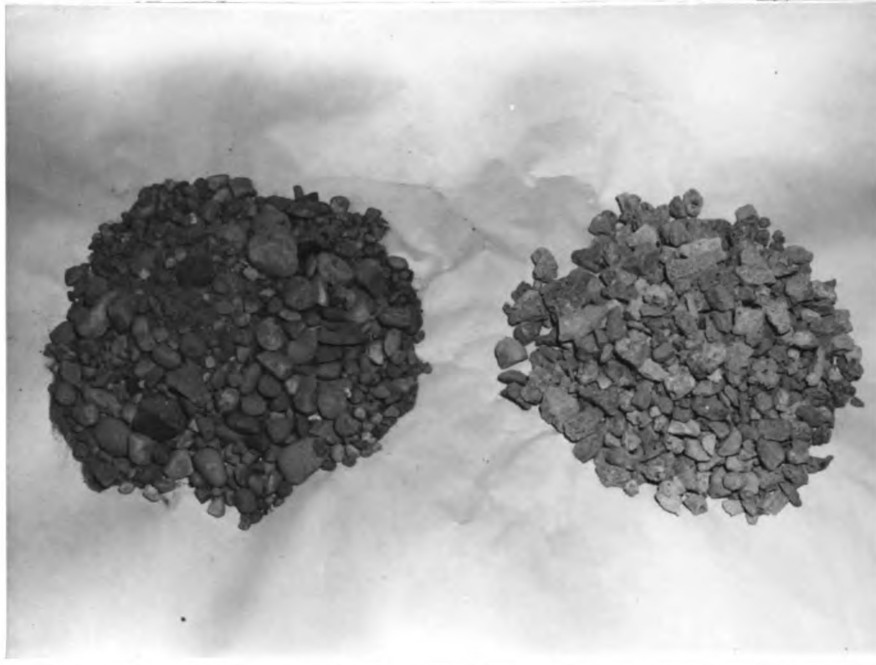


Fig. 4

6A Gravel

Slag



Fig. 5

2NS Sand

Pea Gravel

TABLE I
SIEVE ANALYSIS

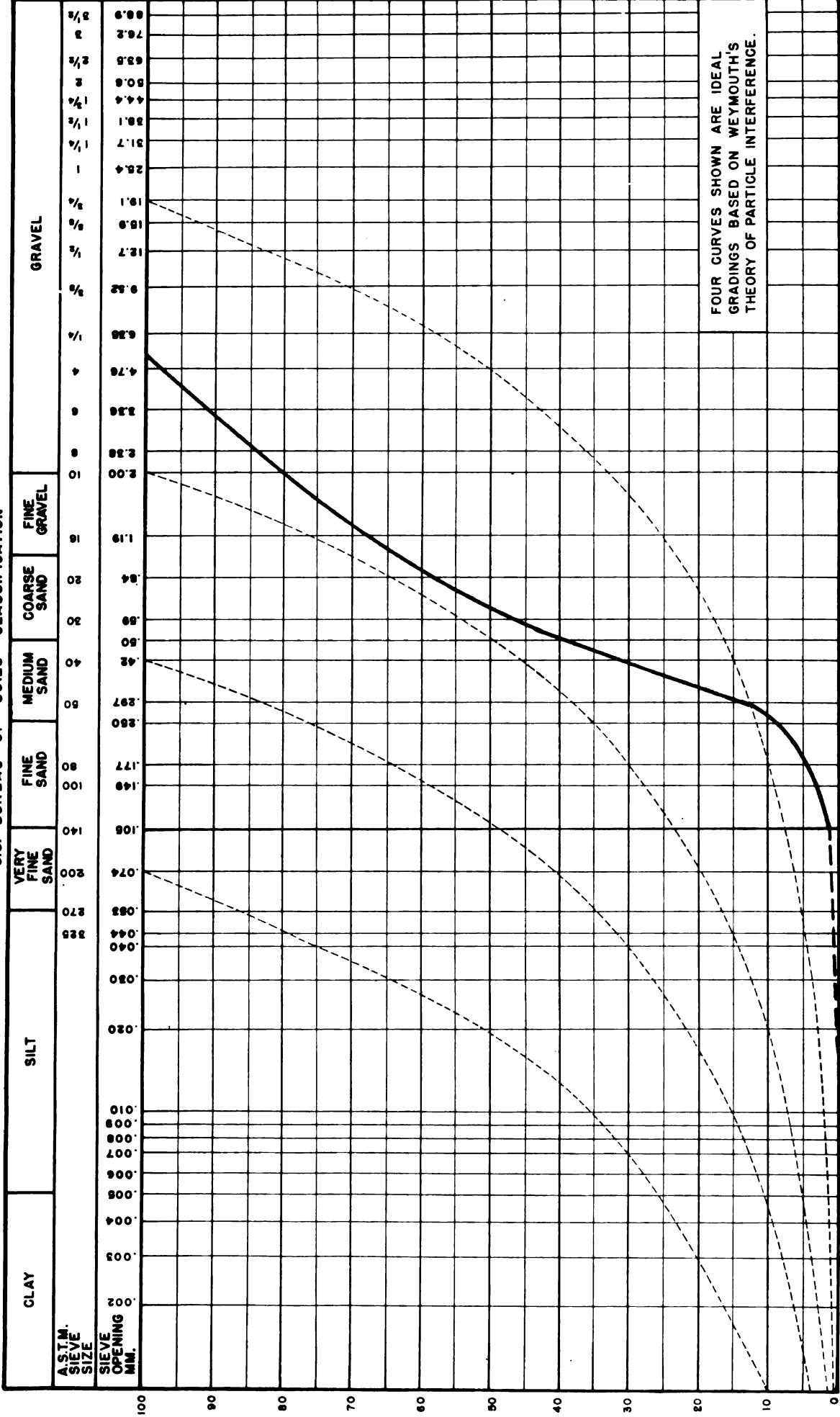
2NS Sand - 2,000 g. Sample

<u>Sieve</u>	<u>Weight Retained</u>	<u>Per Cent Passing</u>	<u>Standard³ % Passing</u>
3/8	0	100	100
No. 4	30	98.5	95-100
No. 8	176	89.8	65-95
No. 16	376	70.9	35-75
No. 30	446	48.6	15-55
No. 50	672	15.0	10-30
No. 100	288	0.6	0-10
Pan	12	0	

6A Gravel - 1992 g. Sample

<u>Sieve</u>	<u>Weight Retained</u>	<u>Per Cent Passing</u>	<u>Standard % Passing</u>
2"	0	100	100
1-1/2"	0	100	95-100
1"	102	34.9	60-90
1/2"	480	69.8	25-55
No. 4	716	33.8	0-8
Pan	694		

U.S. BUREAU OF SOILS CLASSIFICATION



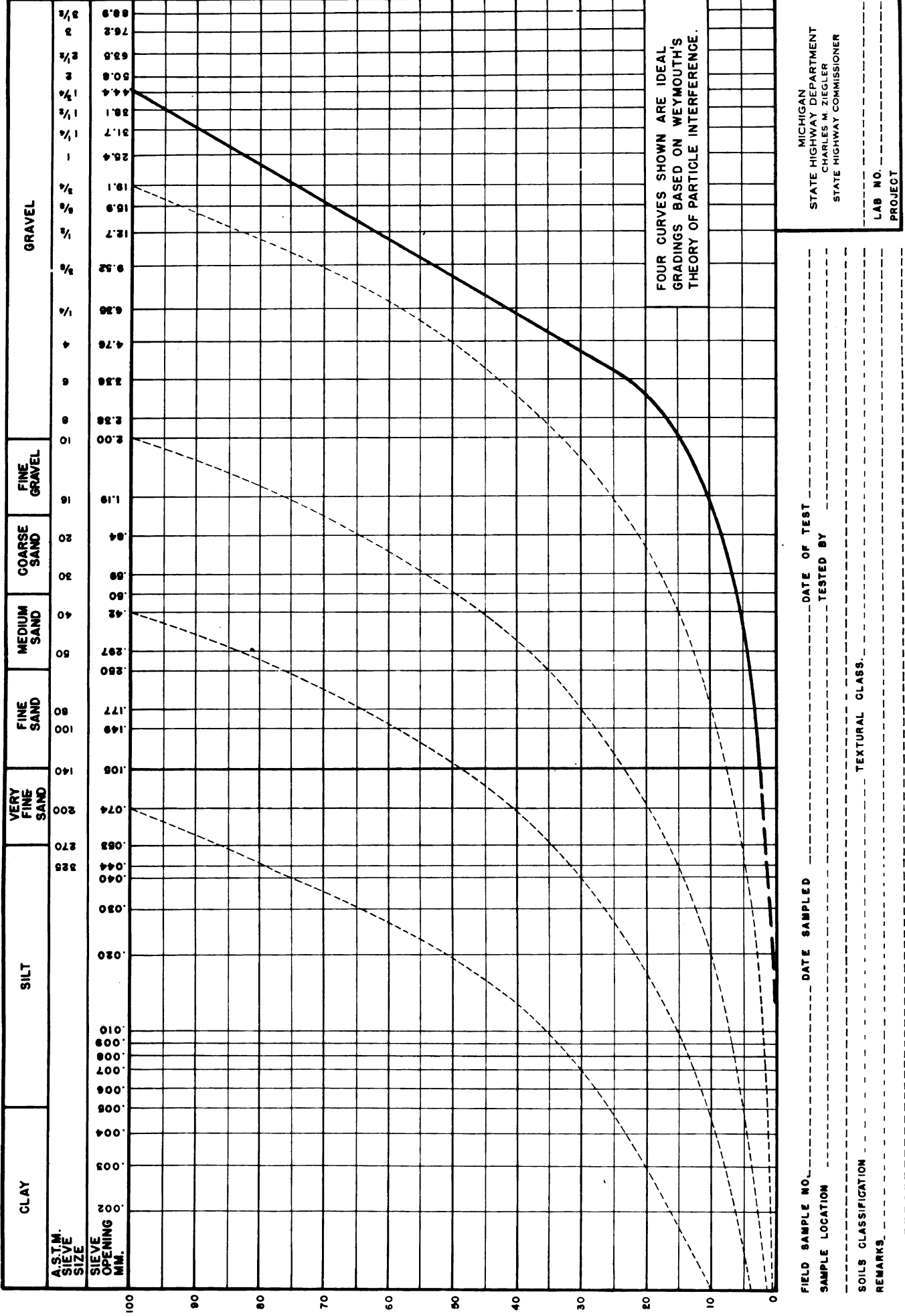
MICHIGAN
STATE HIGHWAY DEPARTMENT
CHARLES M. ZIEGLER
STATE HIGHWAY COMMISSIONER

LAB NO. _____
PROJECT _____

FIELD SAMPLE NO. _____ DATE OF TEST _____
SAMPLE LOCATION _____ TESTED BY _____
SOILS CLASSIFICATION _____ TEXTURAL CLASS _____
REMARKS _____

2NS SAND

U.S. BUREAU OF SOILS CLASSIFICATION



MICHIGAN
STATE HIGHWAY DEPARTMENT
CHARLES M. ZIEGLER
STATE HIGHWAY COMMISSIONER

LAB NO. _____
PROJECT _____

FIELD SAMPLE NO. _____ DATE SAMPLED _____
SAMPLE LOCATION _____ DATE OF TEST _____
TESTED BY _____

SOILS CLASSIFICATION _____ TEXTURAL CLASS _____

REMARKS _____

6A GRAVEL

TABLE II
APPARENT SPECIFIC GRAVITY

Sample	Dry Weight	Weight Con. + Soil	Weight Con. + Soil+H ₂ O	Weight H ₂ O	Vol. Soil + Per. Voids	Apparent Specific Gr.
1. 2NS Sand	412.9	669	1030.6	361.6	138.4	2.98
2. 6A Gravel	4898	5362	7243	1881	1881	2.60
3. Pea Gravel	2071.0	2529.4	3343.1	731.5	781.5	2.66
4. Slag	2204.1	2862.5	3749.5	887	837	2.49

TABLE III
2NS SAND VIBRATION TESTS

Test No.	1	2	3	4	5	6	7	8	9	10	11
Initial Reading	3.35	3.20	3.35	3.15	3.10	3.00	3.35	3.35	3.05	3.10	3.32
Init. Length Sample	3.10	2.95	3.10	2.90	2.85	2.75	3.10	3.10	2.80	2.85	3.07
Initial Vol.	2630	2510	2630	2460	2420	2330	2630	2630	2380	2420	2610
Wet Weight	4102	3867	4000	4000	4000	4000	4000	4000	4000	4000	4000
Dry Weight	3983	3685	3770	3682	3630	3992	3964	3947	3982	3959	3932
% Moisture	2.98	4.93	6.12	8.60	10.20	0.20	0.92	1.35	0.45	0.98	1.74
Dry Bulk Sg.	1.52	1.47	1.43	1.50	1.50	1.71	1.51	1.50	1.67	1.63	1.57
App. Sg.	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
% Initial Voids	49.2	50.5	52.0	49.7	49.6	42.6	49.4	49.7	44.0	45.3	49.5
Final Reading	2.80	2.60	2.65	2.65	2.55	2.65	2.75	2.80	2.75	2.65	2.74
Final Length	2.55	2.35	2.40	2.40	2.30	2.40	2.50	2.55	2.50	2.40	2.49
Final Vol.	2160	1995	2040	2040	1950	2040	2120	2162	2120	2040	2110
Dry Bulk Sg.	1.85	1.85	1.85	1.78	1.86	1.96	1.87	1.82	1.88	1.94	1.86
% Final Voids	38.0	38.0	38.0	40.4	37.6	34.4	37.2	38.7	37.0	35.5	37.6
% Consolid.	11.2	12.5	14.0	9.3	12.0	3.2	12.1	11.0	7.0	10.3	11.9
Dry Density	115.1	118.2	115.2	112.8	115.9	122.0	112.0	113.8	117.1	121.2	116.0

TABLE III (continued)

2NS SAND VIBRATION TESTS

Test No.	12	13	14	15	16	17	18	19	20	21	22
Initial Reading	3.32	3.32	3.32	3.32	3.25	3.25	3.20	3.15	3.20	3.20	3.20
Init. Length Sample	3.07	3.07	3.07	3.07	3.00	3.00	2.95	2.90	2.95	2.95	2.95
Initial Vol.	2610	2610	2610	2610	2545	2545	2500	2460	2510	2510	2510
Wet Weight	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Dry Weight	3924	3894	3880	3864	3822	3788	3728	3593	3660	3730	3730
% Moisture	1.74	2.72	3.10	3.33	7.97	5.71	7.32	11.4	9.29	7.23	7.23
Dry Bulk Sg.	1.51	1.49	1.49	1.43	1.50	1.49	1.49	1.43	1.43	1.49	1.49
App. Sg.	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93
% Initial Voids	49.3	50.0	50.0	50.3	49.7	50.0	50.0	51.0	51.0	50.0	50.0
Final Reading	2.73	2.73	2.77	2.73	2.80	2.75	2.75	2.55	2.65	2.70	2.65
Final Length	2.43	2.53	2.52	2.53	2.55	2.50	2.50	2.30	2.40	2.45	2.40
Final Vol.	2105	2145	2140	2145	2160	2120	2120	1950	2040	2080	2040
Dry Bulk Sg.	1.87	1.81	1.81	1.80	1.73	1.73	1.73	1.84	1.79	1.80	1.83
% Final Voids	37.5	39.4	39.4	39.6	40.8	40.0	41.0	38.2	39.8	39.7	38.6
% Consolid.	12.3	10.6	10.6	10.7	8.9	10.0	9.0	12.8	11.2	10.3	11.4
Dry Density	113.2	113.0	113.1	112.0	110.2	111.3	109.5	114.6	112.1	111.4	114.0

TABLE III (concluded)
2NS SAND VIBRATION TESTS

Test No.	23	24	25	26	27	28	29	30	31	32
Initial Reading	3.20	3.25	3.35	3.35	3.35	3.32	3.32	3.32	3.32	3.32
Init. Length Sample	2.95	3.00	3.10	3.10	3.10	3.07	3.07	3.07	3.07	3.07
Initial Vol.	2510	2545	2630	2630	2630	2610	2610	2610	2610	2610
Wet Weight	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Dry Weight	3775	3829	3845	3905	3962	3854	3821	3790	3744	3702
% Moisture	6.00	4.47	4.03	2.42	0.95	3.79	4.67	5.56	6.83	8.06
Dry Bulk Sg.	1.51	1.50	1.43	1.43	1.51	1.47	1.46	1.45	1.44	1.42
App. Sg.	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98	2.98
% Initial Voids	49.4	49.5	50.9	50.0	49.5	50.5	50.8	51.2	51.8	52.5
Final Reading	2.70	2.75	2.80	2.80	2.75	2.78	2.69	2.70	2.67	2.48
Final Length	2.45	2.50	2.55	2.55	2.50	2.53	2.47	2.45	2.42	2.33
Final Vol.	2080	2120	2160	2160	2120	2145	2100	2080	2060	1980
Dry Bulk Sg.	1.81	1.81	1.78	1.81	1.87	1.79	1.82	1.82	1.82	1.87
% Final Voids	39.3	39.3	40.3	39.3	37.4	39.8	38.9	38.9	39.0	37.3
% Consolid.	10.1	10.2	10.6	10.7	12.1	10.7	11.9	12.3	12.8	15.2
Dry Density	113.1	112.5	110.9	112.2	115.2	111.7	113.4	113.7	114.0	116.5

TABLE IV
PROLONGED VIBRATION TESTS

Fifteen Minute Vibration - 4000 g., 2NS Sand

<u>Test</u>	<u>Final Length</u>	<u>% Moisture</u>	<u>Dry Density</u>
1	2.41	3.93	117.5
2	2.40	1.59	119.4
3	2.30	9.4	117.3
4	2.41	4.61	116.2
5	2.32	6.92	118.7
6	2.45	8.06	115.7

From the data of Table III, a curve was drawn on the following graph using mean values of dry density and per cent moisture. This curve represents thirty-two tests using moderate vibration on 2NS sand.

From the data of Table IV a curve was drawn on the following graph using mean values of dry density and per cent moisture. This curve represents six tests using prolonged vibration of 15 minutes on 2NS sand.

TABLE V
RATE OF COMPACTION TESTS
2NS SAND

Test No. 1 - % Moisture 1.21%

<u>Time</u>	<u>Reading</u>	<u>Length</u>	<u>Dry Density</u>
0	2.90	3.03	95.7
5	2.51	2.64	111.1
10	2.46	2.59	112.2
15	2.43	2.56	113.1
20	2.42	2.55	113.5
30	2.41	2.54	114.1
40	2.41	2.54	114.1
60	2.40	2.53	114.8

Test No. 2 - % Moisture 2.82%

<u>Time</u>	<u>Reading</u>	<u>Length</u>	<u>Dry Density</u>
0	2.90	3.03	94.2
5	2.61	2.74	104.4
10	2.56	2.69	106.4
15	2.53	2.66	107.8
20	2.52	2.65	108.5
30	2.50	2.63	109.0
40	2.50	2.63	109.0
50	2.49	2.62	109.7
60	2.49	2.62	109.7

Test No. 3 - % Moisture 3.79%

<u>Time</u>	<u>Reading</u>	<u>Length</u>	<u>Dry Density</u>
0	2.90	3.03	93.4
5	2.63	2.76	102.7
10	2.57	2.70	105.0
15	2.54	2.67	106.2
20	2.52	2.65	106.9
40	2.51	2.64	107.5
50	2.50	2.63	108.0
60	2.49	2.62	108.4

TABLE V (concluded)
 RATE OF COMPACTION TESTS
 2NS SAND

Test No. 4 - % Moisture 5.56%

<u>Time</u>	<u>Reading</u>	<u>Length</u>	<u>Dry Density</u>
0	2.90	3.03	91.7
5	2.50	2.63	105.7
10	2.45	2.58	108.0
15	2.45	2.58	108.0
20	2.44	2.57	108.5
30	2.43	2.56	108.9
40	2.42	2.55	109.4
50	2.42	2.55	109.4
60	2.40	2.53	110.0

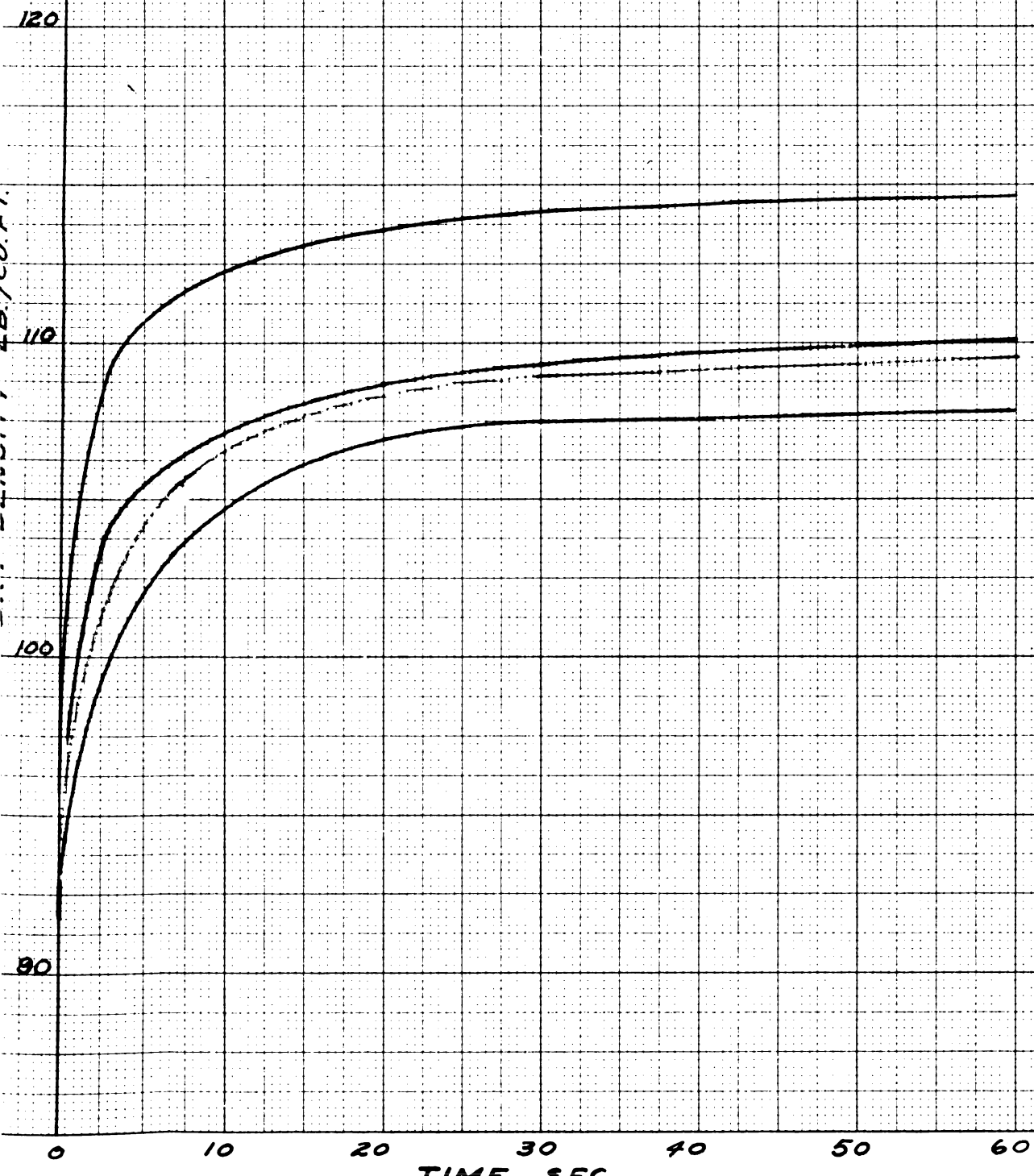
From the data of Table V, four curves were drawn on rate of consolidation of 2NS sand with time plotted against dry density. This graph is on the following page.

1

GRAPH NO. 2 2NS SAND

MOISTURE CONTENT

—	1.2%
—	2.8%
—	3.8%
—	5.6%



1

TABLE VI
PEA GRAVEL VIBRATION TESTS

Test No.	1	2	3	4	5	6	7
Initial Reading	3.34	3.35	3.35	3.19	3.19	3.19	3.13
Initial Length	3.09	3.10	3.10	2.94	2.94	2.94	2.88
Initial Volume	2620	2630	2630	2495	2495	2495	2445
Wet Weight	4000	4000	4000	4000	4000	4000	4000
Dry Weight	3981	3971	3949	3930	3918	3883	3868
% Moisture	0.20	0.72	1.26	1.77	2.08	3.02	3.40
Dry Bulk Specific Gravity	1.52	1.51	1.50	1.57	1.57	1.56	1.53
App. S. G.	2.66	2.66	2.66	2.66	2.66	2.66	2.66
% Initial Voids	42.9	43.3	43.6	41.0	41.0	41.4	40.6
Final Reading	3.03	3.00	3.00	2.97	2.97	2.97	2.88
Final Length	2.78	2.75	2.75	2.72	2.72	2.72	2.63
Final Volume	2360	2335	2335	2310	2310	2310	2232
Dry Bulk Specific Gravity	1.69	1.70	1.69	1.70	1.69	1.68	1.74
% Final Voids	36.6	36.0	36.6	36.0	36.4	36.8	34.6
% Consolidation	6.3	7.3	7.0	5.0	4.6	4.6	6.0
Dry Density	105.5	104.9	104.2	106.1	105.9	104.9	108.0

On the following page is a graph with a possible curve for the moisture-density relation on vibration of pea gravel. Due to the diversion of the points this curve is only a possible one and may be proved or disproved by the results of more tests. However, it seems to be a logical

curve since it is a mean of all points except the point plotted from test No. 7. This result presumably is in error and it is likely that a straight line curve showing no effect of moisture would seem to be the most conclusive from the data available. This curve, moreover, is in accord with the theory that due to the size of the voids and the weight of the individual particles the effects of moisture would be negligible.

GRAPH NO. 3
PEA GRAVEL

————— POSSIBLE CURVE

115

110
LB./CU. FT.

DRY DENSITY

105

100

0

1

2

3

4

5

6

TABLE VII
6A GRAVEL VIBRATION TESTS

Test No.	1	2	3	4	5	6	7	8	9	10
Initial Reading	2.90	2.90	3.82	4.12	4.12	4.12	4.12	4.12	4.12	4.12
Initial Length	3.53	3.53	4.45	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Initial Volume	2995	2995	3780	3820	3820	3820	3820	3820	3820	3820
Wet Weight	6000	6000	7000	7000	7000	7000	7000	7000	7000	7000
Dry Weight	5780	5863	6762	6784	6987	6963	6918	6784	6683	6674
% Moisture	3.64	2.34	3.52	3.26	0.20	0.53	1.76	3.19	4.74	4.90
Dry Bulk Sp. Gravity	1.93	1.95	1.79	1.78	1.83	1.83	1.81	1.77	1.75	1.75
App. Sp. Gr.	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60
% Initial Voids	25.7	25.0	31.0	31.5	29.5	29.5	30.5	32.0	32.6	32.6
Final Reading	2.23	2.25	2.92	2.98	2.93	2.93	2.77	2.70	2.63	2.70
Final Length	3.23	3.25	3.92	3.98	3.93	3.93	3.77	3.70	3.63	3.70
Final Volume	2740	2760	3320	3380	3340	3340	3200	3140	3080	3140
Dry Bulk Sp. Gravity	2.11	2.12	2.04	2.01	2.09	2.09	2.16	2.16	2.16	2.12
% Final Voids	18.8	18.5	21.5	22.6	19.5	19.5	17.0	17.0	16.4	19.5
% Consolidation	6.9	6.5	9.5	8.9	10.0	10.0	13.5	15.0	16.0	13.1
Dry Density	127.6	132.2	126.5	125.0	130.4	130.0	134.1	134.2	135.1	132.2

TABLE VII (concluded)
6A GRAVEL VIBRATION TESTS

Test No.	11	12	13	14	15
Initial Reading	4.12	4.12	4.12	4.12	4.12
Initial Length	4.50	4.50	4.50	4.50	4.50
Initial Volume	3820	3820	3820	3820	3820
Wet Weight	7000	7000	7000	7000	7000
Dry Weight	6837	6825	6730	6711	6691
% Moisture	2.40	2.56	3.25	4.32	4.62
Dry Bulk Sp. Gravity	1.79	1.79	1.77	1.76	1.75
App. Sp. Gr.	2.60	2.60	2.60	2.60	2.60
% Unitial Voids	31.0	31.0	31.7	32.4	32.6
Final Reading	2.88	2.97	2.75	2.86	2.84
Final Length	3.88	3.97	3.75	3.86	3.84
Final Volume	3290	3370	3180	3280	3260
Dry Bulk Sp. Gravity	2.08	2.02	2.13	2.04	2.05
% Final Voids	20.0	22.4	18.0	21.5	21.0
% Consolidation	11.0	8.6	13.7	10.9	11.6
Dry Density	129.2	126.2	132.2	127.6	128.0

On the following page is a moisture density graph giving a possible curve from data in Table VII. Conclusive results are not available due to the wide diversion of the points. More tests on 6A gravel are necessary to obtain more specific results.

TABLE VIII
SLAG VIBRATION TESTS

Test No.	1	2	3	
Initial Reading	4.42	4.42	2.00	Note: Test No. 1 - Slag Retained on .742" sieve. Test No. 2 - Slag Retained on .371" sieve. Test No. 3 - Slag Retained on Pan.
Initial Length	5.10	5.10	2.68	
Initial Volume	4325	4325	2270	
Weight	5000	5000	3400	
Dry Weight				
% Moisture				
Dry Bulk Specific Gravity	1.16	1.16	1.50	
App. Sp. Gr.	2.49	2.49	2.49	
% Initial Voids	53.4	53.4	39.8	
Final Reading	3.61	3.65	1.33	
Final Length	4.29	4.33	2.01	
Final Volume	3640	3670	1705	
Dry Bulk Specific Gravity	1.37	1.36	1.99	
% Final Voids	45.0	45.4	20.0	
% Consolidation	8.4	8.0	19.3	
Dry Density #/ft. ³	85.7	85.0	124.1	

DISCUSSION OF RESULTS

2NS Sand

The results attained with the 2NS sand were very satisfactory. Thirty-two tests were run and the dry densities of the compacted volumes were plotted against the moisture contents for each test. The curve, Table III, indicates that there are two optimum moisture contents for this sand, they being zero moisture content and complete saturation, which occurs at approximately 10 per cent moisture content. The density of the vibrated mass decreases from zero to around 5% moisture and then increases to the saturation point. However, at the saturation point the densities obtained were still below the densities at zero moisture content.

Five tests were run using prolonged vibration of 15 minutes and a moisture density curve drawn (Table IV). This curve shows greatly increased densities between zero and the saturation point and seems to indicate that prolonged vibration tends to equalize all densities regardless of the moisture content. However, even with 15 minute vibration, densities at 5% moisture could not be brought up to the zero moisture density.

Four tests were run to determine how the moisture content effects the rate of consolidation. Readings were taken every five seconds up to 20 seconds and every twenty seconds up to one minute. Dry densities for these tests were plotted against time, and the moisture content was determined for each sample (Table V). From these curves it is evident that the dry sample compacts at a much faster rate than the samples with a moisture content up to 4%. However, the 5.6% moisture sample compacts at a faster

rate than the 3.8% sample, so it appears that increasing the moisture content over 4% increases the speed of compaction.

From a study of the moisture density curve, Table III, it is evident that a slight amount of moisture in the sand decreases the rate of vibrational compaction. This is probably due to the effects of surface tension which, at a low moisture content, tends to hold the individual particles in place. However, at a moisture content of from 4 to 5% the lubricating effect of the water tends to overcome the holding effect of the surface tension plus the internal friction and so consolidation increases to the saturation point.

Pea Gravel

The results of seven tests on pea gravel of 1/8 to 1/2 inch gradation seems to indicate that the moisture content has no effect upon compaction by vibration (Table VI). This can be explained by the fact that there are no fine particles under 1/8 inch in this gradation. Because of this the voids are very large and no matter how high the water content is short of complete saturation, the voids will not be filled. This, together with the large size of the particles, makes surface tension have little or no effect upon the rate of consolidation.

6A Gravel

The results of 15 tests on 6A gravel gave such an indefinite arrangement of points on the density-moisture graph, Table VII, that no valid conclusions could be obtained. This is probably due to the fact that the 6A gradation contains stones over 1 inch in size, and when aggregate of this size is placed in such a small volume as an 8 inch cylinder, the various arrangements of these large stones would effect the results of the

tests. For testing aggregate of this size it would be advisable to obtain a cylinder of at least 12 inches inside diameter and long enough to take an 8 to 10 inch sample. This would give enough volume so that the arrangements of the large stones would have much less effect upon the results.

Slag

Three tests were made on three gradations of dry slag, the first being retained on the .742 sieve; the second, on the .371 sieve; and all the rest passing the .371 sieve. The .742 slag and the .371 slag gave approximately the same compacted densities of 85-86 #/cu. ft., but the smaller gradation passing the .371 sieve compacted to 124 #/cu. ft. This is due to the fact that many fine particles were present to fill the voids.

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