A Study of Some of the Factors Likely to Affect the Performance of Impact Compactors on Soil

Étude de Quelques Facteurs qui Semblent Devoir Influer sur l'Efficacité d'un Compacteur par Chocs

by W. A. LEWIS, B.Sc., A.M.I.C.E., Road Research Laboratory, Department of Scientific and Industrial Research, Harmondsworth, England

Summary

To provide information for the design of improved machines for compacting soil by impact, a simplified theoretical analysis has been made of the pressures produced in soil by a rammer. The analysis showed that the impact pressure and, by inference, the state of compaction produced were a function of the area and kinetic energy of the rammer and the deformation properties of the soil.

As a check on the analysis and to provide data for design purposes, measurements were made of the states of compaction of a sandy clay and a sand obtained with a dropping-weight apparatus in which the weight, area and height of drop of the rammer could be varied. A limited study was also made of the pressures generated in the sandy clay.

The experimental results largely confirmed the conclusions reached in the analysis and showed that the simplified theory could be used to estimate impact pressures in soil.

Sommaire

Afin de renseigner les constructeurs de compacteurs par chocs, une théorie simplifiée a été élaborée, permettant le calcul des pressions produites dans le sol par ces engins. Cette théorie a montré que cette pression d'impact, et par suite l'augmentation de compacité produite, étaient fonction de l'aire d'impact, de l'énergie cinétique de la dame, et de la déformabilité du sol.

Pour vérifier cette théorie, et fournir des valeurs numériques aux constructeurs, on a mesuré l'augmentation de compacité obtenue dans une argile sableuse et dans un sable, par une dame, dont on pouvait faire varier le poids, la hauteur de chute et la surface d'impact. Des mesures, en nombre limité, ont aussi été faites sur les pressions produites par le damage dans une argile sableuse.

Les résultats expérimentaux ont très bien confirmé les conclusions de la théorie simplifiée, et montré que celle-ci pouvait être utilisée pour évaluer les pressions d'impact.

Introduction

Full-scale compaction tests carried out by the Road Research Laboratory, England, have shown that impact compaction is one of the most promising methods of compacting soil in the field. With this type of compaction it is possible to obtain a close control of the compactive energy with the result that it should be possible to devise a compacting machine capable of operating efficiently over a wide range of soil types and moisture contents.

To give an indication of the important factors to be considered in the design of impact compactors, a simplified theoretical analysis has been made of the impact pressures produced in soil by a rammer. As a check on the theoretical analysis, and to provide quantitative data for design purposes, compaction tests have been carried out on a sandy clay and a sand using an experimental dropping-weight apparatus.

Theoretical Analysis

Let W = weight of rammer, V = velocity of rammer on impact, ρ = deformation of soil during impact, p = pressure generated on surface of soil by the impact, f = deceleration of rammer on striking soil, k_s = dynamic modulus of deformation of subgrade p/ρ, A = area of rammer base.

From the well-known equations of motion

$$V^2 = 2f\rho \quad \text{and} \quad pA = \frac{w}{g}f$$

Hence

$$p = \sqrt{\frac{W}{g}\cdot\frac{k_s}{2}\cdot\frac{V^2}{A}}$$

In the case of a rammer falling freely from a height h,

$$p = \sqrt{\frac{W.h.k_s}{A}}$$

These relationships indicate that the impact pressure is a function of the energy per unit area of the rammer base and the deformation properties of the soil under dynamic conditions of loading. The latter factor is also likely to be a function to some extent of the area and shape of the rammer base but little information is available on this aspect. However, if it is assumed that the dynamic modulus of deformation is inversely proportional to the square root of the loaded area in the same way that the static modulus of deformation is often found to be $\left(\text{i.e. } k_s = \frac{C}{\sqrt{A}}, \text{ where } C \text{ is a constant}\right)$, the expression for the impact pressure developed can be written:

$$p = \sqrt{\frac{W}{g}\cdot\frac{V^2}{A}\cdot\frac{C}{2\sqrt{A}}}$$

where C = a constant for the particular soil conditions. That is, if the rammer area is changed, the compactive energy provided by each blow per unit area of rammer base

$$\left(\frac{1}{2}\cdot\frac{w}{g}\cdot\frac{V^2}{A}\right)$$

has to be kept proportional to the square root of the area of the rammer base ($\sqrt{A}$) for a constant pressure to be developed.

Factors Investigated in the Tests

The following principal factors were studied in the tests:

(1) The effect of height of drop of the rammer (or impact velocity) on the state of compaction produced in soil for a constant size of rammer base and a constant total energy of compaction.

(2) The effect of the area and the shape of the rammer on the state of compaction produced for a constant height of drop of the rammer, for a constant total energy per unit area of rammer

base and for a total energy per unit area kept proportional to the square root of the area of the rammer base.

(3) The effect of the moisture content of the soil on the state of compaction produced when the size of rammer base, the height of drop of rammer and the total compactive energy were kept constant.

(4) The effect of the energy per unit area of rammer base of each blow and of the moisture content of the soil on the state of compaction produced when the size of rammer and the total compactive energy were kept constant.

(5) A limited study was made of the pressures generated in the soil beneath the rammer on impact.

Apparatus Employed

The equipment used in the tests (Fig. 1) comprised a special rammer working in conjunction with a pile-driving frame suspended from the jib of an excavator. The rammer consisted of a fabricated light-alloy cage, the weight of which could be adjusted from about 1 cwt. to about 4½ cwt. by bolting steel plates inside the cage. The area and shape of the rammer base could also be altered from a minimum size of 1 sq. ft. to a maximum size of 2¼ sq. ft. by bolting on to the base of the rammer special steel plates. The rammer could be lifted to any height up to about 9 ft. above the ground and, using a quick-release mechanism, could be allowed to drop freely on to the surface of the soil.

Soils Used in the Tests

The two soils used in the tests were a sandy clay from the grounds of the Laboratory and a well-graded sand from Hertingfordbury, Hertfordshire. The particle size distributions of the two soils and the results of index tests are given in Fig. 2. (The results of standard laboratory compaction tests (British Standards Institution, 1948; U.S. War Department, Office of Chief Engineers, 1951) are given later in Figs. 5 and 6).

Experimental Procedure

Compaction studies—Before each test the soil was broken up to form a loose tilth about 12 in. thick. Any adjustment of moisture content was effected by spraying water on to the soil followed by mixing with a rotary cultivator or by aerating the soil if a reduction in the moisture content was required.

An area of soil about 15 ft. long and three times the width of the rammer base was then compacted, the rammer being advanced a distance equal to the length of its base after each blow. The average state of compaction in the top 6 in. of compacted soil was determined by measuring the dry density using the sand-replacement method (British Standards Institution, 1948). All the density measurements were made along the centre of the compacted strip in order to avoid edge effects.

Pressure measurements—To provide some indication of the pressures developed in soil beneath the rammer, a few measurements were made using the piezo-electric pressure gauges developed by the Laboratory (Whiffin, 1954). The gauges were buried at depths of 6 and 12 in. below the surface in the sandy clay compacted at approximately the average natural moisture content of the soil (16 per cent) and to approximately the same state of compaction as was obtained in the compaction tests (105 lb./cu. ft.).

Results

Compaction studies—The results obtained in the investigation of the effect of the height of drop of the rammer (or impact velocity) and the effect of the size and shape of the rammer on the states of compaction obtained with the two test soils at their average natural moisture contents after two and five passes over the compacted area are given in Tables 1 and 2. In the study of the effect of the size of the rammer base, tests were made with a constant compactive energy per unit area of the base plate (12·6 and 31·5 ft. lb./sq. in.) and also with the compactive energy kept proportional to the square root of the area of the rammer base (12·6 and 31·5 ft. lb./sq. in. for the base 12 in. square and 18·8 and 47 ft. lb./sq. in. for the base 18 in. square). The latter tests were included because, theoretically, if the dynamic modulus of deformation of soil is inversely proportional to the square root of the loaded area, the energy provided by each blow per unit area of rammer base would

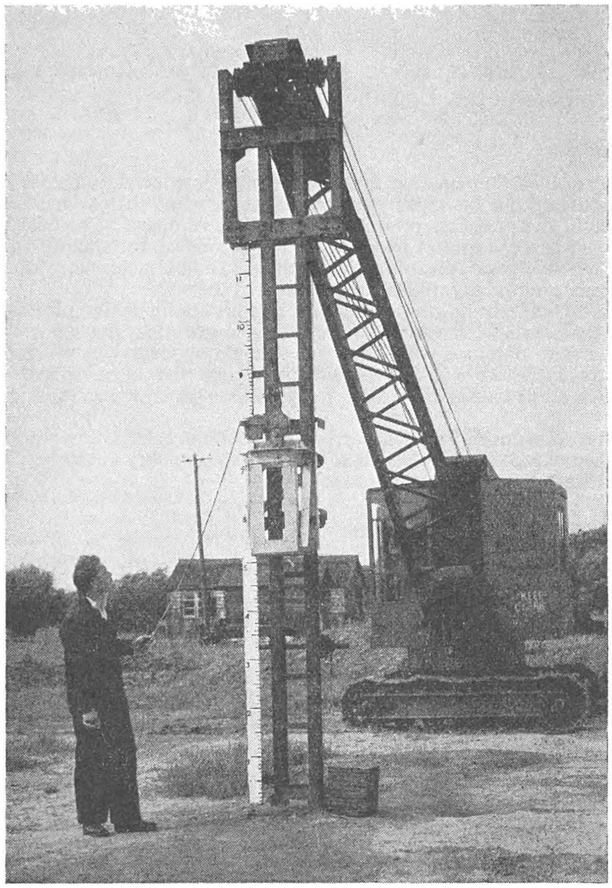

Fig. 1 General view of the equipment used in the investigation. The rammer has been raised to a height of about 5 ft. and the operator is about to trip the quick-release mechanism

Vue générale du matériel employé pour cette étude. La dame à été élevé à une hauteur de 5 pieds à peu près et l'opérateur va actionner le mécanisme de déclenchement rapide

have to be kept proportional to the square root of the area of the rammer base if constant pressures were to be obtained.

The effect of the moisture content of the soils on the state of compaction produced for a constant size of rammer base (12 in. square), a constant height of drop (8 ft.) and a constant total energy of compaction per unit area of rammer base (12·6 and 31·5 ft. lb./sq. in.) is shown in Figs. 3 and 4. (Fig. 7 shows the effect of the compactive energy per blow (4·5, 6·3 and 8·0 ft. lb./sq. in. per blow) at various moisture contents of the two soils for the 12 in. square rammer and for a constant total compactive energy of 31·5 ft. lb./sq. in.)

Pressure measurements—The impact pressures recorded in the sandy clay by the piezo-electric gauges at depths of 6 and 12 in. below the surface under the 12 in. square rammer are

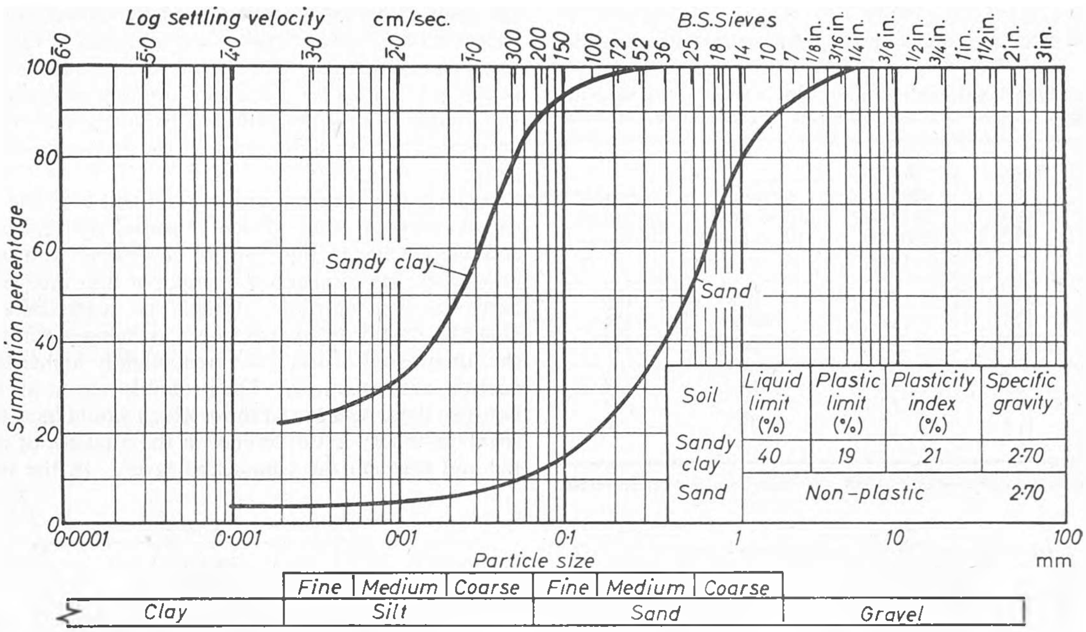

Fig. 2 Particle size distributions and results of classification tests for the soils used in the investigation
Distribution granulométrique et résultats d'essais de classification des sols employés dans cette étude

Table 1

Effect of height of drop of rammer or impact velocity on state of compaction obtained with sandy clay and sand at approximately the average natural moisture contents of the soils

Effet de la hauteur de saut d'une dameuse ou de la vitesse de choc sur le degré de compactage obtenu avec une argile sableuse et un sable à environ la moyenne teneur en eau naturelle des sols

Size of rammer base plate (in.)	*Height of drop of rammer* (ft.)	*Theoretical impact velocity of rammer* (ft./s)	*Total weight of rammer* (lb.)	*Number of passes over compacted area*	*Total compactive energy per unit area of rammer* (ft. lb./sq. in.)	*Sandy clay*		*Sand*	
						Moisture content (%)	*Dry density* (lb./cu. ft.)	*Moisture content* (%)	*Dry density* (lb./cu. ft.)
12 × 12	8	22·7	113	2	12·6	16	101	8	118
	4	16·0	226	2	12·6	17	102	9	120
	2	11·3	452	2	12·6	18	106	8	118
12 × 12	8	22·7	113	5	31·5	16	113	8	124
	4	16·0	226	5	31·5	17	114	8	126
	2	11·3	452	5	31·5	17	116	8	125

Table 2

Effect of size and shape of rammer base plate on the state of compaction obtained with sandy clay and sand at approximately the average natural moisture contents of the soils

Effet de la dimension et la forme de la plaque de base de la dameuse sur le degré de compactage obtenu avec une argile sableuse et un sable à environ la moyenne teneur en eau naturelle des sols

Size of rammer base plate (in.)	*Height of drop of rammer* (ft.)	*Total weight of rammer* (lb.)	*Number of passes over compacted area*	*Total compactive energy per unit area of rammer* (ft. lb./sq. in.)	*Sandy clay*		*Sand*	
					Moisture content (%)	*Dry density* (lb./cu. ft.)	*Moisture content* (%)	*Dry density* (lb./cu. ft.)
12 × 12	8	113	2	12·6	16	101	8	118
18 × 18	8	254	2	12·6	17	101	8	119
12 × 24	8	226	2	12·6	16	102	8	117
18 × 18	8	381	2	18·8	17	104	8	121
12 × 12	8	113	5	31·5	16	113	8	124
18 × 18	8	254	5	31·5	16	113	8	125
12 × 24	8	226	5	31·5	17	113	8	125
18 × 18	8	381	5	47·0	16	115	8	128

Table 3

Measured and calculated impact pressures developed in sandy clay soil beneath a 12 in. square rammer

Pressions (mesurées et calculées) produites par le choc sur un sol d'une argile sableuse au-dessous d'une dameuse de 12 pouces d'équarrissage

Height of drop of rammer (ft.)	*Weight of rammer* (lb.)	*Initial depth of pressure gauge* (in.)	*Recorded pressures* (lb./sq. in.)	*Calculated* pressures* (lb./sq. in.)
2	452	6	91	120
4	226	6	102	134
8	113	6	100	143
2	452	12	67	59
4	226	12	68	65
8	113	12	77	70

* Based on measured impact velocities which were slightly less than the theoretical values

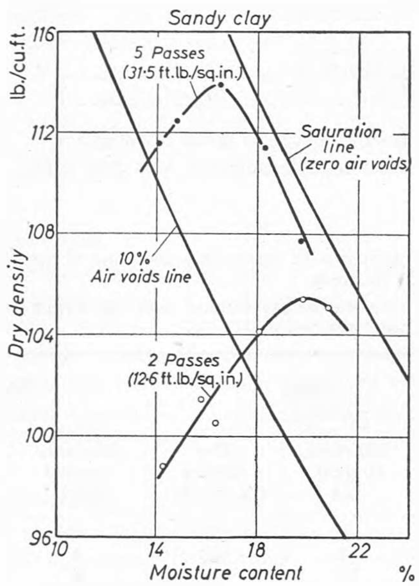

Fig. 3 Relationship between moisture content of a sandy clay and the state of compaction produced by a 12 in. square rammer for a constant height of drop of 8 ft. and constant total energy of compaction per unit area of rammer base of 12·6 and 31·5 ft. lb./sq. in.

Relation entre la teneur en eau d'une argile sableuse et le degré de compactage effectué par une dame de 12 pouces d'équarrissage pour une hauteur de saut constante de 8 pieds et une énergie de compactage totale constante par unité de surface de la base de la dame de 12·6 et 31·5 pieds livres/pouce carré

given in Table 3. Each value is a mean of at least five observations and an empirical allowance of 20 per cent has been made for gauge error in over-recording the actual pressure. Gauge errors are usually considered to arise from the difference between the elastic properties of the gauge and the soil in which it is embedded. Values of the impact pressure at the depths of the gauges, calculated using the theory outlined earlier in this paper, together with the Boussinesq distribution of stress with depth, are also included in this table. Measured impact velocities which were slightly less than the theoretical values and a measured static modulus of deformation of 600 lb./sq. in./in. were used in the calculations.

Discussion

The results obtained in the initial compaction tests (Table 1) confirm the conclusion reached in the theoretical analysis that the state of compaction produced by impact compaction is a function of the kinetic energy per unit area of the rammer for a given size of rammer. The small variations that were obtained in the dry density for a constant amount of compactive energy were either within the limits of experimental error or can be accounted for by differences in the moisture contents of the soils.

A comparison of the results obtained with the 12 and 18 in. square rammer bases (Table 2) shows that constant states of compaction in the top 6 in. of compacted soil were obtained only when the compactive energy per unit area of the rammer base was kept constant. When the compactive energy provided by the 18 in. square base was increased in proportion to the square root of the plate area, slightly higher states of compaction were obtained. The probable reason for the difference between these results and those which would have been expected from the theory is a difference in the gradient of dry density of the soil through the compacted layer. In the tests, only the

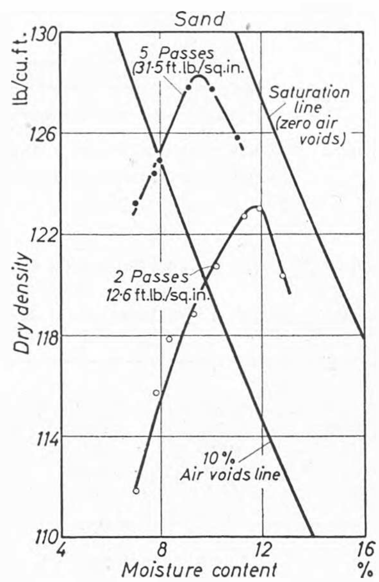

Fig. 4 Relationship between moisture content of a sand and the state of compaction produced by a 12 in. square rammer for a constant height of drop of 8 ft. and constant total energy of compaction per unit area of rammer base of 12·6 and 31·5 ft. lb./sq. in.

Relation entre la teneur en eau d'un sable et le degré de compactage effectué par une dame de 12 pouces d'équarrissage pour une hauteur de saut constante de 8 pieds et une énergie de compactage totale constante par unité de la surface de la base de la dame de 12·6 et 31·5 pieds livres/pouce carré

average state of compaction in the top 6 in. of the 7 to 8 in. thick compacted layer was determined. Using the Boussinesq distribution of stress with depth, the average stress in the top 6 in. under the 18 in. square base would be about 7 per cent higher than that beneath a 12 in. square base. Thus, for a constant impact pressure and hence constant dry density in the surface, a higher average dry density in the top 6 in. would be expected with the 18 in. square rammer as compared with the 12 in. square rammer.

As far as the design of impact compactors for the compaction of 6 to 8 in. thick compacted layers is concerned, it appears that for the range of rammer sizes and shapes likely to be considered in practice, the only design factor likely to affect the average state of compaction of the layer is the compactive energy per unit area of the rammer base. If, however, the rammer size is increased in order to compact layers thicker than about 8 in., then the energy per unit area provided by the rammer should be increased in proportion to the square root of the area of the rammer as indicated by the theory.

The relationships between moisture content and state of compaction for constant total energies of compaction of 12·6 and 31·5 lb./sq. in. (Figs. 3 and 4) are of the usual form and show that the maximum dry density increases and the corresponding optimum moisture content decreases with increase in the compactive energy. For purposes of comparison the dry density/moisture content relationships obtained in the tests are shown together with the results of the B.S. compaction test (British Standards Institution, 1948) and the modified A.A.S.H.O. compaction test (U.S. War Department, Office of Chief Engineers, 1951) in Figs. 5 and 6. The results obtained on the sandy clay in a previous investigation (LEWIS and PARSONS, unpublished) with a prototype single-pass dropping-weight compactor which provided 23 ft. lb./sq. in. of compactive energy are also shown in Fig. 5. The curve for the prototype compactor fits in very well about half-way between the two curves obtained in the present investigation with a 12 in. square rammer for 12·6 and 31·5 ft. lb./sq. in. of compactive energy. Figs. 5 and 6 suggest that, to provide a state of compaction in the field in 6 to 8 in. thick layers similar to that which is obtained in the B.S. compaction test, about 20 ft. lb./sq. in. of compactive energy would have to be provided by the rammer. For a state of compaction equivalent to that obtained in the modified A.A.S.H.O. test, about 80 ft. lb./sq. in. would be necessary.

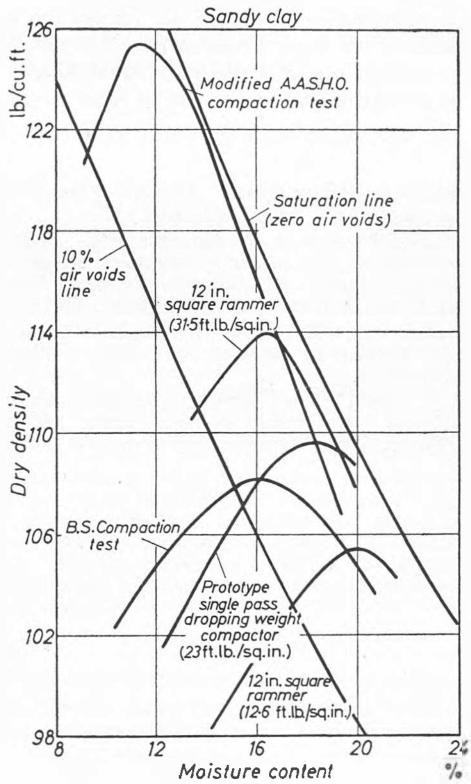

Fig. 5 Relationships between the moisture content of sandy clay and the state of compaction produced in standard laboratory compaction tests and in tests with impact compactors providing various amounts of compactive energy

Relations entre la teneur en eau d'argile sableuse et le degré de compactage effectué dans des essais de laboratoire standard, et dans des essais avec engins de compactage au choc qui fournissaient divers énergies de compactage

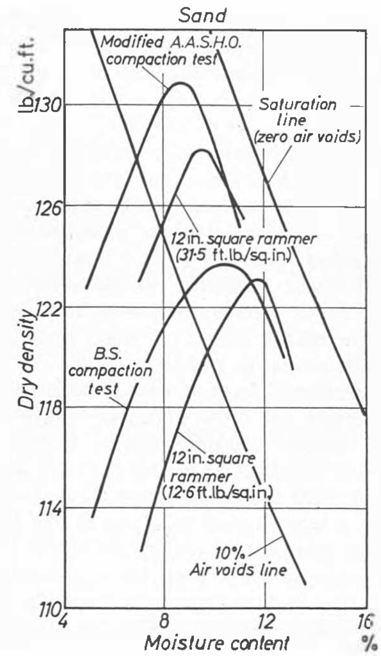

Fig. 6 Relationships between the moisture content of sand and the state of compaction produced in standard laboratory compaction tests and in the tests with the 12 in. square rammer for two different amounts of compactive energy

Relations entre la teneur en eau de sable et le degré de compactage effectué dans des essais de compactage au laboratoire et dans les essais avec la dame de 12 pouces d'équarrissage pour deux différentes énergies de compactage

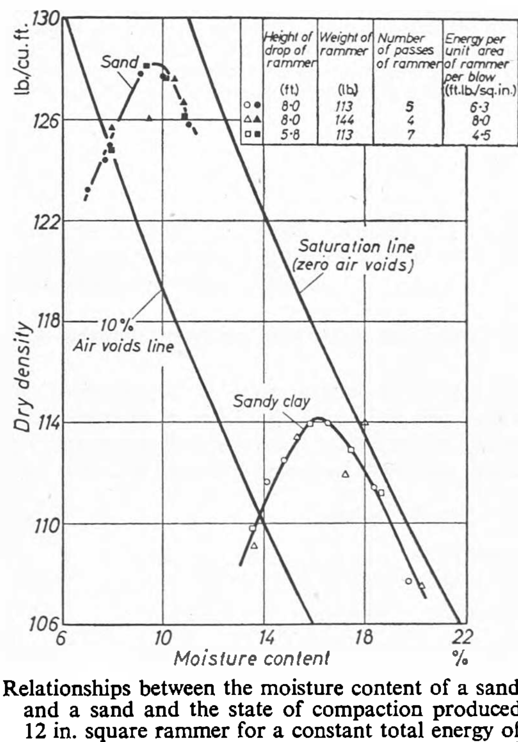

Fig. 7 Relationships between the moisture content of a sandy clay and a sand and the state of compaction produced by a 12 in. square rammer for a constant total energy of compaction per unit area of rammer base of 31·5 ft. lb./sq. in. but with compactive energies per blow of 4·5, 6·3 and 8·0 ft. lb./sq. in.

Relations entre la teneur en eau d'une argile sableuse et d'un sable et le degré de compactage effectué par une dame de 12 pouces d'équarrissage pour une énergie de compactage totale constante par unité de surface de la base de la dame de 31·5 pieds livres/pouce carré mais avec des énergies de compactage par coup de 4·5, 6·3 et 8·0 pieds livres/pouce carré

So far, in the investigation with the 12 in. square rammer, the compactive energy provided per blow was kept constant at 6·3 ft. lb./sq. in. To investigate the effect of the energy per blow, tests were also carried out with energies of 4·5 and 8·0 ft. lb./sq. in. per blow which were considered to be about the limits for a practical design of rammer. The results obtained (Fig. 7) show that within this range the energy per blow had no significant effect on the state of compaction obtained at any moisture content for a constant total compactive energy. It is probable that the higher states of compaction which would have been expected with the higher energies per blow, particularly at the lower moisture contents, were not obtained because of the lower number of passes required to keep the total compactive energy constant which counterbalanced the effects of the higher energy per blow.

It seems clear, therefore, that within the range of maximum compactive energies per blow which are likely to be adopted from practical design considerations, it is only necessary to consider the total compactive energy per unit area of rammer. Nevertheless, in order to avoid overstressing during compaction of soils having a low bearing capacity, it will be necessary to employ a lower compactive energy per blow than would be possible with soils having a high bearing capacity. Thus, in the design of any impact compactor capable of compacting satisfactorily a wide range of soils, provision should be made for altering the energy per blow from a minimum of about 2 ft. lb./sq. in. up to the maximum practicable from a mechanical design viewpoint.

Only a very limited investigation was made of the pressures developed in the sandy clay beneath the 12 in. square rammer. The results obtained for a constant compactive energy (Table 3) show that the height of drop or impact velocity had relatively little effect on the impact pressures developed, thus confirming the conclusion reached in the theoretical analysis. The calculated impact pressures at the depths of the gauges also show reasonable agreement with the measured values.

The magnitude of the peak transient pressures developed in the soil by the rammer were much greater than those developed by an 8 ton smooth-wheeled roller at the same depths in the soil at the same dry density and moisture content measured in an earlier investigation (Whiffin, 1954). (The values were about 20 and 10 lb./sq. in., respectively.) The duration of the pressure pulse was of the order of 0·02 seconds in the case of the rammer and about 2 seconds for the roller. The fact that the same state of compaction was produced by the two machines suggests that the duration of the pressure pulse must have a significant effect on the state of compaction produced.

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