Compaction of Sands by Vibration Alone

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• THIS RESEARCH was started as a continuation of the work of Lino Gomes (1). The following recommendations for future research were given in that paper.

> 1. Laboratory maximum density might be determined by using a circular tamper of about a 4-in. diameter with the vibrator used in this experiment. The sand could be contained in a plastic cylinder about 4 in. high with a collar like a Proctor mold. The sand could be placed in four layers. The first layer should be 3 in. thick and the other three layers should be 1 in. thick. Each layer could be compacted at critical frequency for 6 min. The collar could be removed and the excess sand trimmed off as in the Proctor test. The first layer is to permit room for the maximum compaction which would occur in the third inch below the surface with a 4-in. tamper. As the other layers are added, the point of maximum density would move up and the procedure should result in 4 in. of maximum density material.
> 2. Field compaction by vibro-tampers should be run at critical frequencies which could be estimated in situ or determined in the laboratory for each soil.
> 3. The experiment on dry sand should be repeated with more variety of tamper dimensions to permit correlating the depth of maximum compaction with tamper dimensions.
> 4. The effect of moisture on the compaction of sand by vibration should be investigated.

The current investigators are concentrating on the first and second recommendations but hope to include some work on the third. This paper concerns itself with the first two only. Other researchers reported at the 1962 meeting that saturated sand compacts under vibration like dry sand.

APPARATUS

The compaction apparatus was constructed by attaching an aluminum plate 3.95 in. in diameter and 0.125 in. thick to the cone of a heavy-duty radio loud-speaker (Fig. 1).

The speaker and plate were made to vibrate by an audio-oscillator augmented by an amplifier. A voltmeter across the supply line controlled the input voltage to prevent overloading the speaker. A cathode-ray oscillograph helped in the calibration of the audio-oscillator and also in the regulation of the precise frequency during the tests.

The sand to be compacted was contained in an ordinary steel Proctor mold. This mold was supported on a hydraulic jack to permit raising and lowering the mold during the compaction process. The loud-speaker was supported over the Proctor mold in such a way that the aluminum plate could enter but not touch the mold and contact the soil as the jack was raised.

MATERIAL

Three sands, two crushed limestones, a crushed quartzite, and some plastic pellets were used. Gradations covering more than one sieve size are shown in Figure 2, whereas single sieve sizes are shown in the tables of results. The concrete sand is the same as that used by Gomes and the sizes were obtained by sieving a concrete sand from pits near South Bend, Ind., in a glacial outwash area. The silica sand is manufactured silica sand from near Ottawa, Ill. The Plymouth sand is a natural sand soil used as fill

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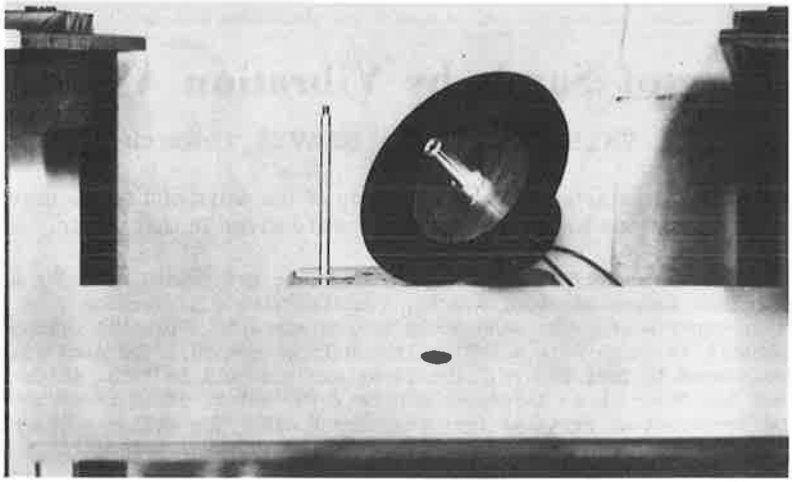

Figure 1. Details of speaker and tamper.

under a schoolhouse floor near Plymouth, Ind. The two crushed limestones are from quarries near Huntington and Pipe Creek, Ind. The quartzite and plastic pellets are from laboratory supplies.

PROCEDURE

In the compaction process 3 in. of sand was placed in the Proctor mold by pouring through a funnel with no free fall. The mold was then raised by the hydraulic jack until the metal tamping plate made contact with the sand surface. Because this contact could not be established visually, it was determined by sound. After some practice, it was easy to note the particular humming sound that came from the speaker at the point of firm but not excessive contact pressure. The load on the tamper at this point was 0.375 lb or a contact pressure of 0.03 psi. With the contact pressure maintained constant by sound, the tamper was vibrated for the chosen length of time at the chosen frequency. At the end of the vibration time, the mold was lowered away from the tamper, another inch of sand was placed through a funnel, and the vibration process repeated. Four more approximately 1-in. layers of sand were compacted in this fashion, making a total of about 6.5 in. of sand in the mold. At the end of the compaction, the mold was removed from the compaction apparatus, the collar taken off the mold, and the sand trimmed even with the mold as in the ordinary Proctor test. The mold and sand were then weighed to determine the density obtained.

TABLE 1

DENSITIES OBTAINED IN LAYERS OF CONCRETE SAND GRADING A

Trial No.	Vibration		Density (pcf) of Sand After Compaction of					
	Frequency (cps)	Time (min)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Mold
1	25	6	115.5	116.1	119.5	119.8	119.0	116.4
2	25	6	112.5	-	-	120.0	119.2	120.0
3	25	6	118.0	119.5	119.0	119.2	121.0	119.7

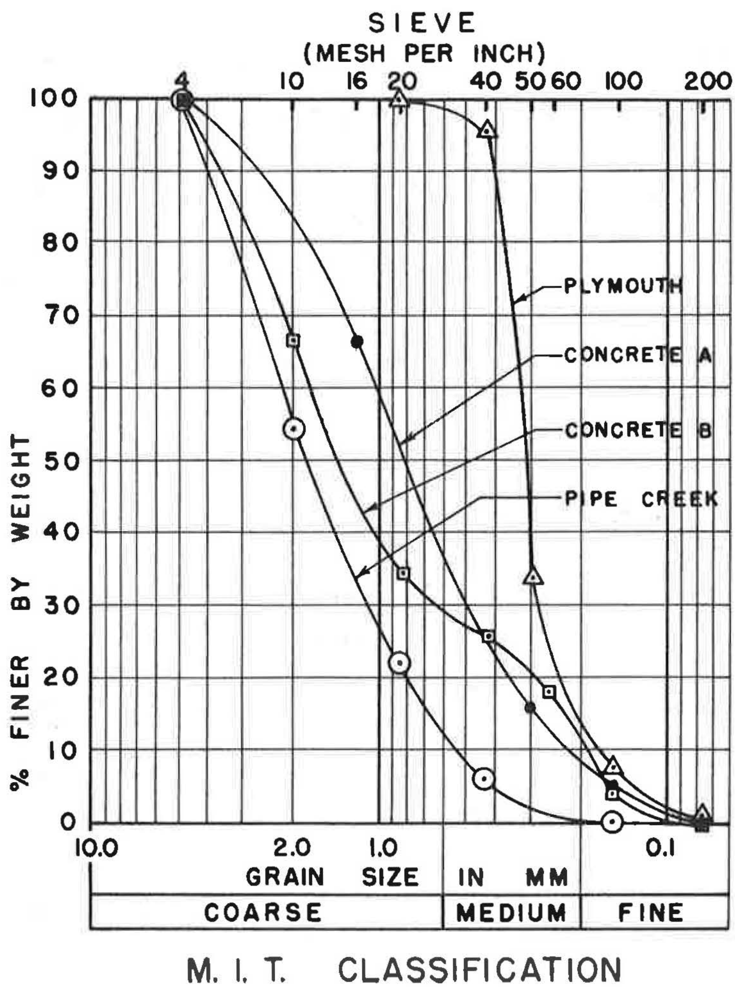

Figure 2. Mechanical analysis of sands.

RESULTS

The results of this research are given in Tables 1 through 6 and in Figure 3. Tables 1 and 2 give the results of tests made to compare the essentially two-dimensional results of the research by Gomes with the three-dimensional results of this study. The density of the soil increased as each layer was added. Also, the process of removing the collar must have loosened the sand because the density in the mold alone was less than that before the collar was removed.

Table 3 gives the results of compaction tests run at various frequencies of vibration on a few sands having essentially one-size gradings. A frequency of 25 cycles per second (cps) caused the greatest density for every sand but the variation in density was not as much as that noted by Gomes for the better graded sand. The greatest amount of energy was delivered by the tamper at 25 cps.

Table 4 gives data showing the effect of time of vibration on the density of a variety of sands and gradings. The data seem to indicate that all types and gradings of sand have about the same exponential relation between time and degree of compaction as that found by Gomes for the well-graded concrete sand. The better graded samples reached higher densities and lower void ratios than the one-size sands.

TABLE 2

DENSITIES OBTAINED IN LAYERS OF PLYMOUTH SAND

Trial No.	Vibration		Density (pcf) of Sand After Compaction of					
	Frequency (cps)	Time (min)	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Mold
1	25	6	96.8	96.5	97.3	98.5	98.8	96.6
2	25	6	98.0	98.2	99.0	99.5	100.0	98.4
3	20	6	95.0	97.5	97.3	99.0	98.3	97.5
4	30	6	99.5	100.5	100.5	101.5	102.2	99.2

TABLE 3

EFFECT OF VIBRATION FREQUENCY ON SAND DENSITY

Sand	Grading	Vibration		Energy (in.-lb)	Density (pcf)
		Frequency (cps)	Time (min per layer)		
Concrete	20-40	25	6	302	100.8
		23.5	6	293	100.3
Concrete	40-60	25	6	302	98.7
		28	6	256	98.4
Plymouth	40-100	20	6	270	97.5
		25	6	302	98.7
		30	6	223	97.8
Plastic cubes	4-10	20	3	135	33.6
		25	3	151	34.8
		30	3	112	34.2

The data in Table 5 indicate that the particle shape and surface smoothness of one-size sands have a large effect on the void ratio reached under a vibration time of 6 min per layer and a vibration frequency of 25 cps. The data are very consistent for sands with great differences in specific gravity and significant differences in particle sizes.

The data of Table 6 show that there is no consistent relation between the specific gravity of a sand and the void ratio reached after 6-min per layer compaction at a frequency of 25 cps. In the concrete sand, gradings having the same particle shape and surface smoothness reached lower void ratios when the particle sizes were larger and sands with the same grain shape and size reached lower void ratios when the specific gravity was higher.

Figure 3 shows the results of standard Proctor (AASHO T 99, method A) compaction on grading B of the concrete sand, the graded and standard Ottawa sand, and the Plymouth sand. In addition to the normal erratic curves, the one-size gradings in the dry state reached densities higher than the vibration densities, whereas the better graded sand did not.

ANALYSIS OF RESULTS

Apparently, the conclusion by Gomes that the greatest density occurs some distance below the tamper holds true for the three-dimensional case represented by the results

TABLE 4

EFFECT OF VIBRATION TIME ON SAND DENSITY

Sand	Grading	Vibration Frequency (cps)	Vibration Time (min per layer)	Density (pcf)	Void Ratio
Concrete	A	25	1.0	120.9	0.32
		25	2.0	121.8	0.31
		25	3.0	123.0	0.30
Concrete	B	25	1.5	120.9	0.32
		25	2.0	121.5	0.31
		25	3.0	123.6	0.29
		25	6.0	123.9	0.29
Concrete	4 - 10	25	1.5	101.0	0.58
		25	2.0	102.0	0.56
		25	3.0	102.6	0.55
		25	6.0	102.0	0.56
Concrete	10 - 20	25	2.0	97.5	0.64
		25	3.0	99.0	0.61
		25	6.0	99.9	0.60
Concrete	20 - 40	25	2.0	99.3	0.60
		25	3.0	100.0	0.59
		25	4.0	100.8	0.58
		25	5.0	100.5	0.59
		25	6.0	100.8	0.58
Concrete	40 - 60	25	1.0	96.8	0.65
		25	2.0	98.0	0.63
		25	3.0	97.7	0.64
		25	4.0	98.0	0.63
		25	5.0	98.0	0.63
		25	6.0	98.0	0.63
Ottawa	Std.	25	1.0	104.5	0.59
	20 - 30	25	1.5	105.6	0.57
		25	3.0	106.0	0.57
		25	6.0	105.6	0.57
Ottawa	Graded	25	1.5	103.0	0.61
	30 - 100	25	3.0	103.8	0.60
		25	6.0	103.8	0.60
Plymouth	40 - 100	25	0	98.1	0.62
		25	0.5	98.7	0.61
		25	1.0	98.7	0.61
		25	1.5	99.0	0.60
		25	3.0	99.3	0.60
		25	6.0	98.7	0.61
		25	10.0	99.9	0.59
Plastic spheres	20 - 30	25	1.5	40.3	0.61
			3	43.2	0.50
			6	43.5	0.50
Plastic cubes	4 - 10	25	1.5	33.9	0.67
			3	34.8	0.62
			6	35.4	0.60

of this study. The increase of over-all density as each layer was added can be explained by the fact that as each layer was compacted the maximum density layer became a greater portion of the whole. The loosening of the sand when the collar was removed may have been due to an expansion of the sand with shear when the collar was rotated to remove it from the mold.

TABLE 5

EFFECT OF PARTICLE SHAPE ON SAND DENSITY

Sand	Grading	Specific Gravity	Particle Shape	Void Ratio
Plastic spheres	20 - 30	1.04	Spherical, smooth	0.50
Ottawa	20 - 30	2.66	Bulky, rounded	0.57
Concrete	20 - 40	2.55	Bulky, rounded	0.58
Plastic cubes	4 - 10	0.91	Cubical, smooth	0.60
Plymouth	40 - 100	2.54	Bulky, rough, rounded	0.61
Limestone	4 - 10	2.57	Bulky, sharp	0.65
Limestone	4 - 40	2.64	Flat, very sharp	0.69
Quartzite	4 - 10	2.66	Bulky, rough, sharp	0.75

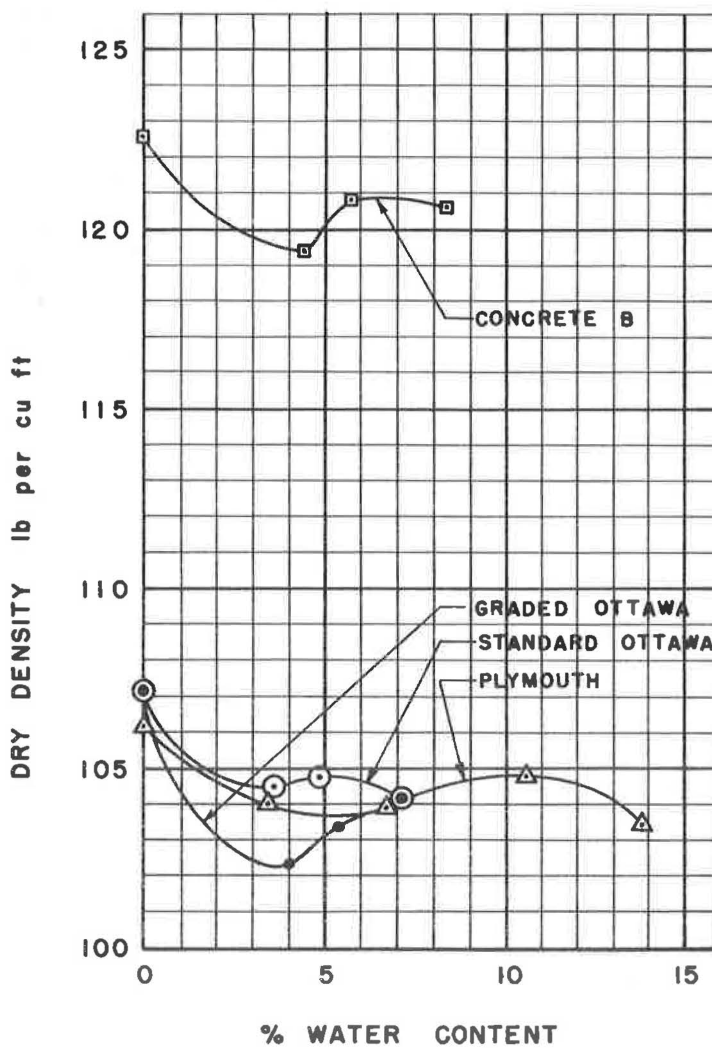

Figure 3. Proctor-moisture-density relation curves.

TABLE 6

EFFECT OF SPECIFIC GRAVITY ON SAND DENSITY

Sand	Grading	Particle Shape	Specific Gravity	Void Ratio
Ottawa	20 - 30	Bulky, rounded	2.66	0.57
Ottawa	30 - 100	Bulky, rounded	2.66	0.60
Quartzite	4 - 10	Bulky, rough, sharp	2.66	0.75
Limestone	4 - 40	Flat, very sharp	2.64	0.69
Limestone	4 - 10	Bulky, sharp	2.57	0.65
Concrete	4 - 10	Bulky	2.55	0.56
Concrete	10 - 20	Bulky	2.55	0.60
Concrete	20 - 40	Bulky, rounded	2.55	0.58
Concrete	40 - 60	Bulky, rounded	2.55	0.63
Plymouth	40 - 100	Bulky, rough, rounded	2.54	0.61
Plastic spheres	20 - 30	Spherical, smooth	1.04	0.50
Plastic cubes	4 - 10	Cubical, smooth	0.91	0.69

The energy delivered by the tamper seems to be another reason behind the optimum compaction at 25 cps rather than a simple critical frequency as the data obtained by Gomes indicated. The amplitude of the tamper became less as the vibration frequency increased varying in a hyperbolic fashion, whereas the force became less as the amplitude decreased varying in a straightline manner. This resulted in a smaller amount of energy being delivered at frequencies above and below 25 cps. However, energy alone does not seem to be the whole reason for the best compaction because the Proctor procedure with its 4,950 in.-lb of delivered energy did not compact the graded concrete sand to as dense a state as 300 in.-lb delivered by the vibration tamper. On the other hand, the one-size sands reached a greater density under Proctor compaction. Thus, factors other than total energy (such as particle gradation, shape, size, and weight as well as manner of energy delivery) must affect the density a sand reaches under compaction. Of course, the data indicate that with other factors held constant the greatest amount of delivered energy results in the greatest density. Also, the compacting effect of the vibration energy is greatest when the sand is loose and decays in an exponential fashion as the sand densifies.

When the compactive energy is held constant, the particle shape and surface roughness seem to have a greater effect on the density reached under vibration than other factors, such as specific gravity or size of sand particles. Although, when all other factors were held constant, sands with higher specific gravities tended to reach higher densities and sands with larger one-size grains also reached higher densities, the differences noted were much less than those caused by particle shape and roughness even when the specific gravity and grain size were variable. This would indicate that the densifying process under a vibrating plate depends less on the attraction of gravity (grains falling into place) than on a shearing action (grains sliding on each other).

The fact that the maximum density occurs at some distance below the plate also points to the importance of shear because that is where the maximum shear occurs. The shear concept might also be used to explain why the large energy of the Proctor procedure did not cause a lower density in the relatively easily compacted graded sand. The force applied was so large that the sand actually moved sidewise and upward along the hammer causing such a large strain that the sand was loosened from its previously compacted state. So, while the sand immediately under the hammer tended to compress to a lower void ratio, that at some depth and to the side became loosened. The net effect was a smaller density than that caused by the much smaller energy of the vibration. In the less easily compacted one-size sands, a smaller amount of excessive shear strain occurred in the Proctor compaction and more of the force was effective in compressing the sand, thus the net effect was greater than that caused by the vibration.

All of the preceding discussion leads to the theory that compaction in clean sand can best be accomplished by applying the correct amount of shearing strain. This shearing strain could be applied in many ways, such as a direct sliding or torsional strain on thin layers or one of the many forms of stressing to cause strain. It is well known that static compressional loading will not produce high densities in a confined sand because the load itself causes large normal stresses between the grains thus giving them resistance to sliding and preventing the development of sufficient strain to cause the particles to rearrange themselves in a more dense manner. Thus, it would seem wise to keep the compressional loads light to permit the necessary strains to occur more easily. This is what Gomes and the authors tried to do with their repeated application of very light loadings. It now appears that not enough strains were caused to reach the lowest possible void ratios even in the well-graded sand. (Hough's textbook reports a minimum void ratio of 0.20 for a sand like the well-graded concrete sand, whereas 0.29 was the lowest void ratio reached in this study.)

Greater strains could be caused by more applications of the loads. This was done with the Plymouth sand when it was vibrated for 10 min but this approach is inefficient because of the exponential decay in the compacting effect. Larger amplitudes of vibration would also cause more strains and more compaction as would larger tamper pressures, but amplitude, frequency, and tamper pressure were all interdependent in the equipment used in this investigation, so their effects could not be studied separately.

CONCLUSIONS

The following conclusions are made from the results of this study:

1. The vibration method of compaction as suggested by Gomes is efficient for the well-graded dry sands of this study and results in low void ratios, but not the lowest possible.
2. The density of the sand should be measured before the collar is removed from the mold, or the collar removed in such a way that the sand is not loosened.
3. The maximum density region of the sand seems to be at some distance below the tamping plate, as found by Gomes.
4. One-size sands do not compact to low void ratios under the vibration time, frequency, and amplitude used in this study.
5. Variations in frequency of vibration do not affect the resulting density as much in one-size sands as in well-graded sands.
6. The highest density in both one-size and well-graded sands was reached at the frequency and amplitude of vibration delivering the most energy to the sand.
7. The exponential relation between time of compaction and density found by Gomes applied to both well-graded and one-size sand.
8. One-size sands with rounded and smooth-surfaced grains reach much higher densities under vibration compaction than sand with sharp and rough-surfaced grains.
9. When other variables are held constant one-size sands of higher specific gravities reach slightly higher densities under vibration compaction.
10. When other variables are held constant, one-size sands with larger particles reach slightly higher densities under vibration compaction.
11. Standard Proctor compaction caused greater compaction in the one-size sands than the vibration compaction but not in the well-graded sands.
12. Standard Proctor compaction caused greater densities in dry sands than in sands having water contents up to 14 percent.
13. The densifying process in a sand under a vibrating plate depends more on particles sliding on each other than on particles falling into place from gravity.
14. The vibration frequency, amplitude, and contact pressure used in this study did not cause the lowest possible void ratios in the sands because they did not cause the right amount of shearing strain to occur.

FUTURE RESEARCH

This study is continuing and equipment is being designed in which vibration amplitude, frequency, and contact pressure can be controlled independently. Thus, total energy delivered and manner of delivery can be controlled. With this equipment the effect of amplitude will be evaluated first because it seems the most promising; then further work will be done on frequency and contact pressure. Should this repeated compression approach fail to produce maximum possible densities, a direct torsional shear strain approach will be tried.

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Discussion

W. H. CAMPEN, and L. G. ERICKSON, Omaha Testing Laboratories, Omaha, Neb.—The authors have done work along a line that deserves immediate attention. Many who furnish control service in connection with construction of embankments, trench backfills and pavement subgrades, subbases and bases are very well aware of the fact that impact methods used for establishing maximum laboratory density are not generally satisfactory for cohesionless mixtures. A method is therefore needed for evaluating such mixtures.

Based on the writers' research and that of others (1), the conclusion has been reached that eventually a method will be developed based on inundation plus vibration. Apparently a small, low-energy vibrator will suffice.

With such a method, it will be necessary to distinguish between truly cohesionless and borderline mixtures. There are mixtures that show no plastic limit by test but contain enough clayey or plastic particles to prevent consolidation by inundation plus vibration. Such mixtures can be evaluated by impact methods.

REFERENCE

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