Recent Research into the Compaction of Soil by Vibratory Compaction Equipment

Recherches récentes sur le compactage du sol à l'aide de matériels de compactage par vibration

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Summary

This paper describes the results of investigations made at the British Road Research Laboratory to determine the performance of vibratory soil compaction equipment. The machines studied comprised vibrating rollers ranging in static weight from 4 cwt to 3¾ tons and vibrating plate compactors ranging in static weight from 4 cwt to 2 tons. The investigations were carried out on a heavy clay, a sandy clay, a well-graded sand and a gravel-sand-clay.

The machines all produced satisfactory states of compaction on the granular soils and high states of compaction were also produced on the clay soils with the heavier types of equipment. On the average, about 10 passes were required with the rollers and about 3 passes with the plate compactors to obtain satisfactory compaction. Changes in the frequency of vibration were not critical and were only of significance with the granular soils.

The outputs and the costs of producing a given state of compaction are compared for the various machines.

Sommaire

Cette communication décrit les résultats des recherches faites par le British Road Research Laboratory pour déterminer les qualités de divers matériels de compactage du sol par vibration. Les machines étudiées comprenaient des rouleaux vibrants dont le poids variait de 200 kilos à 2.750 kilos et des compacteurs à plaques vibrantes dont le poids variait de 200 kilos à 2.000 kilos.

Les essais ont été effectués sur une argile grasse, une argile sablonneuse, un sable bien classé et une argile gravier-sable.

Toutes les machines produisirent des conditions de compactage satisfaisantes sur le sol graveleux ; des conditions excellentes de compactage furent également produites sur les sols argileux avec les types d'équipement les plus lourds.

En moyenne, il fallait environ dix passes avec les rouleaux et trois passes avec les compacteurs à plaques pour obtenir un compactage satisfaisant.

Les modifications de la fréquence de vibration n'étaient pas critiques et étaient seulement importantes sur le sol graveleux.

Le rendement et le prix de revient du compactage sont comparés pour les différentes machines et un même résultat.

Introduction

A wide variety of types and sizes of vibrating compaction equipment has recently been developed. Vibratory compactors are usually much lighter than conventional dead-weight rollers and are therefore usually cheaper and more readily transportable to compaction sites. As a result, vibratory compactors are being used to an increasing extent on all types of work ranging from the backfilling of trenches to the compaction of large earthworks.

Extravagent claims are often made about the value of vibratory compactors and, to provide data on the performance of such equipment, the British Road Research Laboratory has carried out investigations of the performance of a range of vibrating rollers and plate compactors in the compaction of soils and granular base materials. These studies have included investigations of the effect of frequency of vibration and the compacting speed on the states of compaction produced.

The results of investigations on the compaction of granular base materials using vibrating equipment has already been reported (Lewis and Parsons, 1960) and the object of the present paper is to review the results obtained on soils.

Details of the Plant Studied

The investigations were carried out with six sizes of vibrating roller and five sizes of vibrating-plate compactor. These machines were representative of the range of vibratory compactors available at present.

Vibrating rollers—In all the vibrating rollers tested, the vibrations were produced by a single rotating shaft having an out-of-balance weight (or weights) mounted within the vibrating roll. Thus a rotating vibration is produced having a radial resultant force. With most of the machines the speed of the vibrator shaft could be varied only by altering the engine speed by changing the governor or throttle setting, and therefore the machines were normally used with a fixed frequency of vibration. One roller (3¾-ton tandem) was fitted with a special variable-speed transmission to the vibrator shaft, enabling any frequency within a wide range to be selected. Relevant details of the vibrating rollers are given in Table 1

Vibrating plate compactors—With the vibrating plate compactors the vibrations were produced by driving two counter-rotating shafts each having one or more out-of balance weights. In this way a directional vibration was produced in which the magnitudes of the horizontal and vertical components of the vibrational force depended on the relative setting of the out-of-balance weights on the two shafts. The horizontal component was used to drive the machine forward and the vertical component produced the compacting effect. With some of the machines the relative positions of the out-of-balance weights could be varied, thus producing forward and reverse speeds. As with the rollers, the plate compactors were normally operated with a fixed frequency of vibration. Details of the plate compactors are given in Table 2.

Table 1
Details of vibrating rollers

Machine	4-cwt.	6¾-cwt.	19½-cwt.	2½-ton.	3¾-ton. (*towed*)	3¾-ton. (*tandem*)
Total weight of roller as tested (tons)	0·21	0·34	0·97	2·4	3·8	3·8
Power unit (h.p.)	1·3 (petrol)	2·7 (petrol)	5·5 (petrol)	10 (petrol)	36 (diesel)	25 (diesel)
Engine speed (rev./min.)	2600	2200	2200	2000	1400-1800	2000
Average speed when compacting (ft./min.)	30 (hand-propelled)	60	67	42	120 (towed)	73
Average speed when travelling (ft./min.)	—	120	140	0-250	—	143
Diameter and width of vibrating roll (in.)	21 × 24	22½ × 28	26 × 32	30 × 32	48 × 72	35 × 39½
Diameter and width of non-vibrating roll (in.)	Single roll	Single roll	26 × 32	30 × 32	Single roll	30 × 27½
Static load on vibrating roll (lb./in.)	20	27	47	68	119	157
Static load on non-vibrating roll (lb./in.)	—	—	21	100	—	89
Frequency of vibration (cycles/min.)	4500	4500	4000	4800	1800-2320	1800-2950

Table 2
Details of vibrating-plate compactors

Machine	4-cwt.	13-cwt.	14-cwt.	1½-ton.	2-ton.
Total weight of compactor as tested (tons)	0·24	0·66	0·70	1·5	2·0
Power unit (h.p.)	4·5 (petrol)	6 (diesel)	6 (petrol)	10 (diesel)	8 (diesel)
Engine speed (rev/min.)	1800	2000	1500	1500	1200
Average speed when compacting (ft./min.)	28	53 (slow speed 26)	42	25	27
Length and width of vibrating plate (in.)	19 × 15	27 × 24½	24 × 24	32½ × 30	50 × 34
Static load on vibrating plate (lb./sq.in.)	1·87	2·24	2·72	3·45	2·64
Frequency of vibration (cycles/min.)	1800	1200	1500	1100	1050

Soils Used in the Investigations

The four soils used were a heavy clay, a sandy clay, a well-graded sand and a gravel-sand-clay. The particle-size distributions and the results of classification tests are given in Fig. 1. The results of the B.S. laboratory compaction test (BRITISH STANDARDS INSTITUTION, 1948) on the soils are included in Figs. 2-5 and the maximum dry densities and optimum moisture contents obtained in the B.S. and the modified A.A.S.H.O. laboratory compaction test (U.S. WAR DEPARTMENT, 1951) are given in Table 3.

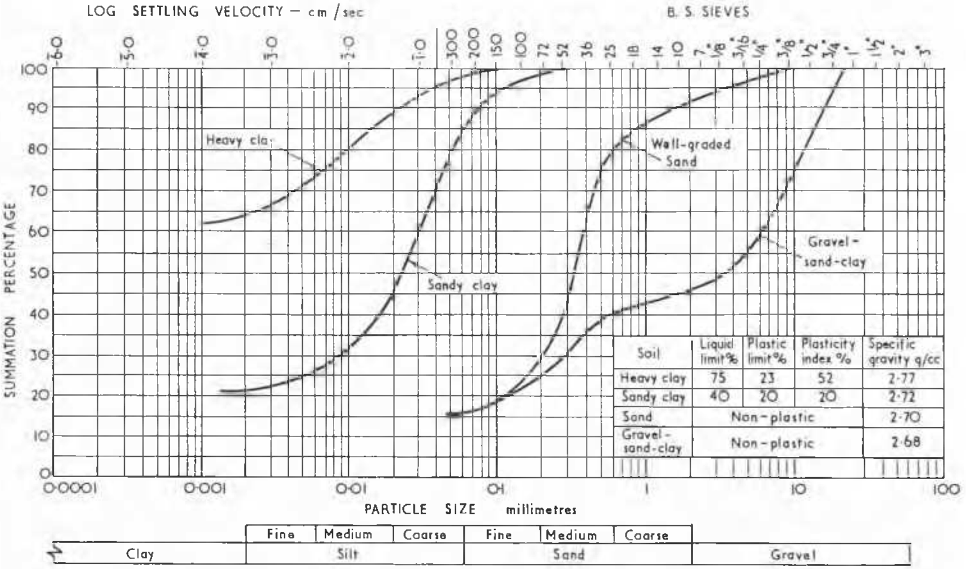
Table 3
Results of laboratory compaction tests on soils used in the full-scale compaction investigations

Soil	*B.S. test*		*Modified A.A.S.H.O. test*	
	Max. dry density (lb./cu.ft.)	*Optimum moisture content* (%)	*Max. dry density* (lb./cu.ft.)	*Optimum moisture content* (%)
Heavy clay	100	23	118	15
Sandy clay	109	16	126	12
Well-graded sand	124	10	131	8
Gravel-sand-clay	129	9	137	6

Test Installation and Experimental Procedures Employed

The test installations and the experimental procedures employed in the full-scale compaction studies of the performance of compaction plant have been described fully elsewhere (LEWIS, 1954 and 1959) and are, therefore, outlined only briefly in this paper.

Before the main investigations with each machine, preliminary tests were made to provide an indication of the thickness of loose layer to be employed. The thickness of



Soil	Liquid limit %	Plastic limit %	Plasticity index %	Specific gravity g/cc
Heavy clay	75	23	52	2·77
Sandy clay	40	20	20	2·72
Sand	Non-plastic			2·70
Gravel-sand-clay	Non-plastic			2·68

Fig. 1 Particle-size distributions and results of plasticity and specific gravity tests for the soils used in the investigations.
Granulométrie et résultats des essais de plasticité et de poids spécifique pour les sols utilisés dans les essais.

loose layer selected was such that in general satisfactory average states of compaction could be obtained throughout the full depth of the layer. The thicknesses of loose layer used in the main investigations ranged from about 9 inches with the lightest machines to about 14 inches with the heaviest compactors.

The test layers of soil of appropriate thickness and moisture content were prepared by mixing the soil with rotary cultivators to give a uniform loose tilth. After compaction, the dry density was determined using the sand-replacement method (British Standards Institution, 1948), 6 to 10 measurements of dry density being made to obtain a mean value.

The relations between the moisture content of the soil and the state of compaction were obtained after compaction to refusal. That is, a sufficient number of passes was given to ensure that no significant increase in the state of compaction could be obtained. The relations between the number of passes of the machine and the dry density and the variation in the dry density with depth were usually determined with the soil at the optimum moisture content for compaction to refusal by the machine.

Results of the Investigations

Relations between dry density and moisture content—The relations between dry density and moisture content obtained with the four soils with the various vibratory compactors are shown in Figs. 2-5.

Although the vibrating mechanisms of the various compactors undoubtedly produced widely different dynamic forces, the results suggest that the static weight of the vibrating equipment in relation to the width of the roll or the area of the base plate gives a reasonable guide to the likely performance of the equipment. Generally the maximum dry density increased with increase in the static load per inch width of the vibrating rollers or with increase in the static pressure of the plate compactors, with a corresponding decrease in the optimum moisture content. There were, however, some departures from this general rule. Thus unexpectedly high dry densities were obtained with the 13-cwt vibrating plate compactor despite the relatively low static pressure of this machine (Table 2). The operation of this machine was, therefore, closely examined by taking high-speed ciné films at about 2 000 frames/second. From the film the movements of the various parts of the machine could be measured (Fig. 6). These records indicated that the base plate vibrated at a frequency of about 1 200 cycles/min. with an amplitude of about 1 inch and, superimposed on this, the main body of the machine was bouncing at a frequency of about 240 cycles/min. The machine operated more like a tamper than a vibrator and this probably explains the particularly satisfactory performance of the machine especially on the cohesive soils. It can be concluded that the performance of plate vibrators could possibly be greatly improved by redesigning the suspension systems to enable the plate to tamp with an amplitude of 1 to 2 inches.

As would be expected, all the vibratory compactors produced satisfactory states of compaction with both granular soils. However, a surprising result was the excellent compaction produced by the heavier vibrating rollers and the 13-cwt. plate compactor on the two cohesive soils. It is clear, therefore, that there must be a revision of the widespread belief that vibratory compactors are suitable only for the compaction of granular soils. However, for the successful compaction of cohesive soils high compacting stresses are undoubtedly necessary to compensate for the very short duration of stress.

Comparison of the results of the standard compaction tests (Figs. 2-5 and Table 3) with those obtained with the compactors indicates that the laboratory tests provide only a very approximate guide to the performance of vibratory equipment particularly in the compaction of the granular

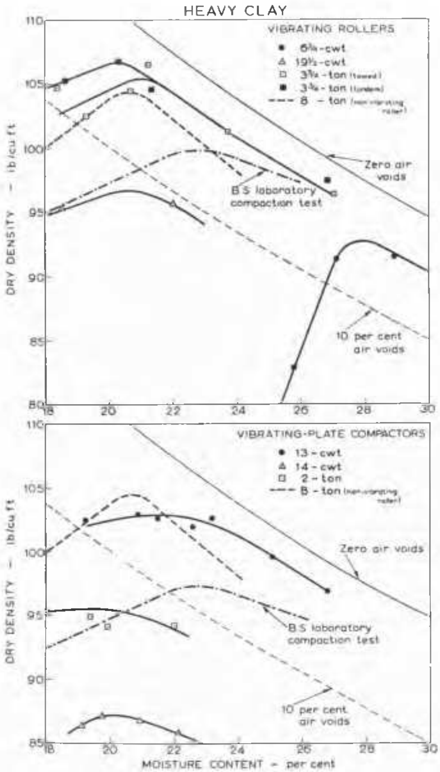


Fig. 2 Relations between dry density and moisture content obtained on the heavy clay.

Relations entre la densité sèche et la teneur en eau avec l'argile compacte.

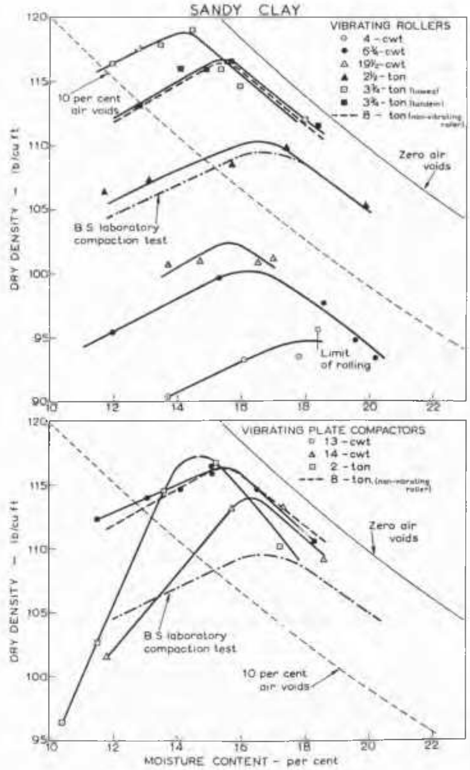


Fig. 3 Relations between dry density and moisture content obtained on the sandy clay.

Relations entre la densité sèche et la teneur en eau avec l'argile sableuse.

soils. On these soils the lightest vibratory equipment tested produced results comparable with or slightly superior to those obtained in the B.S. compaction test whilst the heavier equipment produced significantly higher states of compaction than those obtained in the modified A.A.S.H.O. test. With the cohesive soils, however, the results of the B.S. test were more in agreement with those produced by the heavier compactors.

Claims are often made that vibratory compactors are equivalent in their compacting effect to dead-weight rollers many times the static weight of vibratory plant. The results obtained in an earlier investigation (Lewis, 1954) with a non-vibrating 8-ton smooth-wheeled roller have, therefore, been included for comparison in Figs. 2-5. It is difficult to make accurate comparisons as the widths and diameters of the rollers and the speed of compaction varied considerably. In addition the relative performances of the machines changed from soil to soil. However, very broadly, the 8-ton roller with an average loading of about 310 lb./in. width of the rear rolls had a compaction performance similar to those of the 2½-ton vibrating roller and the more efficient plate compactors. On this basis, therefore, a vibrating roller is roughly equivalent in its compacting effect, although not necessarily in output, to a static roller having about four times the loading.

Relations between dry density and the number of passes—From the relations between the dry density and the numbers of passes of the various machines, Fig. 7 has been prepared to show the average percentage of the dry density corresponding to compaction to refusal at approximately the optimum moisture contents which was obtained after various numbers of passes of each machine. In this way the results can be considered on a reasonably common basis.

In general the vibrating rollers required a rather greater number of passes to achieve a given percentage of their maximum dry density than was necessary with the plate compactors. Thus to achieve 97 per cent of the maximum dry density (the probable economic limit of compaction) about ten passes were required on the average with the rollers as compared with about three passes with the plate compactors. This difference in performance for the two types of equipment is probably due to the generally lower speed of compaction and larger area of contact of the plates compared with the rollers. The effect of speed is illustrated by the results with the 13-cwt. plate compactor. When used at the fast speed (about 53 ft./min.) many more passes were required, particularly in the early stages of compaction, to achieve a given state of compaction than were necessary when compacting at the slow speed (about 26 ft./min.).

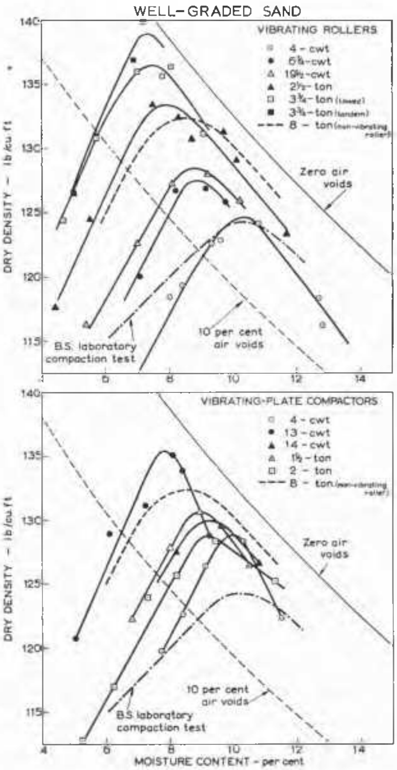


Fig. 4 Relations between dry density and moisture content obtained on the well-graded sand.
Relations entre la densité sèche et la teneur en eau avec le sable à granulométrie continue.

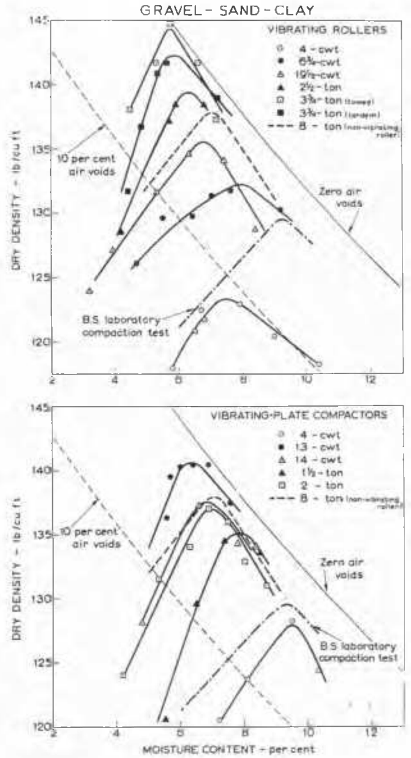


Fig. 5 Relations between dry density and moisture content obtained on the gravel-sand-clay.
Relations entre la densité sèche et la teneur en eau avec le sable argileux.

The tandem vibrating rollers generally required fewer passes than the single-roll machines, the non-vibrating roll of the former machines clearly contributing to some extent to the compaction effect.

Variation in the state of compaction with depth—To simplify the analysis of the results of the investigations of the variation in compaction with depth, the results have been compared on the basis of air voids and have been averaged for the two granular soils (Fig. 8). Only the heavier vibratory compactors were capable of producing satisfactory states of compaction with the cohesive soils and therefore the results for these soils have not been included.

Fig. 8 shows that with all the machines there was a marked decrease in the state of compaction with depth. Generally the depth of soil compacted to any given state of compaction increased with the weight of the compactor, and the compaction effect extended to a significantly greater depth with the plate compactors than with the rollers. This latter effect is no doubt due to the generally larger area of the plate compactors in contact with the soil and hence the deeper penetration of compaction stresses.

In using the results shown in Fig. 7 to estimate the thickness of layer that can be compacted to a satisfactory state by any machine, consideration must be given to the effect of the thickness of layer on the variation of dry density with depth. The results in Fig. 8 were obtained using loose layers generally about 20 inches thick. Somewhat smaller gradients of dry density would have resulted from the use of thinner loose layers and therefore Fig. 8 is only a guide. An estimate of the maximum thickness of loose soil which each machine is capable of compacting satisfactorily is given in Table 4.

Effect of frequency of vibration—The investigations of the effect of frequency of vibration on the state of compaction were carried out using the $3\frac{3}{4}$-ton towed and the $3\frac{3}{4}$-ton tandem vibrating rollers because with these machines the frequency of vibration could be varied without affecting the compacting speed.

The results (Fig. 9) indicate that the effect of changes in the frequency of vibration were significant only with the granular soils. With the cohesive soils, varying the frequency over the full range possible with the machine affected the dry density by only about 1-2 lb./cu.ft. In general there was no very pronounced peak to the curves, suggesting that close control of frequency is not particularly important. Although the two

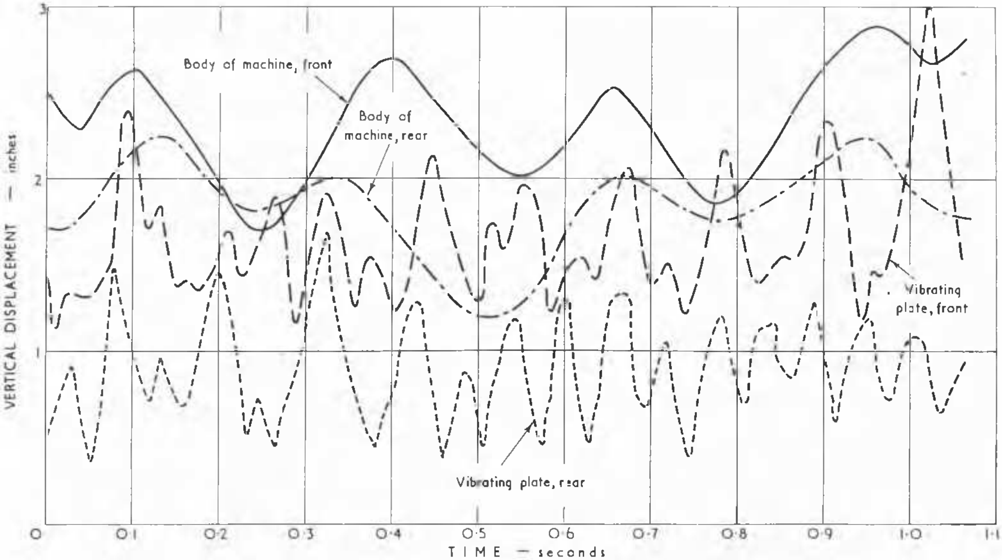


Fig. 6 Vertical displacements of various points of the 13-cwt. vibrating plate when compacting.
Déplacements verticaux de divers points de la plaque vibrante de 13 cwt. pendant le compactage.

Table 4
Outputs of vibratory compactors under favourable conditions

Machine	*Approximate operating costs* (shillings)	*Compacting speed* (ft./min.)	*Number of passes required*	*Area compacted per hour* (sq.yd/h)	*Depth of compacted layer* (in.)	*Output* (cu.yd/h)	*Cost* (pence/cu.yd)
4-cwt. vibrating roller	6·5	30	8	42	3	3·5	22
6 ¾-cwt. vibrating roller	8·5	60	12	65	6	11	9·4
19 ½-cwt. vibrating roller	11·0	67	4	250	6	41	3·2
2 ½-ton vibrating roller	14·0	42	4	160	6	26	6·5
3 ¾-ton towed vibrating roller	36·0	120	6	670	10	180	2·3
3 ¾-ton tandem vibrating roller	18·0	73	4	300	7	57	3·8
4-cwt. plate vibrator	10·5	28	3	65	6	11	12
13-cwt. plate vibrator	12·5	53	4	150	8	33	4·6
14-cwt. plate vibrator	12·5	42	2	230	6	39	3·8
1 ½-ton plate vibrator	17·0	25	2	170	12	58	3·5
2-ton plate vibrator	17·0	27	2	210	12	71	2·9

rollers differed considerably in their design, with both machines the frequency range in which the best results were obtained was about 2 200-2 400 cycles/min. for all four soils.

Effect of speed of compaction—Reference has already been made to the effect of speed of compaction on the results obtained with the 13 cwt. plate compactor. Tests were also carried out with the 3¾-ton towed and tandem vibrating rollers. With both machines the compaction obtained after a given number of passes decreased with increase in the speed of compaction. The output of soil compacted to a satisfactory state (10 per cent air voids) by the 3¾-ton tandem roller was approximately the same for both the slow and fast speeds. However, with the 3¾-ton towed roller, a maximum ouput was obtained at a speed of about 1½ mile/h.

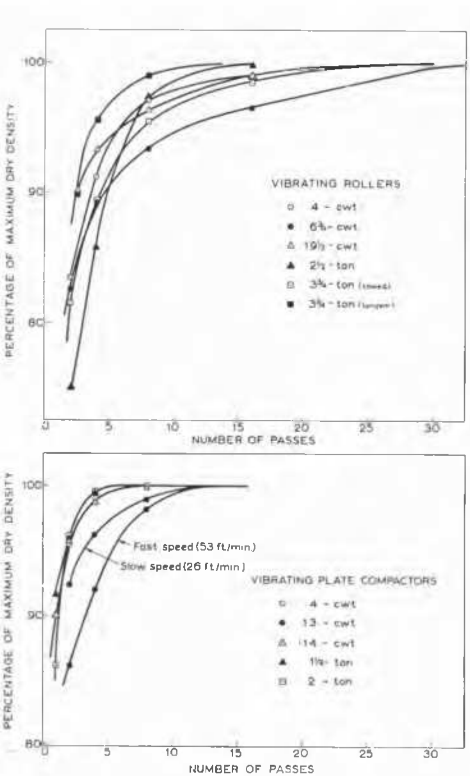


Fig. 7 Average relations between the percentage of the maximum dry density and the number of passes obtained on the test soils.

Densité sèche en fonction du nombre de passagers des engins.

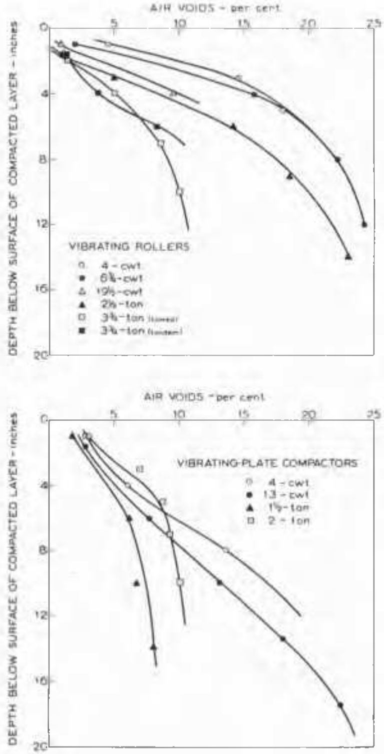


Fig. 8 Average relations between the state of compaction (air voids) and depth below the surface of the compacted layer obtained on the granular soils.

Compactage en fonction de la profondeur sur les sols graveleux.

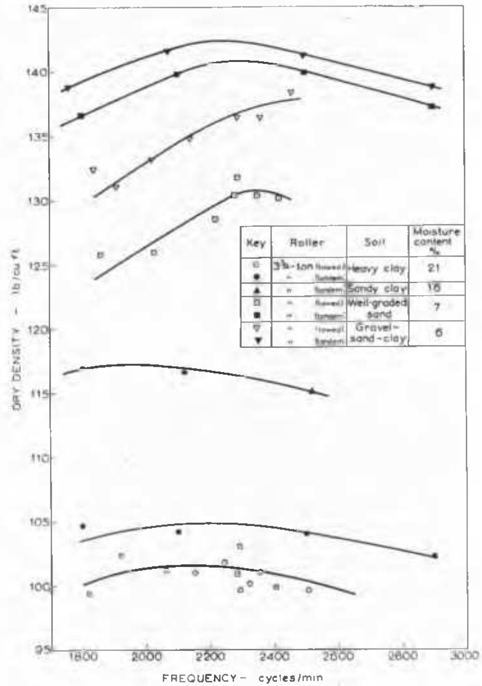


Fig. 9 Effect of frequency of vibration on the state of compaction obtained after 8 passes of the 3¾-ton towed and 16 passes of the 3¾-ton tandem vibrating rollers.

Effet de la fréquence sur l'effet obtenu après 8 passes du rouleau de 3¾ tonnes et 16 passes du rouleau vibrant tandem de 3¾ tonnes.

Outputs of the Various Compactors

The results have been used to estimate the likely outputs under favourable conditions and the costs of compaction for the various machines when compacting soil to a state equivalent to 10 per cent air voids (Table 4). It has been assumed that the machines are operated for 50 minutes in each hour and no other allowance has been made for time lost due to bad weather or for manœuvring the equipment.

Table 4 indicates that there is unlikely to be a significant difference in the costs per cubic yard of compacting soil by the two types of equipment for comparable sizes of plant. The maximum economy will be achieved by using the largest sizes of equipment available.

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