Full-Scale Compaction Studies at the British Road Research Laboratory

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Since 1945 the Road Research Laboratory has been carrying out a program of research on soil compaction, in which studies have been made, under controlled conditions, of most types of compaction plant available to the engineer in the British Isles. The object of this work has been to provide data to enable the engineer to select the most suitable type of plant for soil compaction work. As all the tests have been made on the same range of soils using the same test techniques, it has been possible to make a direct comparison between the performances of the various types of plant. The results of many of these tests have already been published (1, 2).

Apart from full-scale tests on existing plant, studies, more fundamental in their nature, have also been made of a number of aspects of soil compaction. This work has included a detailed investigation of impact compaction by rammers (3) and of the effect of wheel load and tire-inflation pressure on the performance of pneumatic-tired rollers (4).

The object of this paper is to give a brief outline of the test installation and techniques employed at the Road Research Laboratory in carrying out the full-scale compaction tests and to give a summary of the main results obtained in the investigations.

TEST INSTALLATION AND SOILS USED

THE EARLIER investigations of the performance of soil compaction plant were carried out on a circular test track containing five test soils in bays 2 ft deep, 11 ft 6 in. wide and about 45 ft long (1) (Fig. 1). Plant that was not self-propelled was towed by an electric lorry operated by remote control and running on the concrete walls of the soil bays. In this way it was possible to study the performance of the roller under test without introducing any compacting effect of the towing machine.

Although this circular test track was very satisfactory for relatively small types of plant, it was not suitable for testing the large types of compaction equipment, such as the 20- to 50-ton pneumatic-tired rollers, now being used in earthwork construction. These heavier rollers require a greater draw-bar pull than could be provided by the electrically operated towing lorry of the circular test track and, in addition, there was insufficient headroom below the roof for the large rollers. It was also considered that the 2-ft depth of test soil was insufficient for these large rollers in particular.

In view of these and other limitations of the circular track, such as the difficulties introduced in operating machines on a circular path, a special building was constructed in 1954 for carrying out full-scale compaction tests on the largest types of compaction machines (Figs. 2 and 3). This building is approximately 100 ft long and 90 ft wide and provides 16 ft of headroom beneath the roof trusses. The building contains five soil bays, each 35 ft long, 15 ft wide and 3 ft deep. The floor of the bays was left as the natural foundation soil (sandy clay) as this was likely to have elastic properties similar to those of the compacted test soils; the conditions would therefore approximate more closely to those found in the field than if a concrete floor to the bays had been employed.

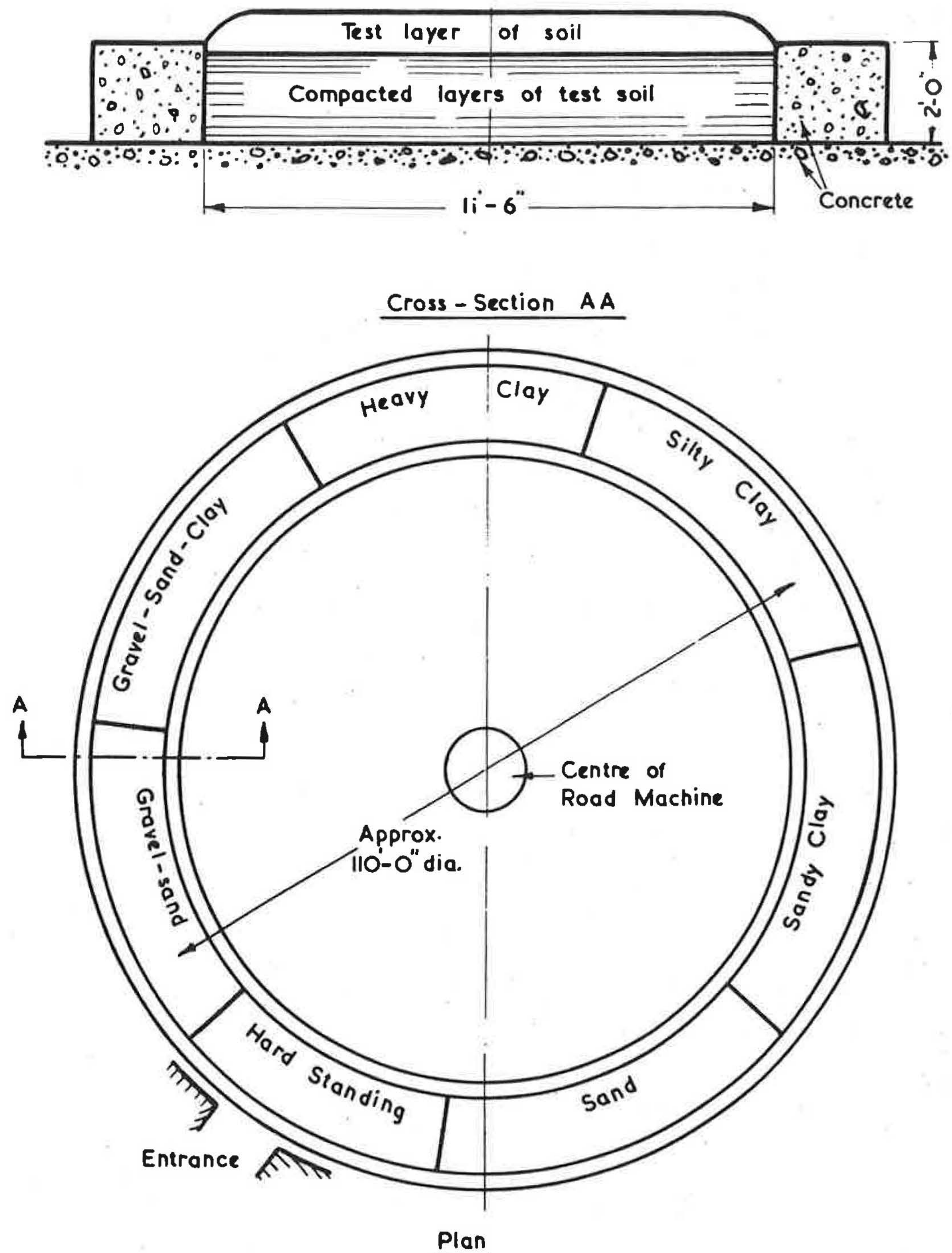


Figure 1. Plan and cross-section of earlier circular track used for full-scale compaction tests.

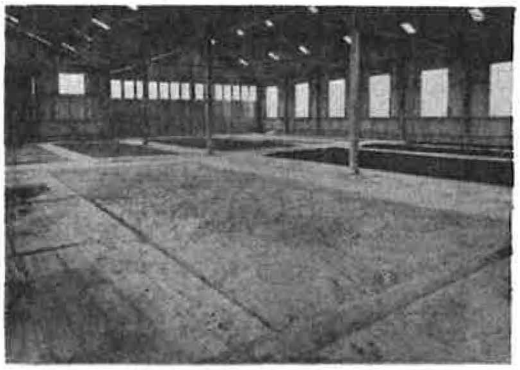


Figure 2. Special building at the Road Research Laboratory for carrying out full-scale tests with the compaction plant.

The five soils used in the bays are a heavy clay, a sandy clay, a well-graded sand, a uniformly graded fine sand, and a gravel-sand-clay. These soils are representative of a wide range of the soils found in Great Britain. The four main soils (heavy clay, sandy clay, well-graded sand and gravel-sand-clay) are almost identical to the corresponding soils of the earlier circular test track but the uniformly graded fine sand is an entirely new soil that was introduced to provide some experience with a difficult material; so far only a few machines have been tested on it. The new building also has two bays containing granular road-base materials (wet-mix graded limestone and wet-mix graded slag) to obtain the performance of plant in the compaction of these types of materials.

Details of the particle-size distributions and plasticity properties of the test soils used in the investigations are given in Figure 4.

FACTORS STUDIED

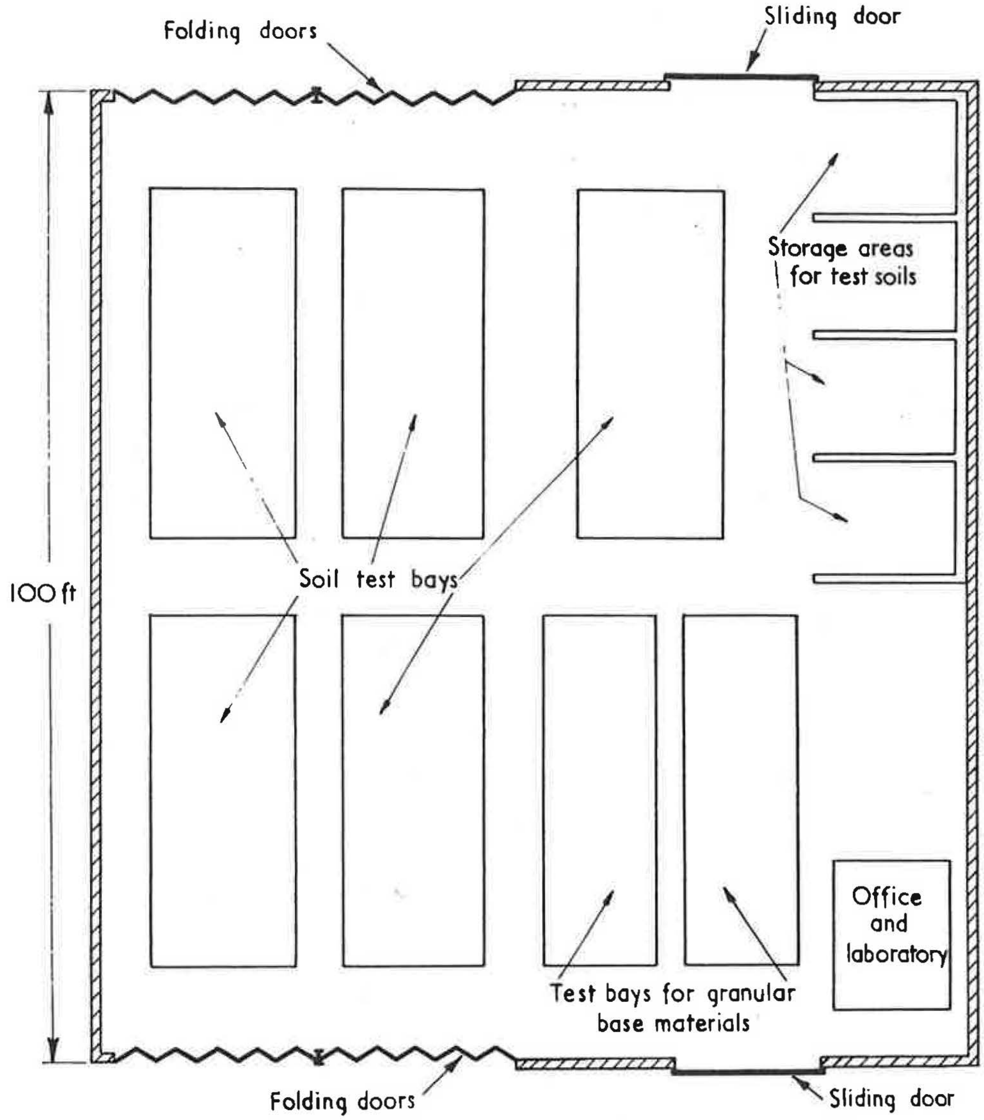
The three main relations determined in the investigations were:

1. Relation between the moisture content of the soil and the state of compaction (dry density) produced.
2. Relation between the number of passes of the plant and the state of compaction produced.
3. Variation in the state of compaction with depth below the surface of the compacted layer.

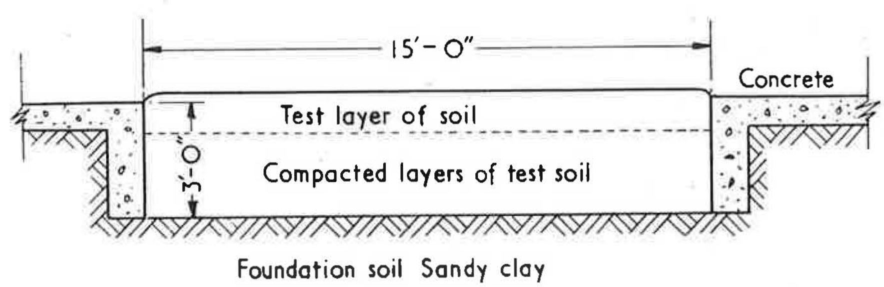
The relation between the moisture content of the soil and the state of compaction obtained is a function of the energy provided per unit volume of soil and is therefore dependent on the thickness of layer and the number of passes of the compacting machine employed. In determining this relation, the thickness of layer used was the maximum that still enabled satisfactory states of compaction to be obtained in the lower portions of the layer. A sufficient number of passes of the plant is provided such that the soil is compacted to a condition where no significant increase in the state of compaction can be produced by further passes of the compaction plant. Thus the relations between the moisture content of the soil and the state of compaction obtained in the investigations correspond to the best performance likely with the machine.

In the determining relations between the number of passes of the plant and the state of compaction produced, the same thickness of layer is employed as in the study of the effect of moisture content. Although the moisture content of the soil has an effect on the relation between the number of passes and the state of compaction, it is impracticable to determine this relation for a range of moisture contents for each soil owing to the amount of work involved. In general, therefore, this study is only carried out at one moisture content—usually the optimum moisture content obtained in the previous investigation with the particular machine under test.

The investigations of the variations in the state of compaction with depth below the surface of the layer are carried out with somewhat thicker layers than those employed in determining the previous two relations. This is done to give a clearer picture of the variations in the state of compaction with depth and an indication of the maximum thickness of layer that can be employed in practice. The relation is determined for the condition of the soils compacted to refusal at approximately the optimum moisture contents for compaction by the plant.

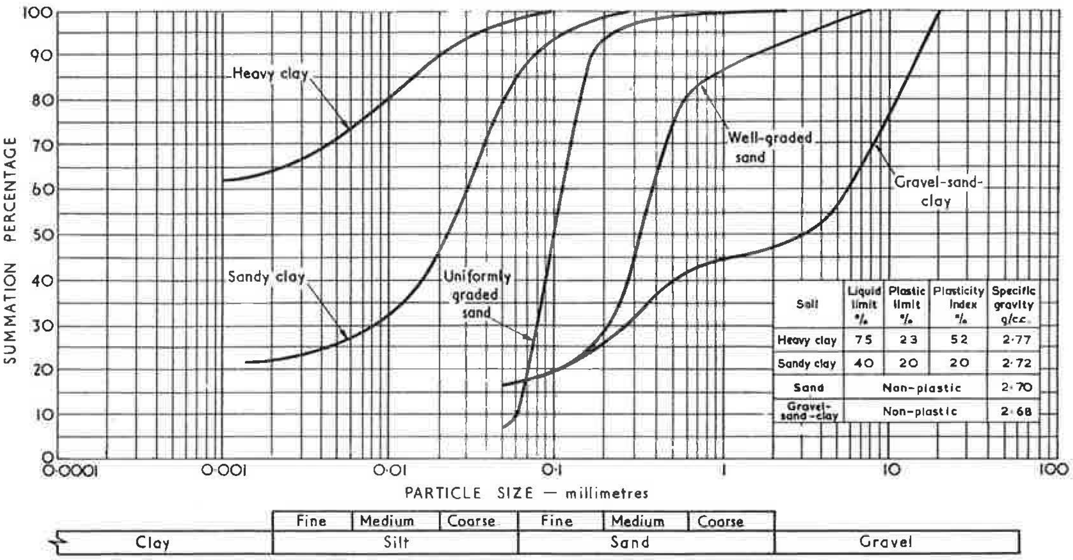


PLAN OF BUILDING SHOWING LAYOUT OF TEST BAYS



CROSS SECTION THROUGH A SOIL BAY

Figure 3. Plan of special building constructed at the laboratory for carrying out full-scale compaction tests and cross-section through a soil bay.



Soil	Liquid limit %	Plastic limit %	Plasticity index %	Specific gravity g/c.c.
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

Figure 4. Particle size distributions and results of plasticity and specific gravity tests for the soils used in the investigations.

TEST PROCEDURE

Preliminary Work

Before the main investigations are carried out, a few preliminary tests are made to provide an indication of the thickness of loose layer to be employed in the studies of the relations between the dry density and the moisture content and between the dry density and the number of passes. In most of the tests, loose layers at 9 in. or 12 in. have been employed.

Dry Density and Moisture Content

To determine the effect of moisture content on the dry density of soil when fully compacted by the plant, loose layers of the test soils of appropriate thickness for the particular machine are brought to a suitable low moisture content by aeration using a rotary cultivator. A small amount of water is then added to the soil followed by further mixing by the rotary cultivator to give a uniform loose tilth which represents a state of minimum compaction. This layer is then compacted by a sufficient number of passes of the plant to insure that little further compaction can be obtained (generally 32 passes with rollers and 16 passes with vibrating plate compactors). The dry density of the top 6 in. of compacted soil is then determined by the sand-replacement method (5), ten measurements of dry density being made to obtain an accurate mean value.

The compacted soil is then broken up and its moisture content increased by 1 to 2 percent by spraying. After further mixing, the procedure outlined above is repeated. In this way the relation between the dry density and the moisture content is built up for the test soils for the plant under test. As in the standard laboratory compaction test (5, 6,), it is essential to start with the test soil at a low moisture content and to increase the moisture content in stages as otherwise considerable scatter could be introduced in the results owing to the small but significant difference in the moisture properties of the soil in the wetting and drying conditions. After making the dry density measurements with the sand-replacement apparatus, the sand used in the density holes is removed by a powerful vacuum cleaner. This not only saves considerable time but results in virtually the complete removal of the sand which otherwise would tend to produce over a period of time some contamination of the test soils.

Dry Density and Number of Passes of the Plant

A loose layer of the test soil of appropriate thickness for the plant under test is prepared at the desired moisture content (generally the optimum moisture content obtained in the previous test). The layer is then compacted by one or two passes of the plant and the state of compaction is determined as outlined previously. After breaking the soil up, a fresh loose layer is prepared, the moisture content is kept constant by the addition of a small amount of water if required. The procedure is repeated with a progressively increasing number of passes of the plant and in this way the complete relations are obtained.

Dry Density and Depth in the Compacted Soil

Loose layers of the test soils about 20 in. thick are prepared at approximately the optimum moisture content for compaction by the machine under test and are then compacted to refusal. The state of compaction of each 2 to 3 in. in depth in the compacted layer is then determined, ten measurements of dry density being made at each level. After the dry density measurements at each depth are completed, 2 to 3 in. of soil is carefully removed to expose a fresh surface.

RESULTS OF FULL-SCALE COMPACTION TESTS

The results of the full-scale tests on the plant listed in Table 1 represent a considerable amount of data and it is impracticable to give more than a brief summary of the results.

TABLE 1

DETAILS OF THE COMPACTION PLANT

Pneumatic-tired rollers	12-ton	20-ton	45-ton
Total laden weight (lb)	26,880	44,800	100,800
Total rolling width (in.)	82	84	93
Number of wheels	9 (4 front, 5 rear)	9 (4 front, 5 rear)	4
Average weight per wheel (lb)	2,990	4,980	25,200
Tire-inflation pressure (lb/sq in.)	36	80	140

Smooth-wheeled rollers	2¾-ton	8-ton
Total laden weight (lb)	6,160	19,010
Total rolling width (in.)	51	70
Diameter and width, front rolls (in.)	34 x 34	42 x 42
Diameter and width, rear rolls (in.)	36 x 16	54 x 18
Weight/in. width, front rolls (lb/in.)	80	186
Weight/in. width, rear rolls (lb/in.)	142	311

Sheepsfoot rollers	Club-foot	Taper-foot
Total laden weight (lb)	11,010	10,080
Size of feet (in.)	4 x 3	2.2 x 2.2
Foot pressure (lb/sq in.)	115	249
Length of feet (in.)	7.0	7.7

Rammers	Frog	Power
Total weight (lb)	1,350	250
Diameter of base (in.)	29	9.5
Approximate height of jump (in.)	12	12

Vibrating smooth-wheeled rollers	4-cwt	6¾-cwt	2½-ton	3¾-ton
Total weight (lb)	480	760	5,400	8,620
Diameter and width of vibrating roll (in.)	21 x 24	22½ x 28	30 x 32	48 x 72
Static weight/in. width (lb/in.)	20	27	68	119
Approximate frequency of vibration (cycles/sec)	4,500	4,500	5,000	2,300

Vibrating plate compactors	4-cwt	13-cwt	14-cwt	1½-ton	2-ton
Total weight (lb)	53	1,480	1,570	3,350	4,480
Approximate area of plate (sq in.)	280	660	570	970	1,700
Width of plate (in.)	15	24	24	30	34
Approximate frequency of vibration (cycles/sec)	1,800	1,200	1,500	1,100	1,050

Track-laying tractors	40-hp	80-hp
Total weight (lb)	12,840	24,160
Width of track (in.)	15	20
Distance between tracks, center to center (in.)	52	72
Average pressure of tracks (lb/sq in.)	7.3	7.2

TABLE 2

MAXIMUM DRY DENSITIES AND OPTIMUM MOISTURE CONTENTS IN LABORATORY AND FULL-SCALE TESTS

Soil Type	Heavy Clay		Sandy Clay		Well-Graded Sand		Gravel-Sand-Clay	
Casagrande Classification	CH		CL		SW		GW	
Avg. Moisture Range for Soils, %	22 - 27		16 - 21		7 - 11		5 - 9	
	Maximum Dry Density (lb/cu ft)	Optimum Moisture Content (%)	Maximum Dry Density (lb/cu ft)	Optimum Moisture Content (%)	Maximum Dry Density (lb/cu ft)	Optimum Moisture Content (%)	Maximum Dry Density (lb/cu ft)	Optimum Moisture Content (%)
British Std. compaction test	99	24	109	16	121	11	129	9
Mod. AASHO compaction test	116	16	126	12	130	9	138	7
Dietrert compaction test	102	23	111	15	109	11	-	-
12-ton pneumatic-tired roller	101	23	111	18	127	10	132	8
20-ton pneumatic-tired roller	106	21	117	15	128	9	139	6
45-ton pneumatic-tired roller	111	19	120	14	131	9	139	6
$2\frac{3}{4}$-ton smooth-wheeled roller	96	21	112	17	131	9	137	7
8-ton smooth-wheeled roller	104	20	116	15	132	9	138	7
5-ton club-foot sheepsfoot roller	107	16	118	12	-	-	130	6
$4\frac{1}{2}$-ton taper-foot sheepsfoot roller	107	15	118	13	-	-	128	5
2-cwt power rammer	110	18	119	11	129	8	137	6
12-cwt frog rammer	106	17	113	14	128	10	136	7
4-cwt vibrating roller	-	-	-	-	124	11	123	8
$6\frac{3}{4}$-cwt vibrating roller	92	28	100	16	127	9	132	8
$2\frac{1}{2}$-ton vibrating roller	96	21	-	-	133	7	139	6
$3\frac{3}{4}$-ton vibrating roller	106	21	119	14	137	7	145	6
4-cwt vibrating plate compactor	-	-	-	-	128	10	127	9
13-cwt vibrating plate compactor	103	21	116	15	135	8	141	6
14-cwt vibrating plate compactor	87	20	114	16	130	9	137	7
$1\frac{1}{2}$-ton vibrating plate compactor	-	-	-	-	129	9	135	8
2-ton vibrating plate compactor	98	17	-	-	128	9	137	7
40-hp track-laying tractor	96	22	-	-	128	10	128	8
80-hp track-laying tractor	99	24	-	-	-	-	126	8

Table 2 gives a comparison of the maximum dry densities and corresponding optimum moisture contents for the four main test soils obtained with the various types of compaction equipment. The results of standard laboratory compaction test (5, 7, 8) have also been included together with an estimate of the average 'equilibrium' or natural moisture content range for the soils in the field for Great Britain.

Although in a few cases there was reasonable agreement between the results obtained with a laboratory compaction test and those obtained with the plant, in general the laboratory compaction tests gave only a poor indication of the maximum dry densities and corresponding optimum moisture contents likely to be obtained with the plant. In any case, the view held at the Road Research Laboratory is that the soil should be compacted in the field close to its equilibrium or natural moisture content rather than at an optimum moisture content obtained in some arbitrary laboratory compaction test. For mass earthworks it is considered that the state of compaction to be achieved in the field with well-graded granular and cohesive soils should be not less than that corresponding to an air void content of 10 percent; that is, to a dry density of at least 90 percent of the saturation dry density.

Table 3 was prepared using the results obtained from the investigations of the relations between the number of passes of the plant and the state of compaction and from the measurements of the variations in the state of compaction with depth. Table 3 shows the possible outputs of the various items of plant tested in compacting soil to a state of compaction corresponding to 10 percent of air voids at the average natural moisture contents. The results obtained on the test soils have been averaged. It must be remembered, however, as indicated in Table 2, that not all the machines operated satisfactorily on all the soils. It has been assumed in the calculations of output that the machines are in operation for 50 min in each hour; no allowance has been made for the time spent in turning machines around, nor for delays due to bad weather. The figures for the cost of operation of the plant are based on average 1958 hire rates for the machines and include an estimate of the operators' wages and the cost of fuel. No allowance

has been made for the cost of transporting plant to and from the site. The operating costs for the pneumatic-tired rollers include the cost of a track-laying tractor of appropriate size for the roller. Because of the limited use of sheepsfoot rollers in Britain, they have been omitted from Table 3.

Table 3 shows that for mass earthworks the most economical items of plant are likely to be heavy smooth-wheeled rollers or pneumatic-tired rollers. Although the output of pneumatic-tired rollers increases with size and loading, the cost of operation also increases because the higher cost of the roller and the necessity of having to employ a more powerful tractor for towing the roller. The resulting cost per cubic yard of compacted soil is not very different for the various sizes of pneumatic-tired roller, with only a slight tendency for the heavier rollers to be more economic. It seems apparent, therefore, that the use of very large sizes of pneumatic-tired roller is unlikely to result in spectacular savings in the cost of compaction of soil in the British Isles as compared with those obtainable with the lighter rollers. Thus the selection of the size and weight of pneumatic-tired rollers is likely to be based more on site conditions, the availability of plant and the compaction requirements, than on the question of the economics of operating the rollers.

The relative outputs and costs of compacting soil (Table 3) can only be considered as a guide since they are based on ideal conditions of working and may be affected by many factors. It is desirable, therefore, that on large earthworks a small compaction trial should be carried out before the construction work to determine the type of plant, the optimum thickness of layer, and the number of passes that will give the desired state of compaction with the lowest cost per cubic yard of fill material.

FUNDAMENTAL INVESTIGATIONS

Apart from the investigations of the performance of compaction plant outlined above, a number of more fundamental studies have been carried out at the Road Research Laboratory. The object of these studies was to provide data for use by manufacturers in the design of improved compacting machines. The principal investigations carried out have been:

1. A study of some of the factors likely to affect the performance of impact compactors on soil (3).
2. An investigation of the effect on the compaction of soil of varying the diameter

TABLE 3

ESTIMATED PLANT OUTPUTS IN COMPACTING SOIL[1]

Type of Plant	Approximate Hourly Cost of Operating Plant (including hire, wages of operator and fuel),[2] dollars	Average Output of Plant: Width Compacted by plant, in.	Speed of Rolling, ft per min	Number of Passes Required	Area Compacted per Hour, sq yd	Depth of Compacted Layer, in.	Output of Compacted Soil per Hour, cu yd	Cost per Cu Yd of Compacted Soil, cents[2]
12-ton pneumatic-tired roller	6.1	82	200	4	1,900	5	260	2.3
20-ton pneumatic-tired roller	8.2	84	200	4	1,940	6	320	2.6
45-ton pneumatic-tired roller	14.3	93	200	3	2,900	10	800	1.8
2¾-ton smooth-wheeled roller	2.0	51	180	8	530	5	74	2.7
8-ton smooth-wheeled roller	2.5	70	180	4	1,500	6	250	1.0
2-cwt power rammer	1.2	0.49[3]	60[4]	6[5]	27	6	4.5	27
12-cwt frog rammer	1.8	4.6[3]	50[4]	12[5]	110	12	36	5.0
4-cwt vibrating roller	0.9	24	30[6]	8	42	3	3.5	26
6¾-cwt vibrating roller	1.2	28	60	16	49	6	8.2	15
3¾-ton vibrating roller	4.9	72	120	6	670	6	110	4.5
4-cwt vibrating plate compactor	1.4	15	28	3	65	5	9.0	16
13-cwt vibrating plate compactor	1.7	24	60	4	170	8	37	4.6
14-cwt vibrating plate compactor	1.7	24	42	2	230	6	39	4.4
1½-ton vibrating plate compactor	2.3	30	25	2	170	12	57	4.0
2-ton vibrating plate compactor	2.3	34	27	2	210	12	70	3.3
40-hp track-laying tractor	4.6	30	350	6	810	6	130	3.5
80-hp track-laying tractor	7.3	40	440	6	1,400	6	230	3.2

[1]Compacting soil to 10 percent air voids, the average natural moisture content in the British Isles.
[2]The costs (1958 prices) are those for Great Britain converted into dollars and cents.
[3]Area of soil compacted by each blow (sq ft).
[4]Average number of blows per minute.
[5]Number of blows.
[6]Hand-propelled.

Figure 5. General view of the equipment used in the investigation of impact compaction. The rammer has been raised to a height of about 5 ft and the operater is about to trip the quick-release mechanism.

of a smooth-wheeled roller (9).

3. An investigation of the effect of wheel load and tire-inflation pressure on the performance of pneumatic-tired rollers in the compaction of soil (4).

Impact Compaction

The equipment used in the tests (Fig. 5) comprised a special rammer working in conjunction with a pile-driving frame suspended from the jib of an excavator. The rammer consisted of a frabicated light-alloy cage, the weight of which could be adjusted from about 1 cwt to about $4\frac{1}{2}$ 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 $2\frac{1}{4}$ 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, it could be allowed to drop freely on the surface of the soil.

The results obtained in the investigation showed that, for a given size of rammer, the state of compaction produced was a function of the kinetic energy per unit area of the rammer. When the rammer size was increased, to obtain the same state of compaction the compactive energy per unit area of the rammer had also to be increased in proportion to the square root of the area of the rammer. The compactive energy per blow, within the limits of 4.5 ft-lb per sq in. to 8 ft-lb per sq in., had no significant effect on the state of compaction obtained at any moisture content provided the total compactive energy per unit area was kept constant. Thus, within the range of maximum compactive energies per blow that are likely to be adopted from consideration of practical design, it is only necessary to consider the total compactive energy per unit area of rammer. Nevertheless, to avoid overstressing during compaction of soils with a low bearing capacity, it would be necessary to employ a lower compactive energy per blow than would be possible with soils with a high bearing capacity.

Diameter of Smooth-Wheeled Rollers

One of the factors that might be expected to affect the state of compaction produced in soil by smooth-wheeled rollers is the diameter of the rolls. To give an indication of the importance of this factor, an investigation was carried out using a special apparatus in which rolls of various diameters but constant width could be fitted. The rolls used had diameters of 1, 2 and 3 ft, a width of 2 ft, and were loaded to 142 psi width.

The results obtained showed that there was no significant difference between the states of compaction obtained for any given number of passes with the 2- and 3-ft diameter rolls. It was not found possible to operate with the 1-ft diameter roll since the soil built up in front of the roll and prevented rotation. The results suggest, therefore, that it is unlikely that any significant improvement in the compacting performance of smooth-wheeled rollers can be achieved by small alterations in the diameter of the rolls.

Wheel Load and Tire-Inflation Pressure

Three sizes of pneumatic-tired roller were employed in the investigations with wheel loads ranging from 1.3 tons at a tire-inflation pressure of 36 psi to wheel loads of 10 tons at a pressure of 140 psi. The investigation included a study of the effect of speed of rolling on the state of compaction produced. The following main conclusions were drawn:

1. The contact area and contact pressure under the tires, both of which affect the state of compaction, are functions of the wheel load and the inflation pressure.
2. An increase in the wheel load or in the tire-inflation pressure produces an increase in the maximum dry density with a correspondingly lower optimum moisture content.
3. For the compaction of soils similar to the two clay test soils (Fig. 4), there appears to be little point in employing tire-inflation pressures much in excess of 40 to 50 psi with wheel loads of about 5 tons.
4. For the compaction of granular soils in the British Isles there appears to be some advantage in employing the highest tire-inflation pressures and the heaviest wheel load practicable, consistent with avoiding overstressing of the soils.
5. The magnitudes of the wheel load and tire-inflation pressure had very little influence on the general shape of the curves relating the number of passes of the roller with dry density, very little increase in the state of compaction being obtained after 16 passes.
6. In general, about 4 passes of the rollers were necessary to produce states of compaction equivalent to an air-void content of 10 percent.
7. To achieve the greatest output of compacted soil, the highest practicable rolling speed should be employed with, if necessary, a slight increase in the number of passes to compensate for the slight drop in the state of compaction that might result from employing the higher speed.
8. In general, the higher the wheel load and tire-inflation pressure, the higher was the state of compaction at any given depth.
9. The maximum thickness of loose layer that can be employed to achieve a minimum acceptable state of compaction equivalent to an air-void content of 10 percent ranges between 6 to 9 in. for the lightest combination of wheel load and tire-inflation pressure to 14 to 18 in. for the heaviest combination used.
10. Although the output of the rollers increased with size and loading, the cost of operation is also likely to increase at a similar rate and the resulting cost per unit volume of compacted soil is not likely to be very different for the various sizes of roller.

SUMMARY

The Road Research Laboratory has been carrying out a program of research on soil compaction, in which studies have been made under controlled conditions of the performance of most types of compaction plant available in Great Britain. Special installations have been employed for carrying out the tests; the building contains five soil bays, each 15 ft wide and 35 ft long, filled with a 3 ft depth of test soil. The soils, which are representative of a wide range of the soils found in Great Britain, are a heavy clay, a sandy clay, a well-graded sand, a uniformly graded fine sand, and a gravel-sand-clay.

The results of the full-scale tests are summarized and suggest that, for the compaction of mass earthworks, pneumatic-tired rollers and heavy smooth-wheeled rollers are likely to be the most economical plant. In addition to the tests on compaction machines, a number of studies of a more fundamental nature have been made; these include investigations of impact compaction by rammers and of the effect of wheel load and tire-inflation pressure on the performance of pneumatic-tired rollers.

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