The Compaction of Soil for Earthworks and the Performance of Plant

Le compactage des sols pour les travaux de terrassement, le comportement et l'efficacité du matériel

by W. A. Lewis, B.Sc., A.M.I.C.E., Road Research Laboratory, Harmondsworth, Middlesex, England

Summary

This paper discusses the results of recent research work on soil compaction carried out at the Road Research Laboratory. The work has comprised broadly:—

(1) Consideration of the factors affecting the selection of the moisture content at which to compact soil in earthworks.
(2) Investigation of the state of compaction required in road embankments.
(3) Study of the performance of plant used for compacting soils.

An account is given of investigations of the performance of the types of compaction plant usually employed in the British Isles, and the results are discussed with particular reference to the behaviour of the plant when compacting soils at moisture contents normally prevailing in these islands. Specifications for the state of compaction required in earthworks, in terms of the maximum dry density obtained in the laboratory compaction tests, are considered unsatisfactory, and an alternative method of specification is suggested in terms of a maximum air content of the soil.

Sommaire

Cet exposé passe en revue les résultats des recherches sur le compactage des sols effectuées récemment au Laboratoire de Recherches Routières en Angleterre (Road Research Laboratory). L'étude a compris en général:

1° Le choix de la teneur en eau à laquelle le sol doit être compacté lors de l'exécution de terrassements.

2° Le contrôle du compactage dans l'exécution de remblais.

3° L'observation et la critique des résultats obtenus avec le matériel utilisé dans le compactage des sols.

Les enquêtes entreprises sur l'efficacité du matériel de compactage ordinairement employé en Grande-Bretagne sont décrites et les résultats passés en revue concernent, en particulier, le comportement du matériel lorsque le compactage des sols est effectué à des teneurs en eau telles que celles qui règnent normalement dans ce pays.

L'auteur considère qu'il est peu satisfaisant de spécifier l'état de compactage exigé dans l'exécution de terrassements en considérant la densité sèche maximum, obtenue par des essais de compactage effectués au laboratoire et une méthode de spécification est proposée dans laquelle l'auteur considère la teneur en air maximum du sol.

Introduction

It is now generally recognized by road engineers that there must be a scientific approach to the compaction of road subgrades and embankment fills if the resulting structure is to have adequate stability and if the work is to be carried out economically. Before the engineer can draw up really sound specifications for the compaction work, however, he must have available the following basic information:—

(1) The moisture content at which the soil should be compacted.
(2) The state of compaction that should be achieved.
(3) The performance of plant in compacting soil.

The purpose of this paper is to discuss these matters in the light of the knowledge gained at the Road Research Laboratory; experimental work to provide further information is still in progress.

Selection of the Moisture Content for Compacting Soil

The problem of the selection of the moisture content for the compaction of soil is one which has received considerable attention from those concerned with the construction of large earthworks. It has long been recognized that for a given compactive effort there is an optimum moisture content at which a maximum dry density is obtained. This appeared to provide a convenient basis for the specification of soil compaction and various laboratory tests (*British standards*, 1948, *U.S. War Department*, 1947) involving different amounts of compactive effort per unit volume of soil were devised for determining optimum moisture contents and corresponding maximum dry densities. The moisture content at which the soil in the field was to be compacted was selected from a knowledge of the optimum moisture contents given by these tests. However, it is unrealistic to apply the results of laboratory compaction tests to work in the field since the compactive efforts provided in the laboratory tests generally bear little relation to those of the field compaction plant. Attempts made by the Road Research Laboratory to relate the performance of plant in compacting soil to a particular laboratory test have not been successful, and it is considered that the results of any laboratory compaction tests can generally be used only as a rough guide to the moisture content that will give a maximum state of compaction in the field. The principal value of standard laboratory compaction tests appears to be in the classification and selection of fill material for earthworks.

It is considered at the Road Research Laboratory that there are two distinct procedures to be adopted in the selection of the moisture content for compacting soil depending on the compressibility of the soil. With soils which do not exhibit any significant change in volume with change in moisture content (broadly, the non-cohesive soils) the most satisfactory way of selecting the moisture content for compaction is on the basis of full-scale field trials carried out with the types of plant likely to be used on the actual earthwork. The ideal moisture content will be the one corresponding to the maximum dry density obtained with the type of plant selected for the work, the selection of the plant being based both on the operational costs and on the stability of the compacted soil. In practice, difficulties of moisture control may arise if the natural moisture content of the fill material differs significantly from the moisture content selected for compaction. It is extremely difficult in the British Isles to adjust the moisture content of fill material to some particular value owing to uncertain weather conditions and frequent changes in the soil type. However, the results of a number of full-scale compaction trials carried out on granular soils suggest that the optimum moisture contents for most types of compaction plant correspond fairly closely to the natural moisture contents of the soils in the British Isles (*Williams* and *Maclean*, 1950).

Soils which exhibit significant changes in volume with changes in moisture content (cohesive soils) are considered to require a rather different treatment from that outlined above. Some field evidence has been obtained which suggests that subgrades and embankments for roads consisting of these soils should be compacted at a moisture content which will not change significantly after the construction work. The actual determination of this moisture content for the climatic conditions of the British Isles requires a knowledge of the moisture properties of the soil, the position of the water-table, the weight of the superimposed layers and the previous moisture history of the soil (*Croney*, 1952). However, a study that has been made of the moisture conditions in road embankments (Table 1) suggests that little change in the moisture content of the fill material is likely to occur if it is compacted when at its natural moisture content measured below the top 3–4 ft. of soil usually affected by weather conditions. In any case, as with non-cohesive soils, it would usually be impracticable in the British Isles to alter the moisture content of cohesive soils. Any full-scale compaction trials carried out should, therefore, be confined to tests at the natural moisture content of the soil; the object of the work being to help in the selection of the most suitable plant for compacting the soil at this moisture content.

Table 1 Summary of the Results Obtained in an Investigation of the State of Compaction of the Fill Material of a Number of Old Load Embankments

Site	*Kingston By-pass* (1)	*Godalming By-pass* (2)	*Hailsham By-pass* (3)	*Hailsham By-pass* (4)	*Crawley By-pass* (5)	*Farnham By-pass* (6)	*Lancing Brook* (7)
Year of construction	1926	1930	1934	1937	1937	1940	1947
Traffic conditions	Very heavy	Heavy	Heavy	Heavy	Heavy	Heavy	Medium
Depth of fill (ft.)	20	25	25	10	20	10	15
Soil type	CI	CL	CH	CH	CH	SU	CH
Average liquid limit (%)	46	27	64	52	59	Non-plastic	54
Average plastic limit	19	16	25	21	25		21
Average specific gravity	2.72	2.72	2.72	2.70	2.75	2.73	2.73
Average moisture content (%)	27	17	28	22	25	8	24
Average dry density (lbs./cu.ft.)	98	110	95	95	94	126	94
Average air voids content (%)	0	6	1	10	8	10	9
Approxim. amount of settlem. of road since construction (in.)	3	0*	6	0*	1	0*	0

*) No measurements are available but visual inspection of the road indicates that little settlement has occurred.

State of Compaction to be Attained

The state of compaction required in earthwork construction depends on the amount of ensuing settlement which can be tolerated and the requirements for the stability of the embankment. The permissible settlement is influenced to a considerable extent by the type of construction of the superimposed road pavement as concrete roads are usually more susceptible to damage from settlement than bituminous surfaced roads. Except in the case of relatively high road embankments, problems of stability rarely arise and in general the question of settlement is regarded as the factor governing the necessary state of compaction to be produced.

Little information is at present available on the relationship between the state of compaction of road embankments and the settlements occurring after construction, and it is not possible, therefore, to say with any certainty the state of compaction that is required. To provide some information on this subject, investigations have been carried out by the Road Research Laboratory to determine the state of compaction of the fill material of a number of old road embankments in which settlement has now ceased. The results obtained (Table 1) suggest that the settlement of such embankments is probably a function of the strength and compressibility properties of the fill material as well as of the state of compaction obtained during construction. At sites 1 and 3 where the soils had high moisture contents in relation to their plastic limits and hence would be expected to have a low strength and high compressibility, a considerable amount of settlement had occurred. At sites 4 and 5, however, the soils were much drier and little settlement occurred despite the fact that the states of compaction of the fill were not particularly good. With clay soils at moisture contents close to their plastic limit the state of compaction required to reduce settlements to a negligible amount appears to be no higher than that corresponding to an air voids content of about 10 per cent (a dry density 90 per cent of that corresponding to the condition of zero air voids at the moisture content of the soil).[1]) Wetter clay soils, however, probably require a higher state of compaction.

Little information is available regarding granular soils but it is considered as a general rule that the air voids content of the main bulk of the fill should not exceed about 10 per cent. In addition, however, it is probably necessary to compact the top 1–2 ft. of granular fill to a higher state of compaction as the action of traffic loads and vibrations over a long period of time might cause a further increase in the dry density of the subgrade with corresponding settlement of the pavement.

Performance of Plant in Compacting Soil

During the last few years, investigations have been carried out at the Road Research Laboratory to study the performance of most types of compaction equipment available to the engineer in the British Isles. Papers describing much of this work have already been published (*Williams* and *Maclean*, 1950, *Lewis*, 1951, *Lewis*, 1952) and reference should be made to these for the detailed results that have been obtained.

[1]) The air void content of soil is determined from a knowledge of the moisture content, specific gravity of the soil particles and the bulk density of the soil.

Table 3 Details of the Compaction Plant Tested at the Laboratory

Pneumatic-tyred roller		
Total laden weight (lbs.)	26,880	
Rolling width (in.)	82	
Number of wheels	9 (4 front, 5 rear)	
Wheel mounting	Pairs of wheels fixed to oscillating axles	
Tyre inflation pressure (lbs./sq.in.)	36	
Smooth-wheel rollers	*Heavy*	*Light*
Total laden weight (lbs.)	19,010	6,160
Diam. and width of front rolls (in.)	42 ×42	34 ×34
Diam. and width of rear rolls (in.)	54 × 18	36 ×15
Rolling width (in.)	70	51
Load/in. width–front rolls (lbs./in.)	186	80
–rear rolls (lbs./in.)	311	142
Sheepsfoot rollers	*Club-foot*	*Taper-foot*
Total laden weight (lbs.)	11,010	10,080
Size of feet (in.)	4 ×3	2.2 ×2.2
Foot pressure (lbs./sq.in.)	115	249
Length of feet (in.)	7.0	7.7
Rammers	*Frog*	*Power*
Total weight (lbs.)	1,350	250
Diameter of base (in.)	29	9.5
Approx. height of jump (in.)	12	12
Vibrating smooth-wheel rollers	*4-cwt*	*2½-ton*
Total weight (lbs.)	480	5,040
Diam. and width of front rolls (in.)	Single roll 21 ×24	30 ×32
Diam. and width of rear rolls (in.)		30 ×32
Load/in. width–front rolls (lbs./in.)	20	168
–rear rolls (lbs./in.)		168
Approx. frequency of vibrations (cycles/min) (front rolls)	4,500	5,000
Plate vibrators	*"Vibrosoil"*	*"Vibromax"*
Total weight (lbs.)	4,480	3,350
Approx. area of plate (sq.in.)	1,700	970
Approx. frequency of vibration (cycles/min)	1,050	1,100
Track-laying tractors	*Heavy*	*Medium*
Total weight (lbs.)	24,160	12,840
Width of track (in.)	20	15
Distance between tracks (in.) (centre to centre)	72	52
Average pressure of tracks (lbs./sq.in.)	7.2	7.3

The characteristics and classification of the soils used in the Laboratory's compaction investigations, and the relevant details of the items of plant tested, are given in Tables 2 and 3 respectively. The highest dry densities capable of being

Table 2 Characteristics of the Test Soils used in the Full-Scale Compaction Studies

Soil type	*Casagrande classification*	*Particle-size distribution*)*				*Index tests*)*			*Specific gravity*
		Gravel %	*Sand %*	*Silt %*	*Clay %*	*Liquid limit %*	*Plastic limit %*	*Plasticity index %*	
Heavy clay	CH	0	4	33	63	68	23	45	2.77
Silty clay	CI	0	17	49	34	40	20	20	2.69
Sandy clay	CL	0	40	36	24	34	17	17	2.70
Sand	SW	10	79	6	5	Non-plastic	Non-plastic	Non-plastic	2.70
Gravel-sand-clay	GW	54	36	4	6	Non-plastic	Non-plastic	Non-plastic	2.65

*) According to B.S.1377:1948.

Table 4 Maximum Dry Densities Obtained with Items of Plant Tested when Compacting Loose Layers of Soil 9 in. Thick at the Average Natural Moisture Content of the Soils in the British Isles

Soil type	*Estimated average natural moisture content of soil in British Isles (%)*	*Highest dry density attainable with soil at the natural moisture content (%)*	*Maximum dry density obtainable with plant compacting soil at average natural moisture content (lbs./cu.ft)*												
			Pneumatic-tyred roller	*Heavy smooth-wheel roller*	*Light smooth-wheel roller*	*Club-foot sheepsfoot roller*	*Taper-foot sheepsfoot roller*	*12-cwt. frog-rammer*	*2-cwt. power rammer*	*4-cwt. vibrating smooth-wheel roller*	*2½-ton vibrating smooth-wheel roller*	*2-ton "Vibro-soil" compactor (Vibrating-plate compactor)*	*1½-ton "Vibro-max" compactor (Vibrating-plate compactor)*	*Medium track-laying tractor*	*Heavy track-laying tractor*
Heavy clay	25	102	97	96	91	*	92	95	100	—	*	—	—	96	98
Silty clay	21	107	103	104	103	*	103	98	103	—	103	—	—	101	—
Sandy clay	17	116	108	112	113	*	*	111	110	94	—	112	—	—	—
Sand	9	136	123	132	131	—	—	126	128	122	131	128	129	126	—
Gravel-sand-clay	7	140	126	138	133	127	123	136	133	123	138	137	133	126	125

-) Plant not tested. *) Soil too wet for plant to operate satisfactorily.

obtained with the plant, when compacting loose layers of soil 9 in. thick at the average natural moisture content at which the soils are found in the British Isles, are collected together in Table 4. Apart from the dry densities produced, the number of passes of the compaction equipment required to achieve this state of compaction is also an important consideration. The effect of the number of passes of the plant on the state of compaction produced was, therefore, also determined. Table 5 gives the number of passes beyond which little further compaction was achieved, together with the corresponding dry densities.

The results indicate that the heavy smooth-wheel roller is probably the most useful type of compaction equipment at present available for general use in the British Isles. In the case of heavy clays or if the soil is in a very wet condition the pneumatic-tyred roller may be more satisfactory in operation. This type of roller is also more useful if the surface of the fill is in a very rough or uneven condition making it impracticable to employ smooth-wheel rollers. In very restricted sites such as behind bridge abutments or in trenches, it is probably most convenient to employ the 12-cwt. frog-rammer or the 2-cwt. power rammer which have similar compaction performances to the heavy smooth-wheel roller. Granular soils especially when in a dry condition can be well compacted by means of vibrating smooth-wheel rollers or vibrating-plate compactors. These latter machines, however, can be more easily operated if the soil is first compacted by one or two passes of an ordinary smooth-wheel roller as this provides a better surface for the operation of the vibrating compactors which otherwise tend to bog down in loose material. The heavy vibrating-plate compactors have the advantage that good compaction can be produced to a depth of 12 to 18 in., thus enabling relatively thick layers of soil to be compacted.

Table 5 Number of Passes Beyond which Little Further Compaction was Achieved and the Corresponding Dry Densities Produced with Items of Plant when Compacting Loose Layers of Soil 9 in. Thick at the Average Natural Moisture Content of the Soils in the British Isles

Soil type	*Number of passes and corresponding dry density produced (lbs./cu.ft)*												
	Pneumatic-tyred roller	*Heavy smooth-wheel roller*	*Light smooth-wheel roller*	*Club-foot sheepsfoot roller*	*Taper-foot sheepsfoot roller*	*12-cwt. frog-rammer*	*2-cwt. power rammer*	*4-cwt. vibrating smooth-wheel roller*	*2½-ton vibrating smooth-wheel roller*	*2-ton "Vibrosoil" compactor (Vibrating-plate compactor)*	*1½-ton "Vibro-max" compactor (Vibrating-plate compactor)*	*Medium track-laying tractor*	*Heavy track-laying tractor*
Heavy clay	4 (94)	4 (91)	8 (89)	*	8 (90)	2^{+} (92)	$2^{\times}$ (98)	—	*	—	—	5 (94)	8 (95)
Silty clay	4 (102)	4 (103)	8 (98)	*	20 (100)	2^{+} (95)	—	—	—	—	—	—	—
Sandy clay	4 (103)	4 (106)	8 (102)	*	*	2^{+} (107)	—	—	—	2 (105)	—	—	—
Sand	4 (117)	4 (125)	4 (125)	—	—	2^{+} (122)	$3^{\times}$ (122)	6 (112)	6 (126)	2 (125)	2 (121) 3 (127)	5 (120)	—
Gravel-sand-clay	4 (120)	4 (128)	8 (128)	32 (123)	20 (120)	2^{+} (131)	$3^{\times}$ (123)	6 (120)	—	—	—	—	8 (118)

-) Plant not tested.
*) Soil too wet for plant to operate satisfactorily.
$^{+}$) Coverages (6–8 blows/coverage).
$^{\times}$) Coverages (2–3 blows/coverage).

This compensates somewhat for the slower speed of the plate vibrators as compared with rollers.

Although track-laying tractors are capable of producing good compaction, their use purely for soil compaction work can seldom be justified owing to their high cost and relatively low output due to the poor coverage by the tracks of the machines. When used in conjunction with other equipment for transporting and spreading fill material, however, tractors may produce a useful compacting effect. Table 4 also shows that sheepsfoot rollers are unlikely to be of much value for compaction work in the British Isles as soils are usually too wet for the satisfactory operation of these rollers.

In considering the performance of compaction plant it must be remembered that the dry density achieved is inter-related with the thickness of the loose layers being compacted, the moisture content of the soil and the number of passes of the plant. Although most of the full-scale compaction investigations carried out by the Road Research Laboratory were confined to tests with loose layers of soil 9 in. thick in order to keep the work within reasonable limits, some tests were also made using a range of thicknesses of layer from 3 in. to 24 in. The results obtained indicate that a loose layer 9 in. thick probably represents an optimum thickness of layer for most compaction plant available in the British Isles. On large works it will usually be impracticable to spread soil in thinner layers than about 9 in.: if much thicker layers are employed, a very poor state of compaction will be produced in the lower portion of the layer.

Selection of Plant for the Compaction of Soil

The guiding principle in the selection of the type of plant for compaction work is that the equipment should be capable of producing efficiently the desired state of compaction when the soil is at the selected moisture content for compaction. Apart from the ability of the compaction plant to satisfy these requirements the availability and cost of operation of the plant are important considerations. On small works the question of availability will probably be the deciding factor in the choice of compaction equipment. On large projects, however, the economics of the plant and methods of compaction will probably be the governing factors. Although the results of the Laboratory's investigations provide a guide in these respects it is considered that on large earthworks a small compaction trial should be carried out prior to the construction work to determine the type of plant, the optimum thickness of layer and the number of passes which will give the required state of compaction with the lowest cost per cubic yard of fill material.

Specification and Control of Soil Compaction

Although it is fairly common practice to specify the state of compaction required in earthwork construction as a percentage of the maximum dry density obtained with a standard laboratory compaction test (i.e. as a "relative compaction"), this procedure has certain serious drawbacks. If the moisture content selected for compaction, as discussed earlier in this paper, is found to be much lower than the optimum moisture content obtained with the laboratory compaction test, a poor state of compaction (measured in terms of the air voids content of the soil) would result in the field even if a high "relative compaction" were actually obtained. On the other hand, if the moisture content selected for field compaction is much higher than the laboratory optimum moisture content, the specified relative compaction might well be quite unattainable.

It is suggested that a more logical approach to the problem would be to specify the state of compaction to be obtained in the field in terms of a maximum air voids content for the compacted soil (or alternatively in terms of a minimum percentage of the dry density corresponding to the condition of zero air voids at the moisture content at which the soil is compacted). The problem of the control of soil compaction would be simplified considerably by this procedure as it would eliminate the difficulty which often arises in distinguishing between variations in the dry density due to changes in the state of compaction and changes in the soil type. The determination of the air voids content of compacted soil is no more complicated than the calculation of relative compaction as it requires only a knowledge of the specific gravity of the soil particles in addition to the dry density and moisture content of the compacted soil.

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