Compaction Energy Relationships of Cohesive Soils

J. R. Bell, Department of Civil Engineering, Oregon State University

The energy requirements of laboratory methods of compaction that produce similar results with a sandy silty clay soil of low plasticity were investigated. The purposes were to provide insight into compaction energy relationships, to give a preliminary indication of the possible benefits of improved field compaction equipment design and operation, and to suggest directions for future studies. Three methods of compaction—impact, static, and kneading—were studied. The soil was compacted at three energy levels by the impact method, and for one energy level, nine combinations of rammer mass, number of tamps, and height of drop were used. The moisture versus unit weight relationships for the basic impact method were reproduced by a static compaction method and by a kneading method and the compaction energies determined. The compacted specimens were tested for as-compacted undrained strength. The static method is always the most efficient for the soil tested, but the relative efficiencies of the other methods vary with the moisture content of the soil, the rammer force per unit area, and the rate and duration of loading. In this study, the most efficient method was always at least three times as efficient as the least efficient method with respect to the energy required to produce the same dry unit weight. A view of the compaction process for cohesive soils that considers energy and distinguishes between penetration due to densification and plastic deformation is presented.

It is frequently possible to meet a given set of compaction specifications with a wide range of equipment and field procedures. To select the most efficient equipment and method requires knowledge of the inputs of compaction energy per unit volume of soil that are required to produce end products having comparable properties by different compaction methods. It also requires knowledge of the efficiencies of different types of field compaction equipment and of the procedures used in applying useful compaction energy to soil. This report presents the results of a preliminary study of the energy requirements of various laboratory methods of compaction that produce comparable results. The purposes of the study are to provide a better understanding of the compaction energy relationships for cohesive soils, a preliminary indication of the possible benefits of improved field compaction equipment, and information for planning further research.

Three laboratory compaction methods—impact, static, and kneading—were studied using one soil. The soil used was a sandy silty clay of low plasticity. The results from this soil are compared with data from the literature by other investigators for other cohesive soils. From the point of view of efficiency in field compaction, it is necessary to consider equipment factors relative to the efficiency of transferring energy from some source to the soil as well as the energy that must be applied to the soil itself to obtain the desired results. This investigation considers only the relationship between the desired end product and the energy applied to a unit volume of soil (the compactive effort).

It is traditional to compare compaction on the basis of density. However, with cohesive soils, different methods of compaction may yield different soil grain structures at the same density (1), and different densities and moisture contents may be required to obtain comparable end properties by different methods. A comparison of the energy per unit volume to obtain a given density may not be a true evaluation of relative efficiencies. Therefore, the compactive efforts required by each method were compared with respect to dry unit weight and as-compacted undrained shear strength.

LITERATURE REVIEW

Considerable, but still incomplete, information about the compaction-energy requirements of cohesive soils is available in the literature. Some of this is summarized briefly below, and a more complete review has been given by Johnson and Sallberg (2).

Several investigations of the effects of the magnitude and distribution of compactive effort in the impact test are reported in the literature. A study relating compactive effort, dry unit weight, and compaction moisture content by Dhawan and Bahri (3) showed that, under conditions drier than the optimum moisture content, increased energy per unit volume results in higher densities. This is true even at high compactive efforts. Under conditions wetter than the optimum moisture content, however, increasing the energy input above some relatively low value does not increase the density because the additional effort is consumed in remolding the soil at constant volume. It is this remolding that produces the different grain structures of cohesive soils compacted above and below the optimum water content (1).

There have been several studies of the details of how a given effort is applied to the soil. Sowers and Kennedy (4) found that the most important factor influencing the effectiveness of a given impact compactive effort was the percentage of the total energy that was applied in each tamp. In studies of the effects of force, velocity, energy, and momentum of the rammer, Proctor (5) showed that for constant compactive effort per unit volume of soil, the variation in dry unit weight due to rammer force was small. Maclean and Williams (6) also found that for constant applied energy, the effect of the force of the rammer was very small. Contrary to Proctor, however, they found that the lighter rammer gave slightly higher unit weights. Maclean and Williams also studied the effects of rammer force at constant momentum and found only a slightly greater effect than for constant energy. Sowers and Kennedy (4) used rammers ranging from 24.5 to 111.2 N (5.5 to 25.0 lbf) and heights of drop from 76.2 to 457 mm (3 to 18 in) and concluded that neither rammer force, velocity, nor momentum had discernible effects on impact compaction effectiveness with respect to dry unit weight.

There are no known data for the moisture and unit weight versus energy relationships for static compaction. Some factors affecting efficiency may be the ratio of the diameter of the specimen to its length, the rate of compression, the time of load application, and whether compression is from both ends or one.

Several studies have been made of the effects of the number of layers, the number of tamps per layer, the foot pressure, and the dwell time on the kneading compaction process. Typical of the results of these studies are those of Seed and Monismith (7), who showed that increasing the number of layers or of load applications per layer has the same general effect as in the impact test, and increasing the foot pressure has the same effect as increasing the rammer force in the impact test. McRae and Rutledge (8) found that increasing the time the foot pressure was maintained on the soil shifted the line of optimum toward the zero air-voids line.

Sankaran and Muthukrishnaiah (9) have compared the energy consumed in laboratory impact and kneading compactions under moisture contents drier than optimum. They concluded that the impact method is more efficient in terms of both dry density and strength. They also found that, for any given molding-water content drier than the optimum, there was a critical compactive effort for each compaction method. Below this critical compaction effort, the as-compacted undrained strength was a linear function of the compactive effort. Above this effort, the strength increased very little with increased compactive effort.

LABORATORY STUDIES

This is a preliminary study; therefore, only one soil and only each method of impact, static, and kneading compaction were studied. Because of the large amount of data (nearly 90 specimens were compacted and tested), typical results only are presented.

Test Soil

The soil was sieved through a 4.75-mm (no. 4 U.S. standard) sieve. The portion passing was air dried, thoroughly mixed, and stored until needed for testing. This soil had 61 percent passing the 0.074-mm (no. 200) sieve; its liquid and plastic limits were 24 and 19 percent respectively. The soil was a sandy silty clay of low plasticity having a unified classification of CL-ML.

For all tests, the air-dried soil was carefully mixed by hand with distilled water to as nearly the desired moisture content as possible and stored in air-tight containers for a curing period of not less than 24 h before compaction. A fresh soil sample was used for each specimen.

Shear Test Method

The undrained strength relationships for all of the specimens were measured to detect any differences in soil structure that might result from the different compaction procedures. A direct shear test was used for these investigations because the sample could be cut from the center third of the cylinder of compacted soil so as to not include the contact planes between the layers in which the soil was compacted.

After compaction, the soil was extruded from the compaction mold, and a sample 63.5 mm (2.5 in) in diameter by 25.4 mm (1.0 in) high was carefully trimmed from the center of the cylinder. The sample was placed in the direct-shear machine, a normal stress of 47.9 kPa (1000 lbf/ft^2) was applied to it, and it was sheared at a rate of 0.01 mm/s (0.025 in/min).

Impact Compaction

Equipment and procedures were as specified by AASHTO T 99 procedure, except as noted. In the basic series of impact tests, only the compactive effort was varied. In addition to the standard 25 blows/layer, 12 and 55 blows/layer were also used. The moisture content versus unit weight curves obtained from these tests are shown in Figure 1, and the stress versus displacement curves obtained from the undrained strength tests of the specimens compacted at standard conditions are shown in Figure 2.

To investigate the effects of rammer velocity and force on the impact test method, a special rammer was made that allowed varying the height of drop and the force. The general design, clearances, and shape and area of the rammer face were the same as the standard rammer. The compactive effort was held constant at 592.5 kJ/m^3 (12 375 ft·lbf/ft^3), which is the energy of the standard test. The number of blows per layer, the heights of drop, and the rammer forces used are listed in Table 1.

For the impact tests, the gross energy applied per unit volume was calculated directly from the product of the force, the height of drop, the number of blows per layer, and the number of layers divided by the volume of soil.

Static Compaction

Specimens were compacted to the desired moisture content and unit weight by mixing the soil to as nearly the desired moisture content as possible, weighing the required amount of moist soil into the compaction mold, and compressing it to a known volume. After compaction, the sample was extruded from the mold, weighed, a moisture sample taken, and the moisture and unit weight computed. The moisture versus unit weight relationships obtained by the basic impact tests were duplicated as nearly as possible by static compaction, and strength tests were performed on these specimens. The results of typical strength tests are shown in Figure 3.

The soil was compacted in a steel cylinder by compression from both ends. The compacted specimen was the same size as that obtained in the impact method. The compression force was recorded at each 2.5 mm (0.1 in) of displacement, and the total energy required for compaction was computed as the area under the force versus displacement curve. The energy relationships are shown in Figures 4 and 5. The normal procedure was to compact at a constant rate of 5 mm/min (0.2 in/min). Tests of the effect of the rate of compression showed that the compaction energy did not increase significantly until the compaction rate was more than doubled.

Kneading Compaction

The kneading compaction tests were performed with a manual press similar to the University of California type (2). The soil was compacted in a standard AASHTO compaction mold, which was placed on a rotating base under the ram of the press. A triangular tamping foot on the ram was pressed into the soil, the foot was raised, the cylinder rotated 30°, and the foot again pressed into the soil. This process was repeated as required. The soil was compacted in three layers with 24 tamps/layer at a foot pressure of 3861 kPa (185 lbf/ft^2). These conditions were selected experimentally to approximately duplicate the moisture versus unit weight curve obtained by the standard impact method.

A hydraulic cylinder and pressure gauge in the ram assembly indicated the force on the foot, and an Ames displacement dial measured the foot penetration into the soil. The foot was pressed into the soil as rapidly as the displacement and the corresponding forces could be read manually. The energy for each tamp was computed as the area under the force versus displacement curve. The total energy was the sum of the energies of the individual tamps.

The strength results for the kneading compaction method are shown in Figure 6, and the energy relationships for this method are shown in Figures 4 and 5.

DISCUSSION OF RESULTS

The compaction results of the basic impact tests at the three energy levels and the undrained, as-compacted strength data are typical of this method. The data given in Table 1 for constant energy with different rammer forces, velocities, and energies per blow, however, show that the way the energy is applied is significant. With respect to the maximum dry unit weight, the maximum variation is only about 0.5 kN/m^3 (3 lbf/ft^3). However, when this is translated into energy considerations, it becomes significant. Figure 7 shows the relationship between the maximum dry unit weight and the compactive effort for the basic procedure and the range of unit weights obtained at 592.5 kJ/m^3 (12 375 ft·lbf/ft^3) of energy with various rammer forces and drop distances. The least efficient combination gives a dry unit weight that could have been obtained with only about 402.2 kJ/m^3 (8400 ft·lbf/ft^3) by the basic method, and the most efficient combination corresponds to a unit weight that would have required about 790.0 kJ/m^3 (16 500 ft·lbf/ft^3) by the basic method. These are relative efficiencies of 68 and 133 percent respectively. On this basis, the most efficient combination is approximately twice as efficient as the least efficient procedure.

With respect to dry unit weight, the most efficient method was the use of the heaviest rammer with the lowest velocity and the highest energy per blow, and the least efficient was the use of the lightest rammer with the highest velocity and lowest energy per blow. Energy per blow was the most important factor: The lower the energy per blow, the lower the efficiency.

The strength test data show that these are also significantly affected by the details of the compaction procedure. Table 1 shows that the peak strength at the optimum moisture conditions for the specimen compacted with the lightest rammer with the highest velocity and the lowest energy per blow is about equal to that for the

Figure 1. Impact compaction: moisture content versus unit weight.

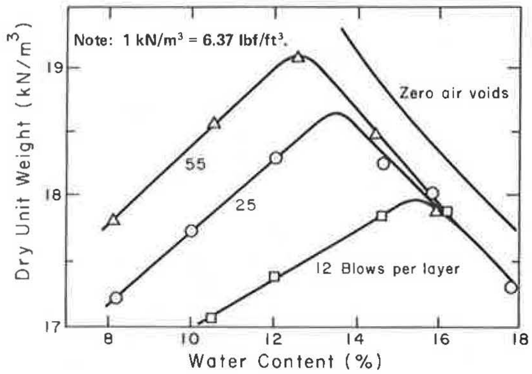


Figure 2. Shear stress: displacement relations for AASHTO T 99 compaction.

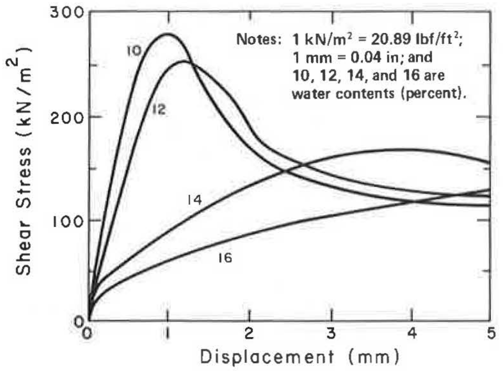


Figure 3. Shear stress: displacement relations for static compaction equivalent to AASHTO T 99 compaction.

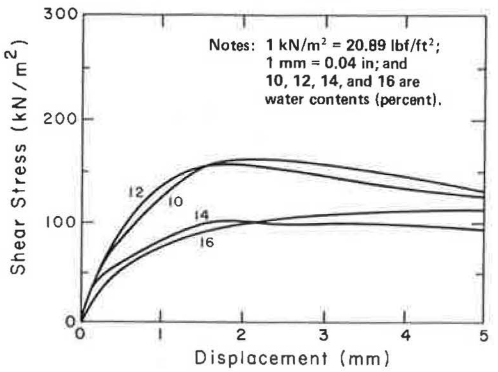


Table 1. Impact compaction variables and results.

			Optimum Conditions		
Blows per Layer	Height of Drop (mm)	Rammer Force (N)	Water Content (%)	Dry Unit Weight (kN/m^3)	Peak Strength (kN/m^2)
55	610	5.6	13.7	18.2	173
55	305	11.1	13.6	18.3	212
55	152	22.2	13.6	18.3	218
25	610	12.2	13.6	18.6	239
25	305	24.5	13.4	18.7	205
25	152	49.0	13.5	18.6	205
12	610	25.5	13.9	18.5	217
12	305	51.0	13.4	18.7	165
12	152	102.0	13.2	18.8	174

Note: 1 mm = 0.04 in; 1 N = 0.22 lbf; 1 kN/m^3 = 6.37 lbf/ft^3; 1 kN/m^2 = 20.89 lbf/ft^2.

Figure 4. Compactive effort required to obtain AASHTO T 99 dry unit weight.

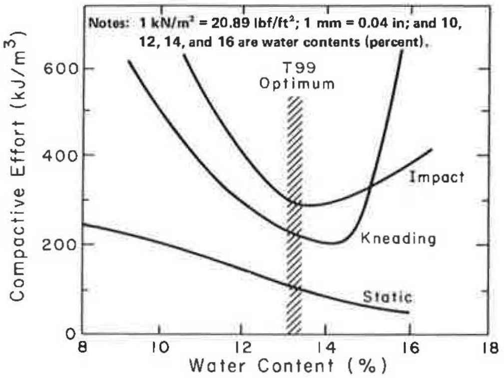
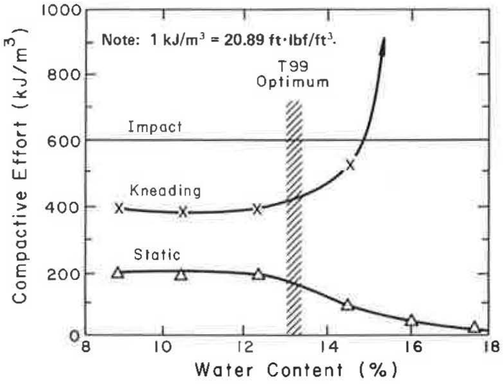


Figure 5. Compactive effort required to obtain dry unit weight of 17.9 kN/m^3 (114.0 lbf/ft^3).



heaviest and slowest rammer and the highest energy per blow, even though this condition yields higher density. The highest peak strengths were those of intermediate conditions. Evidently, the high-energy rammer accomplishes more remolding and shear of the soil and develops a more ordered arrangement of the soil particles that reduces the strength.

The table below for measurements made at a compactive effort of 526 kJ/m^3 (11 000 ft·lbf/ft^3) shows that there were significant differences in the energy applied to the different layers in the kneading test (1 N·m = 0.74 lbf/ft).

	Energy (N·m)		
Tamp No.	Layer 1	Layer 2	Layer 3
1	15.8	17.2	19.7
4	7.5	7.6	9.8
8	5.9	5.9	9.4
12	4.6	6.6	7.8
Subtotal	88.1	93.8	117.6
16	4.6	6.1	6.5
20	3.8	5.3	8.0
24	2.8	4.8	7.0
Total	131.7	159.2	205.5

Layer one consumed less energy because it is underlain by the unyielding metal plate, but the other layers are over soil, which deforms when the foot is applied to the soil. This trend is much greater under conditions wetter than optimum.

Figure 6. Shear stress: displacement relations for kneading compaction equivalent to AASHTO T 99 compaction.

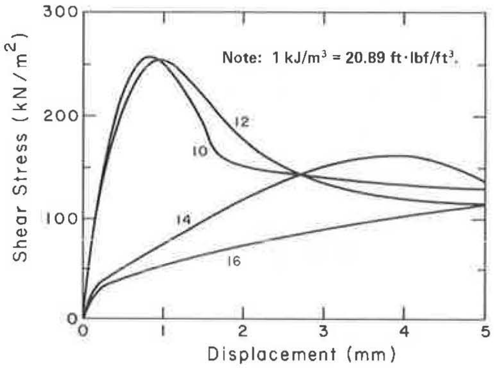
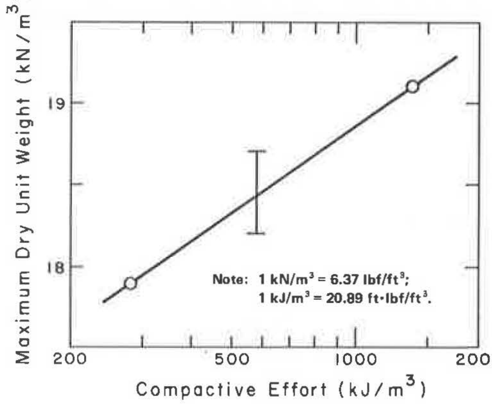


Figure 7. Maximum dry unit weight versus compactive effort for impact compaction.



This table also shows that in the kneading method, the greatest energy is applied by the first tamp. There is a great difference between the first and second tamp and then a steady decrease with succeeding applications of the tamping foot: Approximately two-thirds of the total energy was applied during the first 12 tamps (one coverage of the soil). For the conditions of this kneading method, the energy applied during the first coverage accomplished about 97 percent of the compaction under moisture conditions drier than optimum and virtually 100 percent of the compaction under moisture conditions wetter than optimum. The energy in the second application was consumed almost entirely in remolding at constant volume.

Figure 4 shows the energies required to obtain the standard AASHTO T 99 moisture versus unit weight relationships by the three compaction procedures studied, and Figure 5 shows the energies required to obtain a dry unit weight of 17.9 kPa (114 lbf/ft^3) by the three methods. For the soils compacted under moisture conditions drier than optimum, the energies required to approximate AASHTO T 99 compaction are constant for all methods. Of course, for the impact method, the energy available for compaction is held constant, but for the other methods, more energy is available if required. Under moisture conditions drier than optimum, the density obtained for a constant energy input is essentially a linear function of the water content for all methods, and the static method is the most efficient, with respect to the dry unit weight, and the impact method is the least efficient of the methods. The difference between the kneading and impact methods is probably due, for the most part, to the different rates of loading in the two procedures. The kneading load is applied more slowly and is, therefore, more efficient. If the kneading loads were applied more rapidly and the dwell times reduced, the energy required by this method would be about the same as that in the impact method. As discussed previously, changing the energy per blow in the impact method will change the efficiency of this method.

Under moisture conditions wetter than optimum, the relationships are quite different. The efficiency of the static method compared to that of the impact method with respect to density becomes somewhat higher. This may be because the soil tested has a relatively high permeability and some of its water was squeezed out during static compaction. This trend might be slowed or even be reversed if a more impermeable soil were tested.

Under moisture conditions wetter than optimum, the efficiency of the kneading method is lower than that of the impact method. This is due to the greater remolding of the soil, which consumes energy, but does not increase the density. This greater remolding is also due to the slower rate of loading. If the tamping foot of the kneading compactor is pressed into the soil more rapidly and the dwell time is reduced, there will be less remolding, and the relative efficiency will probably be increased. It is also probable that efficiency could be increased by reducing the foot pressure so that the shear resistance of the soil is not exceeded.

In all cases, the most efficient method is at least three times as efficient as the least efficient method with respect to the compactive effort required to produce the same dry unit weight at a given moisture content.

For both the impact method and the kneading method, there are distinct optimum moisture contents. These optimums are well defined in Figure 5 where they correspond to the point of minimum energy required to obtain the specified dry unit weight. This figure also shows that there is no optimum moisture content for the static compaction method. Efficiency increases with increase in moisture content all the way to complete saturation.

Figure 8. Relative peak strength per unit compactive effort for compaction equivalent to AASHTO T 99.

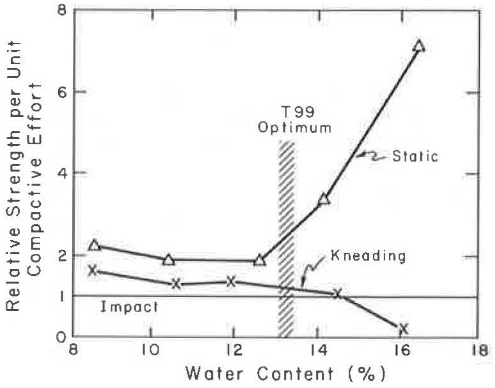
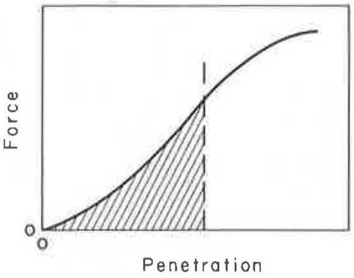


Figure 9. Idealized force versus penetration curve for compactable cohesive soil.



This is a logical extension of the tendency of the line of optimums to move toward the line of zero air voids with increased dwell time during kneading compaction (8).

The optimum moisture content is a function of the compaction procedure and can, for a given soil, be varied by changing the procedure. It appears to correspond closely to the highest moisture content at which there is no significant remolding of the soil at constant volume during compaction. If all of the factors were fully understood, it might be possible to adjust the kneading compaction procedure so that the optimum could be made to correspond to any soil moisture content.

For the procedures and soil used in this study, the peak strength for the same conditions of moisture versus unit weight was very nearly the same for the impact and kneading tests at all moisture contents. This does not agree with the results of Sankaran and Muthukrishnaiah (9) who found their impact method more efficient with respect to both density and strength for moisture contents below optimum. Evidentially their soil, which was more plastic than the one used in this study, and their procedures resulted in more remolding in the kneading method at low moisture contents.

Under moisture conditions drier than optimum, in this study, the kneading method yielded about the same strength with a lower energy input; therefore, it is more efficient with respect to strength than is the impact method. Under moisture conditions wetter than optimum, however, the strength ratio remained near unity, but the energy requirements increased for the kneading method, and the impact method became more efficient. These relationships are shown in Figure 8 in terms of the relative strength per unit energy input per unit volume with respect to the impact method. This was calculated by dividing the strength of a given specimen by the strength of a corresponding impact specimen and then dividing the answer by the corresponding ratio of the compactive efforts.

All of the static compaction specimens have lower strengths than do the corresponding impact specimens. This is inconsistent with the work of Seed, Mitchell, and Chan (10). The reasons for this were not investigated. However, even though the strengths were low, the low energy required by the static method made it the most efficient with respect to strength as well as to dry unit weight.

With respect to strength, the question of efficiency is very complex, and the data of different investigators are contradictory. However, with respect to dry unit weight, the trends appear to be fairly well established. These trends suggest a view of the compaction process for cohesive soils that may be helpful in understanding field as well as laboratory compaction.

As a compaction device is applied to a loose cohesive soil, the load overcomes the ability of the soil to support it, and it sinks into the soil. As it penetrates, the soil directly under the compaction device is densified. Large deformations are restricted to the zone directly beneath the device. Almost all of the input energy is used to densify the soil. As the soil is compacted, its bearing capacity is increased, and if that becomes equal to the applied load, penetration and compaction stop. An idealized force versus penetration curve is shown in Figure 9. The process described above is represented by that portion of the curve to the left of the dashed vertical line. In this region, almost all of the energy applied (which is equal to shaded area) is used to compact the soil. As long as densification is the dominant process, the penetration curve will be concave upward.

If the compaction pressure is increased, compaction will continue until the resistance to densification is approximately equal to the shear resistance to plastic deformation. If the pressure is increased further, the curve will become concave downward, and penetration will be largely the result of shear of the soil beneath the compactor at essentially constant volume. The energy represented by the area beneath the curve to the right of the dashed line is largely expended in remolding at constant volume and is wasted as far as compaction is concerned. For a given soil, the exact shape of the curve, the area under the curve, and the position of the inflection point depend on the moisture content and the details of the compaction procedure. The greatest efficiency is achieved when compaction is accomplished by a few slowly applied loads without excessive remolding. From the standpoint of equipment design and operation, it is necessary to obtain combinations of factors to allow compaction in the region represented to the left of the inflection point in Figure 9. In general, it appears that the most efficient will be that which uses heavy equipment with large contact areas, high contact pressures, and low rates of travel (which approximates static loading).

For dry conditions, the use of slow, heavy, high-pressure compaction equipment does not have serious inherent problems. However, for wet soils, high, slowly applied contact pressures cause inefficient remolding. If it is not possible to approach static compaction for wet conditions, then an impact procedure is the next most efficient. This could be approximated by compacting at high rates of travel, but heavy equipment is difficult to operate at high speeds; therefore, lighter equipment with smaller contact areas is better for compacting wetter cohesive soils. If constant contact pressure is used, efficiency will probably be improved by operating at slower speeds with subsequent passes of the roller. Or if more than one roller were used, the use of higher contact pressures on subsequent passes would increase efficiency. [These general observations are supported by numerous reports of actual field compaction (11).] Specific procedures for selecting appropriate contact pressures and travel speeds do not, however, yet exist.

In real situations it is necessary to consider practical factors other than energy efficiency in the selection of the best equipment and procedures for a given job. Also, in compactor design, the mechanical efficiency in applying the energy to the soil may be more important than the compaction energy required by the soil, but the results of this study suggest that there are opportunities for significant improvements in design.

CONCLUSIONS

Much more information than is available from the literature or from this limited investigation is necessary to provide a thorough understanding of the energy requirements of soil compaction. Nevertheless, some preliminary conclusions about the compaction of cohesive soils appear justified.

1. For all moisture conditions, static compaction is the most efficient.
2. Either impact or kneading compaction may be next most efficient, depending on the details of the procedures used.
3. The optimum moisture content is apparently the lowest at which excessive shear of the soil occurs during compaction.
4. The most important factors controlling the compactive effort required to obtain a specified density with a given cohesive soil at a given moisture content are (a) the magnitude of the compactor-soil contact pressures (the highest contact pressure that does not cause excessive shear is most efficient) and (b) the rate at which the load is applied and the length of time the load is held on the soil (the slower the rate and the longer the load is applied, the higher the efficiency).
5. The data for energy efficiency with respect to the strengths of compacted soils are contradictory. This question needs more study.
6. Much more information is needed, but significant improvements in compaction equipment design could be made that would increase efficiency of operation and yield a compacted soil with better engineering properties. The problem is certainly worthy of additional study.

ACKNOWLEDGMENTS

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Mix Design, Durability, and Strength Requirements for Lime-Stabilized Layers in Airfield Pavements

John J. Allen, Department of Civil Engineering, Engineering Mechanics, and
Materials, U.S. Air Force Academy
David D. Currin, Strategic Air Command, U.S. Air Force
Dallas N. Little, Jr., Texas A&M University

Laboratory and field evaluation programs leading to the development of a design process for lime-stabilized airfield pavement layers are described. The entire process can be completed in 3 to 7 d. The design procedure, which includes selection of the optimum percentage of lime, rapid cure,