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THE COMPACTION OF SOILS AND STABILIZED BASES ON ROADS IN EAST AFRICA

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ABSTRACT

As part of a study of aspects of normal road-building practice in tropical countries, the states of compaction achieved in road bases and earthworks were investigated at ten road construction schemes in East Africa. In addition, where possible, controlled compaction trials were carried out.

The most significant conclusion from the investigation is that the states of compaction achieved in the field correspond quite closely with those obtained in full-scale compaction tests carried out at the Transport and Road Research Laboratory. The relation between compactive effort, moisture content and the dry density obtained in the field followed accepted patterns; overstressing was noted on a uniform sand soil. The optimum moisture condition for compaction in the field was close to the optimum moisture content in the B.S. Compaction test 2.5 Kg (5.5 lb) rammer method, and simple and rapid methods of appraising the moisture conditions were effective in maintaining the moisture contents within an acceptable range.

The study showed that the states of compaction commonly specified for tropical roads can be attained under normal working conditions.

1. INTRODUCTION

On most road construction schemes overseas it is now common practice to construct the road pavement layers shortly after the completion of the earthworks. In these circumstances the practice of allowing earthworks to 'weather' and compact under traffic, as used in stage construction, cannot be employed, and a satisfactory state of compaction must, therefore, be achieved during construction, if subsequent settlements are to be reduced to tolerable amounts.

In 1946, a comprehensive study, which is still continuing, was initiated at the Transport and Road Research Laboratory (then the Road Research Laboratory) to determine the states of compaction obtained with a wide range of compaction equipment.[1-9] Full-scale trials with the various items of compaction plant were carried out on soils and base materials under closely-controlled conditions in specially-constructed buildings. The results of these trials enabled the performance of the various types of compaction equipment to be studied, and the levels of compaction achieved probably approach the best that can be obtained. The present investigation was undertaken to provide data on the levels of compaction that are and can be obtained on actual road construction schemes and so to enable the performance of compaction plant to be assessed under normal working conditions.

The measurements were made on ten road construction schemes in East Africa, the work being carried out in co-operation with the Ministries responsible for road construction in Kenya, Tanganyika (now Tanzania) and Uganda.

2. THE ROAD CONSTRUCTION SCHEMES EXAMINED

The locations of the road construction schemes and details of the amount of testing carried out are given in Table 1. Direct labour was used on eight of the schemes, while at Schemes Nos 4 and 5 the work was undertaken by contractors. The subgrade soils ranged from friable red and brown clays to uniform sand; base and sub-base materials were all natural gravel-sand-clays which were stabilized with either hydrated lime or cement when used as bases. Figs 1-11 and Tables 2-5 summarize the soil classification and compaction data for the soils found on the schemes. A wide variety of compaction plant, including smooth-wheeled rollers, towed and self-propelled pneumatic-tyred rollers, sheepsfoot rollers, vibrating rollers and earthmoving equipment, was used in the compaction processes.

3. FORM OF INVESTIGATION

The investigating team usually spent about a month on each construction scheme. The team normally operated from a simple laboratory set up in the nearest town with mains electricity in accommodation provided by the Ministry responsible for the scheme.

Two types of measurement were made on representative areas at each scheme:

(i) measurements to determine the state of compaction achieved by the normal construction methods being used;

(ii) measurements to determine the effect on the level of compaction of controlling factors such as the moisture content, the number of passes of the compaction plant and the thickness of the layer being compacted.

(i) would also provide information in (ii) when complete details of the compaction operation were obtained. Further subdivision occurs, depending on whether a natural soil or a soil stabilized with hydrated lime or cement was being compacted.

3.1 Field sampling

Ten density determinations using the sand replacement method[10] were generally made on each area tested. This number of measurements usually enabled the mean value of the dry density to be determined with an accuracy of ± 2 per cent for a probability of 9 chances in 10. Representative samples from each area were generally obtained by combining the remainder of the soil dug from each density hole after taking samples for moisture content determinations. This ensured that the samples tested in the Laboratory were as nearly as possible identical with the soil whose dry density had been determined in the field. With stabilized materials, samples of the natural soil were taken from the layer of base material before adding the stabilizer, the dry density measurements being carried out at the same location after stabilization and compaction. Density holes were either 15 cm or 10 cm (6 in or 4 in) deep depending on the thickness of the compacted layers. Where the compacted layers of soil were more than 15 cm (6 in) thick the measurements obtained would tend to overestimate the state of compaction in the complete layer of material. In considering the results, a compacted layer is taken to be two-thirds of the loose layer thickness before compaction, e.g., a 23 cm (9 in) loose layer gives a 15 cm (6 in) thick compacted layer. In presenting the data, the loose layer thickness is quoted since it is this factor that can be controlled during construction.

3.2 Laboratory testing

BS compaction tests,[10] 2.5 kg (5.5 lb) rammer method* were carried out on all the samples and the results obtained are summarized in Fig. 1. These compaction data, together with a visual examination, were used to select typical samples. BS Compaction tests, 4.5 kg (10 lb) rammer method*, particle size distribution, plasticity and specific gravity determinations were carried out on these typical samples, the majority of the results being shown in Figs 2-11.

The testing procedures used on natural soils were generally in accordance with BS 1377:1967.[10] Since irreversible property changes occur with some tropical soils on complete air drying[10,11] only the minimum drying necessary to manipulate the soils for testing was permitted.

The testing of soils stabilized with cement was carried out in accordance with BS 1924:1967[12] with separate specimens for each moisture content; the material was compacted into the mould immediately after mixing. With lime-stabilized soils a single sample was used throughout the compaction test as had been done in the case of the natural soils. In addition, on Scheme No. 8, the effect of a lapse of time between mixing and compaction on the dry density of the gravel-sand-clay base material stabilized with cement or hydrated lime was determined (Fig. 12).

4. DESCRIPTION OF THE NORMAL COMPACTION PROCESS

4.1 Subgrades and earthworks

Except at Scheme No. 6, little effort was made to control the compaction process on earthworks and subgrades. With this exception, soil was excavated in areas of cut using motorized or towed scrapers and was deposited in layers in the areas being filled. Water was not added to the soil at any time and compaction was carried out by uncontrolled trafficking with the earthmoving equipment alone or in combination with smooth-wheeled, pneumatic-tyred or vibrating rollers. At Scheme No. 6, the soil, predominantly a uniform sand on the length of road examined, was bull-dozed in from the side drains to raise the subgrade to formation level. Again control of compaction in the lower layers was poor, but compaction of the top layer of the subgrade was carefully controlled. Water was sprayed copiously on to the shaped subgrade from water tankers and mixed into the soil with a heavy-duty agricultural disc harrow. Compaction followed using pneumatic-tyred, vibrating and smooth-wheeled rollers in that sequence.

4.2 Stabilized bases

On stabilized base construction some water was always added to the materials during mixing of the hydrated lime or cement stabilizer. The amount of water to be added was judged by testing the consistency of a piece of soil squeezed into a lump in the hand. At the optimum moisture content, the lump so formed coheres sufficiently to be broken into two pieces without crumbling yet it is not sufficiently wet and plastic for the fines to tend to squeeze between the fingers or more than lightly stain the hands. Although this method of assessing the moisture requirements appears crude, it has been used successfully elsewhere.[14-16] Its main advantages are the rapidity with which the assessment can be made and its usefulness over a wide range of soil types.

When the base materials had been mixed, the surface was shaped to profile with a motor grader and compaction was begun with light pneumatic-tyred or sheepsfoot rollers when either of these was available. The final compaction passes were carried out with smooth-wheeled rollers, rolling being continued until the required state of compaction was attained or until rolling marks disappeared. Final shaping with a motor grader followed and the base was given a final coverage with the smooth-wheeled roller.

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* The BS Compaction test 2.5 kg (5.5 lb) rammer method (Test No. 11 BS 1377:1967) corresponds closely to the AASHO (AASHO Designation: T99-70) and Proctor Compaction tests. The BS Compaction test 4.5 kg (10 lb) rammer method (Test No. 12, BS 1377:1967) corresponds closely to the Modified AASHO (AASHO Designation: T180-70) and Modified Proctor Compaction tests.

5. ASSESSING THE STATE OF COMPACTION

The state of compaction in a soil can be expressed as a relative compaction[2] where the dry density measured *in situ* is expressed as a percentage of the maximum dry density found in a laboratory compaction test, usually either the BS Compaction test, 2.5 kg (5.5 lb) rammer method, or the BS Compaction test, 4.5 kg (10 lb) rammer method.

It is essential that the laboratory compaction test is carried out on a sample of soil identical with that on which the dry density has been measured in the field. It requires much laboratory compaction testing for the results to be interpreted, since the range of maximum dry density can be quite large on what is visually the same soil.[17]

In the present investigation the state of compaction found in each of the areas sampled has been reported in the Tables in terms of relative compaction based on both the BS Compaction tests (2.5 kg (5.5 lb) and 4.5 kg (10 lb) rammer methods). In the text and figures, relative compaction and moisture conditions are generally considered in relation to the maximum dry density and optimum moisture content obtained in the BS Compaction test, 2.5 kg (5.5 lb) rammer method, as this test or its equivalents appear to be widely used.

The moisture conditions in the soil at the time of compaction can be judged by comparing the moisture content found in the areas tested with the optimum moisture contents of the laboratory compaction tests. For each area, the optimum moisture content in both the BS Compaction tests and the field moisture content have been reported. This has enabled the results of tests on areas where the soil is similar but has different laboratory classification and compaction values to be reduced to a common basis, so permitting the effects of variations in other factors to be assessed.

Soil moisture contents in the areas sampled were obtained from tests on representative portions of the material excavated from each density hole. The digging of a density hole may take up to half an hour and the soil excavated is exposed to the drying effects of the atmosphere during that time. Information on the magnitude of the moisture losses was obtained at Schemes Nos 2 and 7 and is summarized in Table 6. This indicates that, under tropical conditions, about 2 per cent of moisture was lost during the excavation of the density holes. In reporting the results, allowance has been made for this loss of moisture by increasing the average moisture content in each area by 2 per cent.

6. THE STATES OF COMPACTION ACHIEVED USING NORMAL METHODS OF COMPACTION

6.1 The results obtained on natural soils

The states of compaction on the representative areas tested are shown in Table 2. In some areas the dry density and moisture content were measured some time after the compaction operations so that the moisture content at the time of compaction is not accurately known. Data obtained in the controlled compaction trials (Table 4) would suggest that the moisture contents at the time of compaction were somewhat higher than those measured, and the values quoted in Table 7 would be slightly lower than at the time of compaction.

The salient point emerging from Table 7 is that, irrespective of the differences in the compactive effort applied, higher average states of compaction were attained on soils with moisture contents close to the optimum moisture contents of the BS Compaction test, 2.5 kg (5.5 lb) rammer method. It can also be seen that the scatter of results about the average value was much less when the moisture content was at or higher than the optimum moisture content of the BS Compaction test, 2.5 kg (5.5 lb) rammer method, even allowing for the small number of individual areas tested. This is not unexpected since soil at these high moisture contents will, when fully compacted, be nearly saturated and the multiplicity of compaction curves possible at lower moisture contents will have coalesced into a narrow band parallel to, and usually close to, the zero air voids line. However, at these high moisture contents the development of unstable spongy conditions[7] is imminent and care must be exercised to avoid such excessively wet conditions in the soil.

The data in Table 7 further indicate that heavy earthmoving equipment and site traffic can achieve high states of compaction when moisture conditions are favourable. On short embankments the number of passages of the earthmoving plant required to deposit the fill materials is often insufficient to provide complete coverage, even if the plant were to traverse the embankment systematically. More generally, earthmoving plant channelizes, following previously used paths, and so leaves uncompacted zones, particularly towards the edges of the embankment. The provision of plant capable of use solely for compaction and, in drier conditions, watering equipment would appear to be mandatory when consistently high states of compaction are called for.

6.2 The results obtained on stabilized bases

The states of compaction found on the representative areas of stabilized bases tested are shown in Table 3. As the measurements were made shortly after compaction, the moisture contents are representative of the conditions prevailing at the completion of the compaction process.

The effect of the control exercised on the moisture conditions is shown by the fact that at 16 of the 18 areas examined the average moisture content lay within the values of the optimum moisture content of the two BS Compaction tests (i.e., 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods), a range of only some 2 to 4 per cent of moisture content for these gravel-sand-clay soils; in the two remaining areas, the average moisture contents were 1 per cent lower than the optimum moisture content of the heavier compaction test. Thus, the simple method used to control the moisturizing of the stabilized base materials achieved its objective of procuring moisture contents suitable for the production of high states of compaction.

On the base materials stabilized with hydrated lime, the average states of compaction achieved (Table 8) were similar to those obtained on natural soil at comparable moisture conditions. The scatter of results about the average values at the three schemes was also similar.

At Scheme No. 8, with cement-stabilized base materials, although the moisture conditions were satisfactory and the compaction by the smooth-wheeled rollers was completed within 30 mins of mixing, the state of compaction was appreciably lower than that of the lime-stabilized bases. With cement-stabilized materials a lapse of time between mixing and compaction may reduce the dry density. It was considered that this phenomenon might be primarily responsible for the lower states of compaction, the effect probably being accentuated by the use of freshly-manufactured cement delivered daily from the cement works at Athi River. Laboratory compaction tests were, therefore, carried out to determine the magnitude of this effect. In addition to the tests using the fresh cement, parallel tests were run using cement which had been stored for a few weeks and also with two locally-manufactured hydrated limes. The results obtained (Fig. 12) show that with all these stabilizers there was a progressive reduction in dry density with lapse of time after mixing; the effect was more marked with the material stabilized with the fresher cement.

This phenomenon limits the state of compaction that can be obtained and the practical consequences must be recognised. In the United States of America specifications often require that the dry density should not be less than 80 kg/m^3 (5 lb/ft^3) below, or 95 per cent of, the maximum dry density determined in a field moisture-density test.[16,18] This test is similar to the BS Compaction test, 2.5 kg (5.5 lb) rammer method, but is carried out on the site on a sample of the moist stabilized materials obtained when mixing has been completed. On the basis of this criterion, the state of compaction achieved on the stabilized base materials at Scheme No. 8 would just be satisfactory. The data (Table 3) also show that only the initial passes of the smooth-wheeled rollers were effective in compacting the base materials, since there was no difference in the state of compaction found after 5 and 9 passes.

7. CONTROLLED COMPACTION TRIALS ON NATURAL SOILS

Controlled compaction trials were carried out on the natural soils at five road construction schemes (Table 1) and the results are summarized in Table 4. To perform a trial, an area of the earthworks already compacted by normal construction methods was selected and a layer of soil forming part of the normal fill materials was spread on this to the required loose thickness by the earthmoving equipment. A number of passes of the item of equipment being investigated was then applied and the dry density and moisture content determined. These trials studied the effect on the state of compaction of different types and sizes of plant, the number of passes applied, the thickness of the layer and the moisture content of the soil. The trials were integrated into the routine construction operations so that, with the exception of additional control of the initial three factors above, conditions during the trials were similar to those obtaining on the remainder of the construction.

Water tankers were only available at Scheme No. 6 and as a result the range of moisture conditions occurring on any individual scheme was limited. At Scheme No. 6, in addition to the moisturizing equipment, pneumatic-tyred, smooth-wheeled and vibrating rollers and tracked tractors were available for compacting the earthworks. Unfortunately, however, the predominant soil, a uniformly-graded sand, had a flat compaction curve typical of these materials and this would mask any differences in performance of the various items of compaction equipment. For these reasons it was not possible to study an item of compaction equipment over a wide range of conditions on any one scheme. The behaviour of different types of plant in different conditions had, therefore, to be obtained by combining the results of trials for a number of schemes. At the remaining four schemes the soils were predominantly friable red and brown clays typical of large areas of the tropics and the trials on these will be considered first.

7.1 Trials on friable red and brown clays

7.1.1 Pneumatic-tyred plant

The relation between the state of compaction and moisture condition of the soil for four passes of a loaded 14 m^3 (18 yd^3) motorized scraper compacting 23 to 25 cm (9 to 10 in) loose layers of soil is shown in Fig. 13 for a wheel load of about 9 Mg (9 tons) and a tyre inflation pressure of 34 N/cm^2 (50 lb/in^2). The front and rear wheels on these scrapers are in line so that a single pass of the scraper equals two passes of a pneumatic-tyred roller having the same wheel loads and tyre contact pressures. The highest state of compaction under these conditions was achieved at a moisture content a little wetter than the optimum moisture content of the BS Compaction test, 2.5 kg (5.5 lb) rammer method.

Further data on the relation between the state of compaction and moisture conditions in the top 15 cm (6 in) of the compacted layer for four passes of pneumatic-tyred wheels are shown in Fig. 14 and were obtained at Schemes Nos 1, 7, 9 and 10. Although the thickness of the loose layer varied from 15 to 43 cm (6 to 17 in) in these trials, the states of compaction produced in the top 15 cm (6 in) of the compacted layers should not be affected since the stresses produced should be largely independent of the loose layer thickness. This is confirmed by the results given in Table 9 which compares the states of compaction achieved in the top 15 cm (6 in) of compacted soil in pairs of trials in which only the thickness of the loose layer was altered. The approximate shear stresses in Fig. 14 have, with the exception of those for the self-propelled roller, been based on the tyre inflation pressures although the tyre contact pressures may be different. In the case of the self-propelled roller, the manufacturer's data indicate that the actual contact pressure for the wheel load and tyre inflation pressure measured would be 61 N/cm^2 (88 lb/in^2). The data show that for the towed pneumatic-tyred roller and motorized scraper at Schemes Nos 1, 7 and 9 increases in tyre inflation pressure resulted in marginally higher states of compaction. At Scheme No. 10, the difference between the results with the self-propelled roller and the towed scraper was more marked although the states of compaction achieved with the former were somewhat lower than would have been expected from the trials at Schemes Nos 1, 7 and 9. All the data indicate that the state of compaction obtainable on friable red clay soils is relatively unresponsive to a doubling in the stresses applied to the soil and to changes of moisture content at moisture contents more than a few per cent lower than the optimum moisture content of the BS Compaction test, 2.5 kg (5.5 lb) rammer method.

The relation between the state of compaction and the number of passes of the compaction plant is shown in Fig. 15. On the friable red clay soils, increasing the number of passes beyond 4 for the pneumatic-tyred rollers or the equivalent 2 passes of the scrapers resulted in only a slight increase in the state of compaction.

7.1.2 Smooth-wheeled rollers

The relation between the state of compaction and moisture condition of the soil for 4, 8 and 16 passes of the smooth-wheeled rollers compacting 23 cm (9 in) loose layers of soil is shown in Fig. 16. The highest state of compaction was achieved at moisture contents a little higher than the optimum moisture content of the BS Compaction test, 2.5 kg (5.5 lb) rammer method and similar to those giving the highest values for the pneumatic-tyred plant.

The relation between the state of compaction and the number of passes of the smooth-wheeled rollers is shown in Fig. 17. Increases in the number of passes up to 16 resulted in significant increases in the state of compaction, the effect being more marked on the 15 cm (6 in) loose layers. Fig. 17 also shows that reducing the thickness of loose layers from 23 to 15 cm (9 to 6 in) resulted in an appreciable increase in the state of compaction achieved at moisture contents a little less than the optimum moisture content of the BS Compaction test 2.5 kg (5.5 lb) rammer method for 8 and 16 passes of the smooth-wheeled rollers although the value at 4 passes was unaltered. It also resulted in the optimum moisture content for compaction under these conditions using the smooth-wheeled rollers being reduced by amounts increasing to about 3 per cent at 16 passes of the smooth-wheeled roller.

7.1.3 Sheepsfoot and grid rollers

Only five trials were carried out with these rollers on the friable clay soils (Table 4). In these, the grid roller, a modified smooth-wheeled roller with the steel rims replaced by a grid constructed of 19 mm (¾ in) thick steel plating 8 cm (3 in) deep and having 12 cm (4¾ in) square openings, produced results similar to a conventional smooth-wheeled roller. In the trials with the sheepsfoot roller, the states of compaction achieved were less than those obtained with the smooth-wheeled or pneumatic-tyred plant with high wheel loads or high tyre pressures, but were higher than those obtained by the towed scraper with low wheel loads and low tyre inflation pressures used at Scheme No. 10.

7.2 Trials on uniform sands

Ten trials were carried out on Scheme No. 6 on uniform sand with pneumatic-tyred, smooth-wheeled and vibrating rollers and a tracked tractor (Table 4). All trials were on 23 cm (9 in) loose layers of soil prepared by watering and disc harrowing. It proved impossible to apply the smooth-wheeled and vibrating rollers to this prepared layer and two passes of the vibrating roller with the vibrating mechanism inoperative were applied to provide the layer with sufficient bearing capacity to sustain the rollers. Even then it proved difficult to carry out the trials with the smooth-wheeled roller as it still tended to bog down and overstress the soil. After these initial preparations, 4 and 8 passes of the plant being examined were applied to the test areas. The states of compaction achieved by the pneumatic-tyred roller with a wheel load of 0.7 Mg (0.7 tons) and a tyre inflation pressure of 21 N/cm^2 (30 lb/in^2), the vibrating roller with a load of 21.4 kg per cm width (120 lb/in) and the tracked tractor with a contact pressure of 4.8 N/cm^2 (7 lb/in^2) were similar (Fig. 18). The increase in state of compaction with increase in the number of passes was more marked with the pneumatic-tyred roller and the tracked tractor. The relative compaction achieved with the smooth-wheeled roller with a load of 57.1 kg per cm width (320 lb/in) on the rear rolls was some 4 per cent lower and there was no significant improvement with increases in the number of passes.

Considering these trials in conjunction with the normal compaction process shows that the application of compaction plant in sequence commencing with the light pneumatic-tyred rollers followed by the vibrating roller and culminating with the smooth-wheeled roller produced the highest states of compaction. The type of plant used is probably not critical but it is essential to ensure that each successive application of heavier compaction plant does not overstress the layer being compacted.

7.3 Trials on a gravel-sand-clay soil

A trial was carried out on Scheme No. 7 with a smooth-wheeled roller compacting 23 cm (9 in) loose layers to ascertain the effect on the state of compaction attained of increases in the number of passes (Fig. 19).

8. CONTROLLED COMPACTION TRIALS ON STABILIZED BASES

Trials were carried out at Schemes Nos 2 and 4 on areas of the base materials being stabilized with hydrated lime (Table 5). The areas subsequently formed part of the completed road pavement and for this reason the moisture conditions were maintained near optimum for the compaction plant being used and the loose thickness of the layer was determined by the depth of compacted base required. It was, therefore, possible to study only the effect of increases in the number of passes of the rollers.

The results obtained at Scheme No. 2 using a smooth-wheeled roller with a load on the rear rolls of 55.4 kg per cm width (310 lb/in) and a light pneumatic-tyred roller with a wheel load of 1.4 Mg (1.4 tons) and tyre inflation pressure of 10 and 23 N/cm^2) are shown in Fig. 20. As would be expected on gravel-sand-clay materials, the smooth-wheeled roller achieved higher states of compaction than the light pneumatic-tyred roller. This does not mean that the initial passes with the light pneumatic-tyred roller are unnecessary since their purpose is to ensure that compaction is obtained evenly over the area and to eliminate the undulating profile resulting from the application of a high contact pressure to a loose tilth of material.[19]

On Scheme No. 4 a trial was carried out on a lime-stabilized base with a sheepsfoot roller having a foot contact pressure of 90 N/cm^2 (130 lb/in^2) and this (see Table 5), together with the data obtained during the measurement of the states of compaction achieved by the normal compaction procedures on similar materials, enables an assessment to be made of the effect of the sheepsfoot roller on the final state of compaction achieved. The contribution of the sheepsfoot roller to the state of compaction was very small and was less than that of the light pneumatic-tyred roller at Scheme No. 2. Sheepsfoot rollers would appear to have no particular merit when compared with light pneumatic-tyred rollers in the application of the initial passes which assist in the attainment of a good surface finish. It has been suggested, however, that they push the larger particles into the base and so render final grading easier, but 15 to 20 passes are required to obtain a single complete coverage of any area of material.[2]

9. COMPARISON WITH OTHER WORKS

9.1 Comparison with full-scale compaction plant trials at the Transport and Road Research Laboratory

Since 1946, full-scale trials have been undertaken at the Transport and Road Research Laboratory to ascertain, under a wide range of operating conditions, the state of compaction produced by compaction plant in common use. Early investigations were made in a 33.5 m (110 ft) diameter covered circular track where it was possible to maintain better control over the compaction plant and the moisture conditions of the soil than in the field and work could continue through most of the year.[2] Five soils – a heavy clay, a silty clay, a sandy clay, a sand and a gravel-sand-clay (hoggin) – were used and each was contained in a bay about 12.2 m (40 ft) long and 3.5 m (11½ ft) wide between 0.6 m (2 ft) high concrete walls. The soil in each bay was compacted in 15 cm (6 in) layers to a height of 0.6 m (2 ft) to provide a soil bed considered to be of similar stability to that occurring in the field, and the 23 cm (9 in) loose layer of soil on which the compaction trials were to be made was placed on the top. This top layer was broken up after each test into a 23 cm (9 in) layer of loose tilth and the moisture content adjusted to the value required for the next test. Determinations of the mean dry density were made at certain defined stages in the course of the compaction process.

Although the circular track proved satisfactory for the smaller items of compaction plant it could not accommodate the larger pneumatic-tyred rollers. A special building 30.5 m (100 ft) long and 27.4 m (90 ft) wide with 4.9 m (16 ft) headroom beneath the roof trusses was, therefore, constructed.[6] This building contained five soil test bays 10.7 m (35 ft) long, 4.6 m (15 ft) wide and 0.9 m (3 ft) deep, the floor of the bays being left as the natural soil so that conditions would approximate to those in the field. Four of the soils in these test bays – the heavy clay, sandy clay, sand and gravel-sand-clay – had counterparts in the circular track, while the fifth soil was a uniform sand.

In the full-scale plant trials the main factors studied were:

(i) the relation between the moisture content of the soil and the state of compaction when the condition of compaction to refusal had been reached;

(ii) the relation between the number of passes of the roller and the state of compaction produced, the majority of the trials being carried out at the optimum moisture content determined in (i) above; and

(iii) the variation in the state of compaction with depth below the surface of the compacted layer.

The data obtained from these closely controlled trials probably represent the highest that can be produced with the machines investigated and provide a useful yardstick against which the performance of compaction equipment operating in the field may be judged.

The state of compaction produced in soil by compaction plant is affected by the magnitude of the stresses induced by the roller, the number of applications of these stresses, the thickness of the layers of soil being compacted and the bearing capacity of the soil, and allowance must be made for differences in these factors when comparing the results obtained in the field with the full-scale compaction plant trials. Examination of the data collected during the latter trials[2,4,6] enables allowances to be made for differences in the magnitude of the applied stresses and provides an indication of the changes in dry density resulting from differences in the thickness of the layers being compacted. Only a limited amount of data is available on the relation between the number of passes of the roller and the state of compaction produced by rollers operating at different moisture conditions,[2] but they permit allowances to be made for different numbers of passes of the compaction equipment.

Unfortunately, the relation between the bearing capacity and the moisture condition of the soil is more complicated and does not lend itself to the making of simple adjustments. Broadly, the bearing capacity of a soil at constant dry density depends on its moisture content. However, at the same moisture content, a range of bearing values can occur depending on the soil moisture suction within the soil. Fig. 21 shows the suction/moisture content relation for a sample of heavy clay.[20] The bearing capacity, q, of a soil loaded on its surface can be expressed as $q = s\,Nq$ where s is the soil moisture suction and Nq a bearing capacity factor depending on the angle of friction.[21] At constant moisture content, Nq is also constant and q varies directly with s. Most soils being compacted in the field are not homogeneous and consist of collections of aggregated lumps. At the higher moisture contents, compaction will shear and deform these lumps until they are fused into a more or less homogeneous mass. In drier conditions, however, the ultimate strength of the lump is much greater than the strength of the collection of lumps separated by air voids.[22] Compaction will occur by the reduction of major air voids with little or no deformation of the lumps and the maximum state of compaction achieved would be determined by the grading of the lumps. Fig. 22 shows two dry density/moisture content relations obtained on two samples of a heavy clay soil using the same 12 Mg (12 ton) pneumatic-tyred roller.[2,6] Laboratory compaction tests showed that the maximum dry density values of the samples differed by some 48 kg/m^3 (3 lb/ft^3), a difference repeated in the roller trials. However, the shape of the relations on the low side of the optimum moisture content is markedly different; the dissimilarities are considered to be due to differences in the soil moiture suction conditions and homogeneity in the soil at the time of testing.

On the road construction schemes examined in the present investigation in East Africa, friable red clay soils were most common. Unfortunately, none of the soils used in the full-scale compaction plant trials at the

Transport and Road Research Laboratory is closely related to this type of soil and some differences in the behaviour of compaction plant would be expected. However, gravel-sand-clay soils were also encountered; these soils would be expected to behave similarly to the gravel-sand-clay (hoggin) soil used in the full-scale compaction trials and this group of soils will be considered first.

9.1.1 Gravel-sand-clay soils

Many of the soils in this category were stabilized with small proportions of hydrated lime or cement. The reaction between lime stabilizer and soil would not be expected to have an appreciable effect on the level of compaction produced, especially when the compaction operations are completed on the same day (Fig. 12). Data for which there is sufficient information on the amount of compaction applied to enable comparison to be made with the results of the full-scale compaction plant trials were obtained on Schemes Nos 2, 4 and 7. These data are summarized in Table 10, which also shows the levels of compaction that would be expected from the results of the full-scale plant trials. At Scheme No. 4 the state of compaction obtained is considered to be compaction to refusal by a smooth-wheeled roller since the contribution to the final state of compaction by both the sheepsfoot and the light pneumatic-tyred rollers is small (see Table 5, Ref. Nos 2.9, 2.10, 2.11, 2.12 and 4.20).

Table 10 shows that the states of compaction achieved in the field agree reasonably well with those obtained in the full-scale plant trials at the Transport and Road Research Laboratory. There appear to be real differences between the results from the three schemes, with those from Scheme No. 4 showing closest agreement with the values forecast from the full-scale trials. Results on individual schemes also show appreciable scatter.

Normal scatter of results would explain some of this variation. The limits of accuracy of average values are usually ± 2 per cent or less for a probability of 9 chances in 10 and such values when plotted may on occasion lie as much as 4 per cent relative compaction from the dry density/moisture content relation to which they relate.[2,4,6] The remaining scatter within schemes and the differences between schemes are considered to result from differences in the state of compaction of the compacted subgrade soils which supported the gravel-sand-clay layer during the compaction process. In the full-scale plant trials in the Laboratory, a smooth-wheeled roller compacting 61 cm (24 in) thick loose layers of a gravel-sand-clay produced maximum relative compactions of 101 and 88 per cent in the 0-15 cm (0-6 in) and 15-30 cm (6-12 in) compacted layers respectively, compared with 106 per cent in the top 15 cm (6 in) when 23cm (9 in) thick layers were being used.[4] A value of about 88 per cent relative compaction in the subgrade would be quite typical for Scheme No. 7, so that the value of 101 per cent relative compaction with 16 passes of the smooth-wheeled roller would, when all factors are considered, be quite in keeping with the results of the full-scale plant trials in the Laboratory. Further circumstantial evidence of the effect of sub-grade conditions on the state of compaction produced in superimposed layers is found on Scheme No. 4 (Tables 2 and 3) where the relative compaction varied from 87 to 99 per cent and 99 to 106 per cent in the subgrade and base respectively. The latter range of values from the base is little different from that quoted above for the Laboratory trials on 61 cm and 23 cm loose layers.

9.1.2 Friable red clays

These soils, the most common soil type at the schemes investigated, unfortunately have no close counterpart in the soils used in the full-scale plant trials at the Transport and Road Research Laboratory. Comparison of the states of compaction achieved in the field with those estimated from the results of the full-scale compaction plant trials on the heavy clay, sandy clay and gravel-sand-clay soils indicates that agreement is generally poor between the two sets of data at the drier moisture conditions; as would be expected, it is quite close at moisture contents in excess of the optimum moisture content of the BS Compaction test, 2.5 kg (5.5 lb) rammer method, when a saturated condition is approached. Table 11 gives typical examples to show the range of values obtained.

The differences and similarities in the states of compaction produced are probably caused by differences in the compaction characteristics of the soils and by the fact that friable red clay soils consist of a collection of lumps in the drier condition. The latter soils have high angles of internal friction and it is probably that many of the clay particles are firmly interconnected or aggregated.[11,23] These properties result in friable red clay soils having compaction characteristics similar to granular soils in the vicinity of the optimum moisture content, i.e., steep peaked dry density/moisture content relations and differences between the maximum dry densities in the two BS Compaction tests of about 160 kg/m^3 (10 lb/ft^3), but with the optimum moisture content for the compaction plant probably some 2 per cent higher relative to the optimum moisture content in the BS Compaction test, 2.5 kg (5.5 lb) rammer method. At the drier moisture condition, the state of compaction obtainable is independent of moisture content and only slightly affected by the compaction stresses. Such behaviour would occur with a collection of relatively strong lumps and similar compaction characteristics have been exhibited on occasion by heavy clay soils (Fig. 22).

9.1.3 Uniform sands

The state of compaction produced by towed vibrating rollers with the same static loading per unit width of roll was similar on this type of soil at Scheme No. 6 and in the full-scale compaction plant trials at the Transport and Road Research Laboratory.[24]

9.2 Comparison with other compaction trials

Apart from the full-scale compaction plant trials carried out under ideal conditions at the Transport and Road Research Laboratory other less extensive trials have been carried out elsewhere, often under conditions closely resembling those occurring on normal road construction schemes, and the results obtained have been reviewed by Johnson and Sallberg.[25] Again, agreement between the results obtained and those found on the road construction schemes in East Africa is generally good.

Table 12 summarizes the results of trials carried out by the U.S. Army Corps of Engineers[26,27] with a pneumatic-tyred scraper having wheel loadings of 9 Mg (20,000 lb) and tyre inflation pressure of 38 N/cm^2 (55 lb/in^2) on clayey sand and silty clay soils and compares them with the states of compaction achieved in East Africa with motorized pneumatic-tyred scrapers. Agreement is good and would probably have been even better if all the compaction tests had been carried out in standard 102 mm (4 in) diameter moulds.[28]

Table 13 summarizes the states of compaction achieved by smooth-wheeled rollers in trials carried out in the U.S.A.[29] and India[30,31] and compares them with the results obtained in East Africa. In the trials carried out in the U.S.A., the states of compaction achieved equalled those found on Scheme No. 4 and also in the full-scale compaction plant trials at the Transport and Road Research Laboratory, but it must be borne in mind that the method of carrying out the laboratory compaction test will have tended to enhance the values obtained in the Indiana trials. In India, however, the states of compaction achieved were some 8 per cent relative compaction lower and were similar to the results obtained on Scheme No. 7. These differences can again be explained by the different conditions of the soil supporting the layers being compacted. In the U.S.A. the states of compaction recorded were the averages of those found on embankments consisting of numerous layers of compacted soil. In India, on the other hand, the soil layer in which the measurements were made rested on a bed of compacted soil only 15 cm (6 in) or 30 cm (12 in) thick over natural soil.

9.3 Comparison with other construction schemes in Kenya

Data augmenting those obtained during the present investigation are available from three construction schemes in Kenya and are summarized in Table 14. The earth dam at Sasuma[16] was constructed of a friable red clay and compaction was carried out at moisture conditions similar to those on Scheme No. 9. Based on 1801 measurements, the average relative compaction achieved was 101 per cent with a standard deviation of 2.9 per cent, at an average moisture content equal to the optimum moisture content in the BS Compaction test, 2.5 kg (5.5 lb) rammer method; these values are in close agreement with those found on Scheme No. 9. On the experimental road at Makuyu[32] the average relative compaction achieved on the cement-stabilized gravel-sand-clay was only 1 per cent different from that found on Scheme No. 8. The states of compaction achieved on the friable red clay soils stabilized with cement, lime or analine furfural dye were similar to those obtained on similar soil at Scheme No. 9 where moisture conditions at the time of compaction would probably be similar. The differences in the response to compaction of the gravel-sand-clay and the friable red clay soil at Makuyu stress the possibility, though not the inevitability, that a lapse of time between mixing and compaction will affect the dry density that can be achieved.

At the road embankment at Embakasi[33] the soil used was a heavy black clay (black cotton soil). Although such soils occur widely in tropical and sub-tropical areas none had been encountered on the sections of road examined in the present investigation. Compaction of the heavy clay was undertaken by the earthmoving equipment supplemented by a 50 Mg (50 ton) pneumatic-tyred roller similar to that used on Schemes Nos 1 and 7. These heavy black clays have similar characteristics to the heavy clay soil studied in the full-scale compaction plant trials at the Transport and Road Research Laboratory. The average relative compaction, based on 203 determinations, was 103 per cent, with a standard deviation of 4.6 per cent, at moisture contents usually ranging from the optimum moisture content in the BS Compaction test, 2.5 kg (5.5 lb) rammer method to 5 per cent lower than that value. The average relative compaction value is in close agreement with that which would be expected from the data obtained in the full-scale compaction plant trials assuming that the soil received 4 to 8 passes of the compaction equipment. The varying proportions of decomposing rock in the soil would explain the somewhat higher than usual standard deviation.

9.4 Comparison with construction schemes in Great Britain, the U.S.A. and Brazil

Data on the states of compaction achieved on embankments on six motorway construction schemes in Great Britain[34] are given in Table 15. Table 16 summarizes data on the states of compaction obtained in various pavement layers on two test roads in the U.S.A.[35,36] where the levels of compaction specified were chosen to be typical of those being achieved on normal road-building works.

Data on the states of compaction achieved and the moisture contents at six earth dams constructed in Brazil of friable red clay soils derived from gneiss, basalt and sandstone are summarized in Table 17[37]. Relative compaction values of 95 per cent were specified at moisture contents ranging from the BS optimum value to 2 per cent less than that value.

The levels of compaction obtained and the trends in these data are similar to those found on road construction schemes in East Africa in the present investigation. Higher values of relative compaction were obtained on the more granular materials and, where moisture conditions are controlled, there is no difference in the states of compaction that can be achieved in tropical and temperate regions. Thus experience and techniques learned in one area can, when modified in the light of the different environments, be applicable in another.

10. DISCUSSION OF RESULTS

The most important point emerging from the investigation is that the states of compaction achieved in the field correspond quite closely to those obtained in the full-scale compaction plant trials carried out at the Transport and Road Research Laboratory. The field tests covered many types of compaction plant in common use and two of the soils had counterparts in the soils used in the Laboratory full-scale compaction plant trials. Expressed in terms of relative compaction, the results obtained in the field on occasion equalled or exceeded those obtained in the Laboratory trials; more usually they were a few per cent lower.

Although the friable red clays which predominated at the schemes examined had no counterpart among the soils used in the Laboratory trials, the indications are that the maximum relative compaction that can be obtained would be within 2 per cent of that obtained in the Laboratory full-scale trials on the gravel-sand-clay soil. There is thus confirmation of the value of laboratory full-scale trials as a guide to selecting the most suitable plant and assessing the state of compaction that can be attained in the field.

The data from these and other field measurements and the Laboratory full-scale trials show that the performance of smooth-wheeled rollers is affected by the density of the underlying soil layers. This would be particularly important where the state of compaction to be achieved is determined by site compaction trials. Little attention appears to have been given to standardizing the conditions for carrying out site trials, but, with steel-tyred rollers, the results obtained could very much depend on the conditions obtaining in the underlying soil layers.

The relation between compactive effort, moisture content and dry density is now well-established and the data obtained in the present investigation follow generally accepted patterns. Maximum dry density and optimum moisture content are functions of both the applied stresses and the number of applications of these stresses. Thus, increasing the stress – by increasing the contact pressures, or reducing the thickness of the layer being compacted – and/or increasing the number of repetitions of loading, will generally result in increase in the maximum dry density attained, and correspondingly reduce the optimum moisture content. Conditions are more complicated in poorly-graded non-cohesive soils, such as the uniform sand at Scheme No. 6, where overstressing occurred. With these soils, low contact pressures are beneficial and maximum dry density is obtained when the difference between the compacting stresses and the bearing capacity of the soil is minimised.

When the results of compaction plant trials are assessed, it is common to concentrate on the maximum state of compaction obtained for a given effort. However, it must be remembered that this maximum value is only attained at a unique value of the moisture content, i.e., the optimum moisture content for the soil and compactive effort used. Variations from this moisture content lead to reductions in the dry density that can be obtained. It would be unrealistic to expect the road builder to reproduce the optimum moisture condition precisely and repeatedly. Thus working tolerances on moisture content in the field must be considered when assessing the states of compaction that can be consistently attained or exceeded by compaction plant under normal working conditions.

At the schemes examined in the present investigation, moisture control was mainly confined to stabilized road bases. The maximum variation in moisture conditions was found on Scheme No. 4 where the values ranged from 1 to 4 per cent lower than the optimum moisture content in the B.S. Compaction test 2.5 kg (5.5 lb) rammer method; more usually the results on lime-stabilized materials varied from 1 to 3 per cent lower than that value. On Scheme No. 8 with cement-stabilized gravel, the moisture content at compaction varied from the optimum in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method to 2 per cent below that value. Of the 31 measurements made, only three values fell outside the range bounded by the optimum moisture content values in the B.S. Compaction tests, 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods; even these exceptions were only 1 per cent less than the optimum moisture content of the heavier compaction test. This indicates that moisture content control during stabilized-base construction can, in most cases, confine fluctuations in moisture conditions on any scheme to 2 per cent moisture content, and that 3 per cent would cover all the schemes examined.

Control of moisture conditions in earthworks and subgrades would not be expected to be as strict as on base construction. Scheme No. 6 was the only scheme in these investigations where the moisture content of fill materials was adjusted; here moisture conditions ranged from 1 to 5 per cent lower than the optimum moisture content in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method, with most of the results not more than 3 per cent lower.

Current specifications[18] often specify that moisture content variations should not exceed 3 or 4 per cent and the results obtained show that these values are realistic under normal working conditions in the tropics and that even closer tolerances might be practicable on stabilized-base materials.

On road-building schemes the number of passes of the compaction equipment used in the compaction process is usually much lower than the number used to achieve 'compaction to refusal' in the Laboratory full-scale plant trials. Consequently the optimum moisture contents for plant operation in the field are higher. Fig. 16 shows that increasing the number of passes of a smooth-wheeled roller from 4 to 8 and then to 16 reduced the optimum moisture content by 1 per cent on each occasion. This has the effect of narrowing the gap between the optimum moisture content for plant operation and the optimum moisture content of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

The optimum moisture content of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method thus provides a useful guide to the most effective moisture conditions for operating compaction plant in the field.

The data collected in the present investigation enable the states of compaction that can be obtained under normal working conditions on road-building schemes in tropical areas to be indicated. Table 18 summarizes the levels of relative compaction that can be consistently attained with and without control of moisture conditions during the compaction process. The Figures given have been based on a reasonable number of passes by the compaction plant: 4 to 8 passes by pneumatic-tyred plant and smooth-wheeled rollers on earthworks and about 16 passes of the smooth-wheeled rollers in the compaction of stabilized bases.

Comparison of these values with the compaction requirements of the AASHO Guide Specification for Highway Construction[18] which are also summarized in Table 18, shows that the moisture conditions and layer thicknesses used during compaction would need to be controlled to realise those compaction requirements. It is worthwhile noting that the maximum dry density of cement-stabilized soil obtained in accordance with B.S. 1924:1967[12] did not provide a value close to that obtained in the field. This is to be expected since the test method makes no allowance for the effect of a lapse of time between mixing and compaction. Compaction tests for cement-stabilized materials, such as AASHO Designation T134[18] or that in the Soil-cement construction handbook[15] make some allowances for this effect. Specifications using these tests at present provide the best means of prescribing the state of compaction in cement-stabilized materials.

The state of compaction attained in the field is generally assessed by comparison with the maximum dry density found in standard laboratory compaction tests, the most commonly used being the B.S. Compaction tests, 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods, and their American equivalents (see Section 5). An objection to the use of laboratory compaction tests is that they do not indicate the maximum dry density or the optimum moisture content for plant operating in the field. But the states of compaction that can be achieved on many types of soil by the heavier types of modern compaction equipment bear a reasonably constant relation to the maximum dry densities obtained in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (Table 19). Lighter pieces of compaction plant often cannot effectively compact some types of soil, e.g., light vibrating rollers perform poorly on heavy clay soils and sheepsfoot rollers are ineffective on gravel-sand-clay soils; this emphasizes the greater versatility of the heavier compaction plant.

For granular materials with negligible cohesion relative compactions of 110 per cent of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method would be unattainable. These materials are characterized by small differences, of the order of 32 to 64 kg/m^3 (2 to 4 lb/ft^3), between the maximum dry densities obtained in the B.S. Compaction tests, 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods.

Both compaction tests obviously have their place depending on soil type but are even more useful when used together. Thus, for the data in Table 19 the maximum compaction achieved within ± 3 per cent is given by the expression:

Maximum relative compaction is:

EITHER 112 per cent of the maximum dry density in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method

OR 104 per cent of the maximum dry density in the B.S. Compaction test, 4.5 kg (10 lb) rammer method

whichever gives the lower dry density in Mg/m^3 (lb/ft^3).

The difference between the maximum dry density values in the B.S. Compaction tests, 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods gives an indication of the facility with which a soil may be compacted and, by inference, an indication of the susceptibility of soils to subsequent compaction under traffic. On soils where this difference is less than 80 kg/m^3 (5 lb/ft^3), e.g., the uniform sands at Scheme No. 6, it would be prudent to require that they should be compacted to 100 per cent of the maximum dry density in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method, even in subgrades.

The road designer desires to minimize total transport costs, i.e., the costs of road construction and maintenance and of operating vehicles over the road. To do this, he needs to know among other things the cost of compacting materials to different degress, the effect of different states of compaction on the cost of maintenance, the impact on transport costs of differences in riding quality and the costs of delays to traffic resulting from maintenance operations. The complexity of the problem is evident but there is general agreement on the benefits stemming from specifying high states of compaction in the pavement layers and the top layer of the subgrade. This is justified because the cost of compacting these layers rarely exceeds 15 per cent of their cost and is usually much less. On the other hand, the cost of renewing the riding surface, an inevitable consequence of lack of compaction in the upper road layers, would be at the very least three to four times the compaction costs. As some compaction will be needed in any event, if only to provide smooth surfaces on which to lay succeeding pavement layers, the economic arguments for controlled compaction are overwhelming.

At greater depths practice varies, some authorities requiring that all embankment layers be well-compacted while others do not. This is not altogether unexpected because settlement in layers more than 0.6 m (2 ft) below the road surface is less likely to cause significant differential movements of the road surface. It is also likely that the prevailing soil and moisture regimen in road subgrades affects the amount of differential movement that occurs. Thus, in temperate climates, with water-tables close to the surface and plastic soils, compaction would increase the strength and reduce settlement, but in tropical areas, where moisture conditions under pavements are governed by climate, the soil strength will generally be higher and the state of compaction is less critical. This is an aspect of road design meriting further research, especially in arid climates where the cost of compaction might well be 15 to 20 per cent of the cost of embankment construction.

Another economic aspect of the compaction process is the attainment of the correct balance between the compactive effort and the amount of water required to moisturize the soil to a condition suitable for compaction. Where layer thickness is not specified it is often possible to substitute compactive effort for moisture. However, it must be remembered that water is essential to the construction of the base and sub-base, and, in many instances, the major cost of supplying water will be the initial capital cost, e.g., well-boring, and subsequent supply costs will be small. An example of the inter-dependence of compactive effort and moisture conditions is shown by the data from Schemes Nos 9 and 10 (see Fig. 17). There a relative compaction of 94 per cent was achieved using either 4 passes of the smooth-wheeled roller on 23 cm (9 in) loose layers at a high moisture content or by 8 passes of the roller on 15 cm (6 in) loose layers at a moisture content some 6 per cent lower. In that instance, therefore, 89 l/m^3 (15 gal/yd^3) of water could be replaced by a threefold increase in compactive effort or vice-versa. Further research to explore more fully the dry density-moisture content relations of compaction plant operating at few numbers of passes and over a range of loose layer thicknesses would provide the data needed to formulate more economical compaction techniques, especially for areas where water supply is difficult and costly. In such a series of trials the effect of the density of the supporting layers on the stresses induced by steel-tyred rollers could also be usefully studied.

Finally, there are deficiencies in the present data because of the limited range of soils and types of pavement being used on the schemes investigated. The performance of vibrating rollers *vis-à-vis* smooth-wheeled and pneumatic-tyred rollers could not be studied on materials where significant differences were likely to emerge. Compaction of crushed stone and other granular bases and heavy clays was not examined. Additional information on these aspects of the compaction process as used on normal road-building schemes would be useful. However, the need is not pressing in view of the close similarity between the results of laboratory full-scale compaction plant trials and normal field compaction processes as shown by the present investigation, and there are no grounds for believing that the picture would be altered on these other roadmaking materials.

11. THE SPECIFICATION AND CONTROL OF COMPACTION

The state of compaction that can be achieved is in general governed by four factors:

(i) the moisture condition of the material being compacted;

(ii) the thickness of the layer being compacted;

(iii) the pressure applied by the compaction plant; and

(iv) the number of applications of the compaction plant to the layer of material.

Of these, (i) is the most important, but alteration of the other three can, within limits, extend the range of moisture conditions in which the material can be compacted satisfactorily.

11.1 Types of specification

Nowadays an 'end-product specification' is usual on large road-building schemes overseas but the older 'method specification' is still used and has much to recommend it on small jobs and those carried out by direct labour. Both types of specification have advantages and disadvantages but it is noteworthy that a method type of specification was reintroduced in 1969 in the United Kingdom for compaction in roadworks.[38]

A method specification requires control of the four factors mentioned above and the continual presence of a supervisor. When dead-weight rollers are specified the checking of (iii) is simplified but with mechanically-activated machines, e.g., vibrating rollers, it is essential that their mechanical condition is checked regularly and that the activators are operating continually during compaction. The quantity of water required to bring soils to the correct moisture condition for compaction can be a frequent source of disagreement on road-building schemes in tropical areas, where water is often scarce; the inclusion of water as a separate pay item in the bill of quantities, a common practice in the United States of America,[18] has much to recommend it. In areas where supplying water is costly, it might be worthwhile considering schemes which apportion the capital costs of developing a water supply to the basic water requirements of the area including the road construction scheme.

With an 'end-product specification' the choice of compaction plant and techniques is solely the contractor's responsibility and the quality of his work is assessed on the results of dry density and moisture content determinations in the field compared with either laboratory compaction tests or full-scale field trials. The relative compaction method[2] is almost invariably used and here the state of compaction achieved in the field is compared with the maximum dry density found on identical samples in a standard laboratory compaction test. A major difficulty is in ensuring that the field measurements and the laboratory compaction tests are carried out on identical samples. The practice of using material from the density holes will go a long way to eliminate discrepancies from this source.

The present investigation has shown that widely-varying results can be obtained in full-scale compaction plant trials, a not-unexpected result when one considers how closely the conditions of testing for the laboratory compaction tests must be controlled. When the standard of compaction required is to be based on compaction plant trials, it is essential that the conditions of test and the sequence of operations be clearly defined in the specification; otherwise the less able contractor may by his own shortcomings, set himself lower standards to which his work must conform than his more experienced competitors.

11.2 Measurement of dry density and moisture content

The sand replacement method[10] is the most widely used testing method for measuring dry density in the field. Individual density results are normally distributed about the average value owing to minor variations in soil properties and in the testing techniques. To obtain an average value accurate to ± 2 per cent for a probability of 9 chances in 10 requires at least 6 to 10 careful determinations. In the present investigation it was found helpful to estimate the standard deviation of a group of results from the range of wet density values. The limits of accuracy of the mean value could then be estimated from this. The methods employed are summarized in Appendix 1.

Average values of relative compaction are normally quoted but specifications are often not clear in stating whether the required value is a minimum value or an average value. With measurements which show wide variations in individual values the minimum value type of specification is often preferred, e.g., for the crushing strength of concrete.[39] With minimum value specifications, the allowable percentage of values falling below the minimum is often stated and this practice has much to recommend it. A requirement that 9 out of every 10 consecutive values of relative compaction measured in the field should exceed or not exceed, respectively, a given value would be unambiguous of interpretation.[40] It must be remembered when using this method of specification that the value of relative compaction specified should be lower than the average values. Tables 2, 3, 4 and 5 record the relative compaction values equalled or exceeded by 9 out of every 10 dry density determinations. On the basis of these data and the likelihood that routine site testing is often more variable,[34] it is considered that the value of relative compaction to be exceeded in 9 out of every 10 consecutive determinations should be set some 5 per cent below the average values given in Table 18.

Sampling points for dry density and moisture content are often located at fixed intervals. Such an arrangement, though administratively simple, can result in an optimistic picture being obtained, since the road builder, who is only human, will pay particular attention to these locations. Random location of sampling points would eliminate such bias but the engineer should still be watchful for areas which appear to be poorly compacted. When the relative compaction method of assessing compaction is used, greater uniformity in the soil being sampled would be achieved by confining the 6 to 10 density holes needed for a reliable estimation of the state of compaction to a small area; on the present investigation a 7.6 m by 1.2 m (25 ft by 4 ft) area was often used. For random testing, the road, or lengths of it, would be divided into areas of about this size and numbered systematically. One or more of these areas, depending on the staff available, would be chosen for test from each day's work, using a set of random numbers[41] or by drawing lots.

11.3 General

Recent experience in the United Kingdom suggests that the method specification adopted in 1969 is more workable and is producing earthworks and bases compacted to the same degree as the end point specification it replaced. In the United Kingdom moisture control is only considered necessary for bases but it is likely that some modification of that specification would be needed in the drier areas of the tropics for granular soils. Given reliable site supervision and payment for added water there would seem to be no major objection to using a method specification in the tropics.

The previous remarks have been directed mainly at the road designer and resident engineer. The contractors on the job must find a working method to obtain the specified level of compaction. In the initial stages of the contract he must develop a technique which will enable him to compact the various layers in accordance with these requirements. Consistent and unremitting moisture control is the crux of the matter and experienced staff in the foreman and supervisory grades are essential. It is worth noting that more consistent results are obtained when moisture contents are close to the values in the B.S. Compaction tests, 2.5 kg and 4.5 kg (5.5 lb and 10 lb) rammer methods.

12. CONCLUSIONS

1. The states of compaction achieved in normal field practice in East Africa corresponded quite closely with those found in the full-scale compaction plant trials carried out over a range of moisture contents and under carefully controlled conditions at the Transport and Road Research Laboratory.

2. The relations between the magnitude and number of repetitions of the compaction stresses and the dry density and moisture content followed the generally accepted patterns.

3. Overstressing was observed on a uniformly-graded non-plastic sand soil.

4. The optimum moisture condition for compaction in the field was close to the optimum moisture content in the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method, varying by 2 per cent around that figure depending on the compaction pressures induced and the number of passes of the compaction plant.

5. Simple and rapid methods of appraising soil moisture conditions maintained the moisture content of the materials being compacted within a range of 3 per cent on stabilized-soil bases and generally within 4 per cent on earthworks.

6. The states of compaction that can be reasonably attained under normal working conditions in the field would comply with commonly-specified values.

7. Given reliable site supervision and payment for added water there would seem to be no major difficulty in using a method specification for compaction in the tropics.

8. The results obtained in this investigation indicate that the most fruitful lines for further research would be (a) to consider the economic implications of compaction of earthworks to different states of compaction, and (b) to examine the compaction techniques that would secure a more economical balance between the effort involved and the moisture required.

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15. APPENDIX 1

ESTIMATION OF STANDARD DEVIATION AND LIMITS OF ERROR OF MEAN VALUE

15.1 Standard deviation

The standard deviation of a series of samples can be estimated from the mean sample range*. The mean sample range is obtained by segregating the samples into groups with the same number of samples in each group and calculating the range for each group and then calculating the mean value of the range.

By dividing the mean sample range by a factor which depends on the number of samples in the groups, an estimate of the standard deviation is obtained, viz:

$$\text{Estimate of Standard Deviation} = \frac{\text{Mean sample range}}{\text{d}}$$

where the values of d are given in Table 20.

A series of samples for dry density and moisture content determination normally would comprise 6 to 10 measurements and the range of the results of these is then substituted for the mean sample range. In the present investigation the estimates of standard deviation obtained on the wet density values and made at the conclusion of the field sampling provided a reliable indication of the standard deviation of the dry density values.

15.2 Limits of error of mean value

The mean value of a number of samples provides an estimate of the true mean value of the property being studied. The limits within which the true mean value may be expected to lie for any degree of certainty can be calculated from the standard deviation and the number of samples**. Table 21 gives the values of 'a', the factor by which the standard deviation should be multiplied to ascertain the limits within which the true mean may be expected to lie with a probability of 9 chances in 10, 19 chances in 20 and 99 chances in 100. A usual requirement is that the mean value of a set of measurements of dry density should be accurate to ± 2 per cent for a probability of 9 chances in 10.

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TABLE 1

Details of road construction schemes investigated

Scheme number	Location	Number of sections sampled				Date of sampling
		Normal compaction processes		Controlled compaction trials		
		Natural soil	Stabilized soil	Natural soil	Stabilized soil	
1	Mau-Summit, Kericho Road, Kenya.	–	–	24	–	July, 1960
2	Iringa, Morogoro Road, Tanganyika*.	–	2	–	12	Aug., 1960 and May, 1960
3	Mombo, Korogwe Road, Tanganyika*.	3	–	–	–	Sept., 1960
4	Masaka, Mbarara Road, Uganda.	10	9	–	1	Nov. and Dec., 1960
5	Kumi, Soroti Road, Uganda.	3	2	–	–	Jan., 1961
6	South Coast Road, Mombasa, Kenya.	5	–	10	–	Feb., 1961
7	Embu-Meru Road, Kenya.	2	–	6	–	March, 1961
8	Bennetts Ridge Road, Ruiru, Kenya.	–	5	–	–	July – Aug., 1961
9	Kisii-Kisumu Road, Kenya.	4	–	12	–	July, 1961
10	Nairobi-Thika Road, Kenya.	–	–	15	–	Aug., 1961

* Now Tanzania.

TABLE 2

Details of the state of compaction obtained on natural soils by normal construction methods

Scheme No.	Ref. No.	Details of the compaction plant and methods used	Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5kg(5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. compaction tests (per cent)		Casagrande classification
			Mg/m^3	(lb/ft^3)	$\pm Mg/m^3$	$(\pm lb/ft^3)$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	5.6kg(10lb) rammer method	
3	3.1	10-Mg (10 ton) pneumatic-tyred roller and traffic	1.53	99.5	0.034	2.1	93	84	89	14	22	18	CI
	3.2	–ditto–	1.54	96.4	0.022	1.4	94	85	91	16	21	17	CI
	3.3	–ditto–	1.48	92.3	0.014	0.9	88	80	86	16	21	17	CI
4	4.1	Construction plant including heavy tracked tractors and towed scrapers	1.76	110.0	0.030	1.9	99	91	97	16	17	13	CH
	4.2	–ditto–	1.69	105.7	0.037	2.3	96	88	91	13	17	13	CH
	4.3	–ditto–	1.68	105.3	0.042	2.6	87	79	83	7	12	8	CL
	4.4	–ditto–	1.73	108.4	0.027	1.7	94	87	92	10	14	11	CI
	4.5	–ditto–	1.71	106.8	0.030	1.9	94	85	92	16	16	12	CI
	4.6	–ditto–	1.68	105.1	0.035	2.2	88	79	84	9	12	8	CL
	4.7	3.75 Mg (3¾ ton) towed vibrating roller and construction plant	1.68	105.3	0.037	2.3	94	86	91	12	14	11	CI
	4.8	–ditto–	1.71	107.1	0.027	1.7	91	82	88	9	13	9	CL
	4.9	–ditto–	1.60	100.3	0.018	1.1	93	85	92	11	18	14	CH
	4.10	–ditto–	1.78	111.1	0.043	2.7	95	86	91	8	13	9	CL
5	5.1	Construction plant & 8-10Mg (8-10 ton) smooth-wheeled rollers	1.80	112.4	0.042	2.6	95	85	94	10	13	9	CL
	5.2	Construction plant including motorized scrapers and bulldozers	1.51	94.6	0.021	1.3	82	73	81	8	14	10	CL
	5.3	Construction plant including motorized scrapers	1.84	115.3	0.054	3.4	95	85	89	7	10	7	CL
6	6.1	8 Mg (8 ton) pneumatic-tyred, 3 Mg (3 ton) vibrating and 8-10Mg(8-10 ton) smooth-wheeled rollers	1.70	106.1	0.029	1.8	100	91	97	17	19	15	CI
	6.2	–ditto–	1.90	118.9	0.019	1.2	97	91	96	10	11	9	CL
	6.3	16 passes 8 Mg (8 ton) pneumatic-tyred, 5 passes 3 Mg (3 ton) vibrating and 2 passes 8-10 Mg (8-10 ton) smooth-wheeled rollers	1.80	112.8	0.016	1.0	101	99	99	9	12	11	SU
	6.4	6 passes 8 Mg (8 ton) pneumatic-tyred, 2 passes 3Mg (3 ton) vibrating and 6 passes 8-10 Mg (8-10 ton) smooth-wheeled rollers	1.86	116.2	0.030	1.9	103	101	100	8	11	10	SU
	6.5	Construction plant, 3 Mg (3 ton) vibrating and 8-10Mg (8-10 ton) smooth-wheeled rollers	1.83	114.3	0.021	1.3	102	100	100	9	11	11	SU

Table 2 (continued)

Scheme No.	Ref. No.	Details of the compaction plant and methods used	Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5 kg(5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. compaction tests (per cent)		Casagrande classification
			Mg/m^3	(lb/ft^3)	$\pm Mg/m^3$	$(\pm lb/ft^3)$	2.5kg(5.5lb) rammer method	4.5kg(10 lb) rammer method			2.5kg(5.5 lb) rammer method	5.6kg(10 lb) rammer method	
7	7.1	Construction plant including scrapers	1.24	77.8	0.016	1.0	90	81	88	21	32	27	MH
	7.2	–ditto–	1.69	105.7	0.034	2.1	97	90	93	13	20	16	GC
9	9.1	Motorized and towed scrapers and lorries	1.39	86.9	0.014	6.9	99	86	96	30	30	23	MH
	9.2	–ditto–	1.35	84.2	0.075	4.7	97	85	–	32	32	25	MH
	9.3	–ditto–	1.36	85.3	0.021	1.3	98	86	96	32	31	24	MH
	9.4	–ditto–	1.53	95.4	0.029	1.8	88	88	95	28	24	19	CH

TABLE 3

Details of the state of compaction obtained on stabilized bases† by normal construction methods

Scheme No.	Stabilizing agent	Ref. No.	Details of the compaction plant and methods used	Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5kg (5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. compaction tests (per cent)	
				Mg/m^3	(lb/ft^3)	$\pm Mg/m^3$	$(\pm lb/ft^3)$	2.5kg(5.5 lb) rammer method	4.5kg (10 lb) rammer method			2.5kg (5.5 lb) rammer method	4.5kg (10 lb) rammer method
2	Hydrated lime	2.1	10 Mg (10 ton) pneumatic-tyred and 8 Mg (8 ton) smooth-wheeled rollers	1.88*	117.3*	0.04	2.5	100	95	97	11	13	11
		2.2	10 Mg (10 ton) pneumatic-tyred and 5 or 6 passes 7 Ng (8 ton) smooth-wheeled rollers	1.95*	122.0*	0.02	1.5	97	91	94	8	10	8
4	Hydrated lime	4.11	11 passes 5 Mg (5 ton) sheepsfoot, 17 passes 10 Mg (10 ton) pneumatic-tyred, 25 passes 3.75 Mg (3¾ ton) vibrating and 60 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	1.94	121.3	0.04	2.2	100	91	98	12	14	12
		4.12	10 passes 5 Mg (5 ton) sheepsfoot, 47 passes 10 Mg (10 ton) pneumatic-tyred and 39 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	2.16	135.2	0.04	2.6	105	97	101	10	13	10
		4.13	–ditto–	2.16	135.0	0.05	3.4	106	97	101	11	13	10
		4.14	20 passes 5 Mg (5 ton) sheepsfoot, 36 passes 10 Mg (10 ton) pneumatic-tyred and 31 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	2.05	127.9	0.02	1.4	101	92	100	10	13	10
		4.15	14 passes 5 Mg (5 ton) sheepsfoot, 19 passes 10 Mg (10 ton) pneumatic-tyred and 70 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	2.08	129.9	0.02	1.1	106	98	104	11	15	12
		4.16	15 passes 10 Mg (10 ton) pneumatic-tyred and 55 passes 8012 Mg (8-12 ton) smooth-wheeled rollers	2.04	127.6	0.02	1.2	104	96	101	11	15	12
		4.17	16 passes 5 Mg (5 ton) sheepsfoot, 9 passes 10 Mg (10 ton) pneumatic-tyred and 48 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	2.11	132.0	0.03	1.7	104	95	101	11	13	10
		4.18	12 passes 10 Mg (10 ton) pneumatic-tyred and 53 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	1.97	123.4	0.03	2.1	99	91	95	13	14	11
		4.19	9 passes 5 Mg (5 ton) sheepsfoot, 12 passes 10 Mg (10 ton) pneumatic-tyred and 53 passes 8-12 Mg (8-12 ton) smooth-wheeled rollers	2.08	130.0	0.03	1.7	104	96	101	13	14	11

† All the base materials were gravel-sand-clay soils, casegrande classification GC
* 10 cm (4 in) deep density holes.

Table 3 (continued)

Scheme No.	Stabilizing agent	Ref. No.	Details of the compaction plant and methods used	Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5kg (5.5lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. Compaction tests (per cent)	
				Mg/m^3	(lb/ft^3)	$\pm Mg/m^3$	$(\pm lb/ft^3)$	2.5kg(5.5 lb) rammer method	4.5kg(10 lb) rammer method			2.5kg (5.5 lb) rammer method	4.5 kg (10 lb) rammer method
5	Hydrated lime	5.4	26 passes 3 Mg (3 ton) towed vibrating and 33 passes 8-10 Mg (8-10 ton) smooth-wheeled rollers	1.90	118.6	0.01	0.9	100	92	98	10	13	9
		5.5	29 passes 3 Mg (3 ton) towed vibrating and 22 passes 8-10 Mg (8-10 ton) smooth-wheeled rollers	1.88	117.6	0.02	1.2	101	93	99	10	14	10
8	Cement	8.1	5 passes 12-14 Mg (12-14 ton) smooth-wheeled roller within 30 min of mixing.	1.72	107.3*	0.02	1.5	93	87	90	15	15	12
		8.2	–ditto–	1.71	106.9*	0.03	1.8	92	87	89	15	15	12
		8.3	–ditto–	1.76	110.3*	0.02	1.4	95	90	93	15	17	12
		8.4	9 passes 12-14 Mg (12-14 ton) smooth-wheeled roller within 30 min of mixing	1.55	96.8*	0.02	1.4	89	83	88	18	20	17
		8.5	–ditto–	1.59	99.5*	0.02	1.0	92	86	91	20	20	17

* 10 cm (4 in) deep density holes.

TABLE 4

Details of the state of compaction obtained on natural soils during compaction plant trials

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thickness		Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5kg (5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. Compaction tests (per cent)		Casagrande classification
							cm	in	Mg/m^3	lb/ft^3	$\pm Mg/m^3$	$\pm lb/ft^3$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method	
1	4-wheeled towed pneumatic-tyred roller (ballasted to ½ max capacity)	Average tyre inflation pressure $45 N/cm^2$ Average wheel load 7Mg(7ton)	2.4 m (8ft)	3.2-6.4 km/h (2-4 mile/h)	1.1	8	25-30	10-12	1.28	79.7	0.037	2.3	89	77	84	25	30	22	MI
					1.2	4	25-38	10-15	1.38	83.1	0.027	1.7	87	77	86	19	25	19	CI
					1.3	4	23	9	1.38	86.0	0.030	1.9	88	78	84	21	25	19	CI
					1.4	4	43	17	1.27	79.2	0.016	1.0	85	74	84	19	27	19	MI
					1.5	8	43	17	1.26	78.9	0.018	1.1	87	75	85	18	27	19	MI
					1.6	8	23	9	1.34	84.0	0.072	4.5	92	80	–	23	29	21	MI
					1.7	4	15*	6*	1.22	76.5	0.026	1.6	90	77	87	28	30	22	MH
					1.8	4	15*	6*	1.26	78.5	0.026	1.6	90	78	86	29	30	22	MH
					1.9	6	16	16	1.22	76.3	0.019	1.2	93	80	91	32	34	25	MH
					1.10	8	23	9	1.24	77.8	0.011	0.7	89	77	88	27	30	22	MH
					1.11	4	15*	6*	1.23	76.9	0.018	1.1	86	75	84	25	29	21	MH
					1.12	4	30	12	1.21	75.7	0.051	3.2	84	73	80	23	30	22	MH
					1.13	4	23	9	1.28	80.3	0.032	2.0	86	75	83	21	27	19	MI
					1.14	4	15*	6*	1.27	79.2	0.019	1.2	87	75	85	20	29	21	MI
	Self-propelled pneumatic-tyred $13.8 m^3$ ($18 yd^3$) scrapers	Average tyre inflation pressure $34 N/cm^2$ ($50 lb/in^2$) Approx. wheel load 9Mg(9ton)	1.1m (3 ft 6 in)	Up to 6.4km/h (4mile/h)	1.15	6†	23	9	1.25	78.4	0.029	1.8	87	75	83	24	30	22	MH
					1.16	4†	25	10	1.25	77.9	0.027	1.7	87	75	84	22	30	22	MI
					1.17	4†	25	10	1.19	74.6	0.016	1.0	88	75	85	25	31	24	MH
					1.18	2†	30	12	1.27	79.1	0.016	1.0	85	75	84	24	26	20	CI
					1.19	2†	15*	6*	1.32	82.3	0.010	0.6	89	78	87	24	26	20	CI
	5Mg(5 ton) towed sheepsfoot roller	Foot pressure $241 N/cm^2$ $350 lb/in^2$	2.4m (8ft)	6.4-9.7 km/h (4-6 mile/h)	1.20**	10	23-30	9-12	1.15	71.9	0.035	2.2	88	75	–	30	36	25	MH
					1.21	16	28-30	11-12	1.09	68.0	0.021	1.3	83	72	81	24	33	25	MH
					1.22	8	28	11	1.19	74.6	0.018	1.1	86	74	83	30	32	24	MH

* 10 cm (4 in) density holes on 15 cm (6 in) layers

† Since the wheels on a scraper are in line longitudinally, 1 pass scraper = 2 passes normal pneumatic-tyred roller

** Two initial passes given by 3 Mg (3 ton) vibrating roller without vibration.

TABLE 4 (continued)

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thickness		Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry density in 2.5kg (5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture contents in B.S. Compaction tests (per cent)		Casagrande classification
							cm	in	Mg/m^3	lb/ft^3	$\pm Mg/m^3$	$\pm lb/ft^3$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method	
1 Contd	10Mg (10 ton) grid roller (modified smooth-wheeled roller with 120mm(4¾ in) square openings in 19mm x 76mm (¾in x 3in) deep sheet steel grid)	Load per cm(in) width: rear rolls 66.1 kg (370 lb) front roll 37.5 kg (210 lb)	1.8m (5 ft 10 in)	3.2-4.8 km/h (2-3 mile/h)	1.23	4	15*	6*	1.24	77.4	0.013	0.8	88	76	87	30	31	23	MH
					1.24	4	23	9	1.24	77.4	0.006	0.4	87	75	86	29	30	22	MH
6	13 Mg (13 ton) towed pneumatic-tyred roller	Average tyre inflation pressure 21N/cm^2(30lb/in^2). Average wheel load 0.7 Mg(0.7 tons)	2.1m (7ft)	4km/h (2½ mile/h)	6.6	4	23	9	1.70	106.5	0.018	1.1	97	95	95	9	11	10	SU
					6.7	8	23	9	1.77	110.4	110.4	0.8	100	99	99	8	12	11	SU
	8-10Mg (8-10 ton) smooth-wheeled roller	Load per cm(in) width: rear rolls 57.1kg (320 lb) front roll 30.4kg (170 lb)	1.7m (5ft 8 in)	4km/h (2½ mile/h)	6.8	4**	23	9	1.65	103.3	0.021	1.3	95	91	92	8	11	10	SU
					6.9	8**	23	9	1.67	104.5	0.016	1.0	96	92	95	8	11	10	SU

* 10 cm (4 in) density holes on 15 cm (6 in) layers

** Two initial passes given by 3 Mg (3 ton) vibrating roller without vibration

TABLE 4 (continued)

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thickness		Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max dry density in 2.5kg (5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture content in B.S. Compaction tests (per cent)		Casagrande classification
							cm	in	Mg/m^3	lb/ft^3	$\pm Mg/m^3$	$\pm lb/ft^3$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method	
6 (contd)	3Mg (3 ton) towed vibrating roller	Load: 21.4 kg per cm width (120lb/in) vibrator shaft speed 1000 rev/min.	1.4m (4ft 9 in)	2.4km/h (1½ mile/h)	6.10	4**	23	9	1.74	108.5	0.034	2.1	98	96	95	6	11	11	SU
					6.11	8**	23	9	1.79	111.7	0.016	1.0	99	97	97	9	12	10	SU
					6.12	4**	23	9	1.77	110.8	0.019	1.2	99	97	97	9	12	11	SU
					6.13	8**	23	9	1.81	113.0	0.011	0.7	102	100	101	10	11	11	SU
	39kW(52hp) tracked tractor	Contact pressure: $4.8N/cm^2$ $(7lb/in^2)$	0.8m (2ft 6 in)	6.4km/h (4 mile/h)	6.14	4	23	9	1.70	106.4	0.027	1.7	95	93	93	9	11	11	SU
					6.15	8	23	9	1.78	111.5	0.026	1.6	99	97	97	10	12	10	SU
7	4-wheeled towed pneumatic-tyred roller (ballasted to ½ max. capacity.)	Average tyre inflation pressure $41N/cm^2$ $(60 lb/in^2)$ average wheel load 7 Mg (7 tons)	2.4m (8ft)	4.8km/h (3 mile/h)	7.3	4	23	9	1.20	75.0	0.010	0.6	88	79	87	11	32	27	CH
	4-wheeled towed pneumatic tyred roller (fully ballasted)	Average tyre inflation pressure $55N/cm^2$) average wheel load 12Mg (12 tons)	2.4m (8ft)	4.8km/h (3 mile/h)	7.4	4	23	9	1.20	75.0	0.010	0.6	89	80	88	21	33	28	CH
					7.5	4	23	9	1.19	74.6	0.019	1.2	88	79	84	22	32	27	CH

** Two initial passes given by 3 Mg (3 ton) vibrating roller without vibration

TABLE 4 (continued)

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thickness: cm	Loose layer thickness: in	Average field dry density: Mg/m^3	Average field dry density: lb/ft^3	Limits for 9 chances in 10: $\pm Mg/m^3$	Limits for 9 chances in 10: $\pm lb/ft^3$	Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent): 2.5kg(5.5lb) rammer method	Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent): 4.5kg(10lb) rammer method	9th ranked density measurement as percentage of max. dry density in 2.5kg (5.5 lb) rammer test	Field moisture content at compaction (per cent)	Optimum moisture content in B.S. Compaction tests (per cent): 2.5kg(5.5lb) rammer method	Optimum moisture content in B.S. Compaction tests (per cent): 4.5kg(10lb) rammer method	Casagrande classification
7 (contd)	10-12Mg (10-12ton) smooth-wheeled roller	Load on rear rolls: 71.4kg per cm width (400lb/in)	2.1m (6ft 9 in)	3.2km/h (2mile/h)	7.6	4	23	9	1.73	108.0	0.029	1.8	95	89	92	17	19	15	GC
					7.7	8	23	9	1.78	111.4	0.022	1.4	97	91	95	17	19	15	GC
					7.8	16	23	9	1.86	116.3	0.022	1.4	101	95	98	17	19	15	GC
9	Self-propelled pneumatic-tyred 13.8m^3 scrapers	Average tyre inflation pressure 34N/cm^2(50lb/in^2) approx wheel load 9Mg(9tons)	1.1m (3ft 6 in)	Up to 6.4km/h (4 mil3/h)	9.5	2†	23	9	1.38	86.3	0.016	1.0	97	85	96	34	31	24	CH
					9.6	4†	23	9	1.38	86.4	0.010	0.6	98	86	97	33	31	24	CH
					9.7	8†	23	9	1.41	88.2	0.010	0.6	100	87	99	33	31	24	CH
					9.8	2†	23	9	1.22	76.0	0.013	0.8	90	79	90	34	34	27	CH
					9.9	4†	23	9	1.20	75.0	0.022	1.4	89	78	87	33	35	28	CH
					9.10	8†	23	9	1.17	73.1	0.016	1.0	88	77	85	33	35	28	CH
	10-12Mg (10-12tons) smooth-wheeled roller	Load: 85.7 kg per cm width (480 lb/in)	2.0m (6 ft 7 in)	3.2km/h (2 mile/h)	9.11	4	23	9	1.30	81.1	0.008	0.5	94	83	93	35	33	26	CH
					9.12	8	23	9	1.33	83.0	0.013	0.8	97	85	95	35	33	26	CH
					9.13	16	23	9	1.35	84.6	0.011	0.7	100	88	98	36	34	28	CH
9	10-12Mg (10-12ton) smooth-wheeled roller	Load: 71.4 kg per cm width (400 lb/in)	2.0m (7 ft 6 in)	3.2km/h (2 mile/h)	9.14	4	23	9	1.15	71.7	0.022	1.4	83	73	80	30	33	26	CH
					9.15	8	23	9	1.21	75.6	0.019	1.2	89	79	87	32	34	28	CH
					9.16	16	23	9	1.28	80.3	0.032	2.0	94	84	90	33	34	28	CH
10	10-12Mg (10-12 ton) self-propelled 9 wheeled pneumatic-tyred roller	Av. tyre inflation pressure 72N/cm^2(105lb/in^2)average wheel load 1.3Mg(1.3	1.7m (5 ft 9 in)	6.4km/h (4 mile/h)	10.1	4	15	6	1.17	73.2	0.016	1.0	84	76	82	26	31	27	MH
					10.2	8	15	6	1.22	76.1	0.018	1.1	86	78	83	27	30	26	MH
					10.3	16	15	6	1.23	76.9	0.022	1.4	88	79	85	27	31	27	MH
					10.4	4	23	9	1.18	73.9	0.013	0.8	83	75	82	28	30	25	CH/MH
					10.5	8	23	9	1.23	76.9	0.011	0.7	87	78	86	28	30	25	CH/MH
					10.6	16	23	9	1.23	78.1	0.013	0.8	88	79	86	28	30	25	CH/MH

† Since the wheels on a scraper are in line longitudinally, 1 pass scraper = 2 passes normal pneumatic-tyred roller

TABLE 4 (continued)

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thickness		Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurements as percentage of max. dry density in 2.5kg (5.5 lb) rammer method	Field moisture content at compaction (per cent)	Optimum moisture content in B.S. Compaction tests (per cent)		Casagrande classification
							cm	in	Mg/m^3	lb/ft^3	$\pm Mg/m^3$	$\pm lb/ft^3$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method	
10 (contd)		tons) contact pressure (from man's data) $61 N/cm^2$ ($88 lb/in^2$)																	
	Towed $9.2m^3$ ($12yd^3$) scrapers	Average tyre inflation pressure $26N/cm^2$ ($38lb/in^2$) average wheel load 2Mg(2 tons)	1.4m (4 ft 6 in)	Up to 6.4km/h (4 mile/h)	10.7	2†	23	9	1.11	69.4	0.021	1.3	79	72	77	27	30	25	MH
					10.8	4†	23	9	1.10	68.9	0.019	1.2	78	71	77	25	30	25	MH
					10.9	8†	23	9	1.11	69.6	0.016	1.0	79	72	77	25	30	25	MH
	12-14 Mg (12-14 ton) smooth-wheeled roller	Load:82.1 kg per cm width	1.9m (6ft 3 in)	1.6km/h (1 mile/h)	10.10	4	15	6	1.22	76.5	0.027	1.7	87	78	83	26	31	26	MH
					10.11	8	15	6	1.32	82.2	0.021	1.3	94	85	91	27	31	26	MH
					10.12	16	15	6	1.41	87.9	0.019	1.2	101	91	99	28	31	26	MH
					10.13	4	23	9	1.22	76.3	0.019	1.2	87	78	84	26	30	25	CH
					10.14	8	23	9	1.27	79.3	0.013	0.8	90	81	89	26	30	25	CH
					10.15	16	23	9	1.33	83.1	0.013	0.8	94	85	93	27	30	25	CH

† Since the wheels on a scraper are in line longitudinally, 1 pass scraper = 2 passes normal penumatic-tyred roller.

TABLE 5

Details of the state of compaction obtained on lime stabilized bases* during compaction plant trials

Scheme No.	Type of compaction plant	Wheel loads and nominal contact pressures	Rolling width	Rolling speed	Ref. No.	Number of passes of roller	Loose layer thick-ness		Average field dry density		Limits for 9 chances in 10		Average compaction relative to the maximum dry density in the B.S. Compaction tests (per cent)		9th ranked density measurement as percentage of max. dry 2.5kg (5.5 lb) rammer method	Field moisture content at com-paction (per cent)	Optimum moisture content in B.S. Compaction tests (per cent	
							cm	in	Mg/m^3	lb/ft^3	$\pm Mg/m^3$	$\pm lb/ft^3$	2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method			2.5kg(5.5lb) rammer method	4.5kg(10lb) rammer method
2	8 Mg(8ton) smooth-wheeled roller	Load per cm (in) width: rear rolls 55.4kg(310lb) front rolls 35.7kg(200lb)	1.5m (5ft)	5.6km/h (3½ mile/h)	2.3	4	19	7½	2.05	127.9	0.043	2.7	100	95	95	7	9	7
					2.4	8	19	7½	2.04	127.5	0.037	2.3	101	95	99	9	10	8
					2.5	12	19	7½	2.00	125.2	0.032	2.0	99	93	96	9	10	8
					2.6	16	19	7½	2.04	127.3	0.016	1.0	103	97	100	9	10	8
					2.7	4	19	7½	1.97	123.3	0.035	2.2	99	94	98	9	10	8
					2.8	8	19	7½	1.99	124.4	0.037	2.3	99	93	96	8	10	8
	9-wheeled towed pneu-matic-tyred roller	Average tyre pressure 10N/cm^2(15lb/in^2) Average wheel load 1.4 Mg (1.4 tons)	2.1m (6ft 10 in)	3.2km/h(2 mile/h)	2.9	4	19	7½	1.87	116.9	0.048	3.0	95	90	91	8	11	9
					2.10	8	19	7½	1.82	113.9			92	87	90	8	10	8
		Average tyre pressure 23N/cm^2(34lb/in^2) Average wheel load 1.4 Mg (1.4 tons)			2.11	4	19	7½	1.88	117.2	0.029	1.8	94	89	92	8	10	8
					2.12	8	19	7½	1.87	117.1	0.030	1.9	95	90	92	9	10	8
	Dropping weight compaction		1.2m (4ft)	0.14km/h (0.09 mile/h)	2.13	1	19	7½	1.86	116.1	0.027	1.7	94	87	91	9	10	8
					2.14	1	19	7½	1.81	113.0	0.026	1.6	92	85	90	8	10	9
4	4 Mg(4 ton) sheepsfoot roller.	Foot pressure 90N/cm^2 (130lb/in^2)	2.4m (8ft)	3.2-4.8 km/h (2-3 mile/h)	4.20	10	23	9	1.78	111.2	0.040	2.5	90	84	87	14	15	12

* All the base materials were gravel-sand-clay soils, Casagrande classification GC.

TABLE 6

Losses of moisture during the excavation of density holes

Scheme No.	Reference No.	True moisture content (per cent)	Moisture content from dry density samples (per cent)
2	2.1	11.4	9.6
7	7.6	16.5	14.5
	7.7	17.0	14.9
	7.8	17.0	14.6

TABLE 7

Summary of state of compaction obtained by normal construction methods on subgrades

Scheme Number	7	3	4	5	6		9
Climate: Climatic region Average annual rainfall (mm) (in)	Moist sub-humid 1020 40	Dry sub-humid 1020 40	Moist sub-humid 1020 40	Moist sub-humid 1270 50	Dry sub-humid 1140 45		Humid 1780 70
Soil types encountered	Friable red clay and gravel-sand-clay	Friable red clay	Variable sand-clay	Variable sand-clay	Uniform sand	Sand-clay	Friable red clay
Compaction equipment used	Earthmoving plant	Pneumatic-tyred rollers and road traffic	Earthmoving plant and vibrating rollers	Earthmoving plant and smooth-wheeled rollers	Pneumatic-tyred, vibrating and smooth-wheeled rollers		Earthmoving plant
Control and adjustment of moisture content	None	None	None	None	Water added by sprinkling from water tankers		None
Number of areas tested	2	3	10	3	3	2	4
Average compaction relative to the maximum dry density in the B.S. Compaction tests (i) 2.5kg (5.5lb) rammer method (per cent) (ii) 4.5kg (10 lb) rammer method (per cent)	 93 85	 92 83	 93 85	 92 85	 102 100	 99 91	 98 86
Average moisture conditions* (per cent) In-situ moisture content minus optimum moisture contents of the B.S. Compaction tests (i) 2.5kg (5.5 lb) rammer method (ii) 4.5kg (10 lb) rammer method	 −9 −4	 −6 −2	 −4 0	 −4 0	 −3 −2	 −2 +1	 +1 +8
Standard deviation of average compaction relative to the maximum dry density in the B.S. Compaction tests. (i) 2.5 kg (5.5 lb) rammer method (per cent) (ii) 4.5 kg (10 lb) rammer method (per cent)	 4.9 6.4	 3.2 2.6	 3.6 3.8	 7.5 6.9	 1.0 1.0	 2.1 0	 0.8 1.3

* In saome cases the measurements were made some days after compaction, so that these values would be slightly higher at the time of compaction.

TABLE 8

Summary of state of compaction obtained by normal construction methods on stabilized road bases

Scheme Number	2	4	5	8
Compaction equipment used	Pneumatic-tyred and smooth-wheeled rollers	Pneumatic-tyred, sheeps-foot, vibrating and smooth-wheeled rollers	Vibrating and smooth-wheeled rollers	5-9 passes smooth-wheeled rollers within ½ hour of mixing
Adjustment of moisture content	Water added by sprinkling from water tankers	Water added by multi-pass stabilizing machine	Water added by multi-pass stabilizing machine	Water added by single-pass stabilizing machine
Density control measurements	None	Dry density determinations every 70 m (200 ft)	Dry density determinations every 70 m (200 ft)	Occasional dry density determinations
Stabilizing agent	Hydrated lime	Hydrated lime	Hydrated lime	Cement
Number of areas tested	2	9	2	5
Average compaction relative to the maximum dry density in the B.S. Compaction tests:				
(i) 2.5 kg (5.5lb) rammer method (%)	99	103	101	92
(ii) 4.5 kg (10 lb) rammer method (%)	93	95	93	86
Average moisture conditions (per cent) In-situ moisture content minus optimum moisture contents of the B.S. Compaction tests:				
(i) 2.5 kg (5.5 lb) rammer method	−2	−2	−3	−1
(ii) 4.5 kg (10 lb) rammer method	0	0	0	+3
Standard deviation of average compacting relative to the maximum dry density in the B.S. Compaction tests:				
(i) 2.5 kg (5.5 lb) rammer method (per cent)	2.1	2.6	0.7	2.2
(ii) 4.5 kg (10 lb) rammer method (per cent)	2.8	2.7	0.7	2.5

TABLE 9

The effect of loose layer thickness on the state of compaction in the top 15 cm (6 in) of soil compacted by pneumatic-tyred compaction plant

Lesser loose layer			Greater loose layer		
Thickness		Relative compaction* (per cent)	Thickness		Relative compaction* (per cent)
(cm)	(in)		(cm)	(in)	
23	9	86	38	15	87
15	6	87	43	17	85
15	6	88	23	9	88
23	9	92	30	12	89
15	6	89	30	12	85
15	6	83	23	9	84
15	6	87	23	9	86
15	6	88	23	9	88
Average		87.5	Average		86.5

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (55 lb) rammer method.

TABLE 10

Comparison of the states of compaction produced in gravel-sand-clay soils on road construction schemes in East Africa and in the full-scale compaction plant trials at the Road Research Laboratory[2,6]

Compaction plant	Ref. No.	Number of passes of roller	Field moisture content minus optimum moisture content of B.S. Compaction test 2.5 kg (5.5 lb) rammer method (per cent)	Relative compaction* (per cent)		
				Field	Estimated from full-scale plant trials	Difference
Smooth-wheeled roller	2.3	4	–2	100**	102	–2
	2.4	8	–1	101**	102	–1
	2.5	12	–1	99**	103	–4
	2.6	16	–1	103**	104	–1
	2.7	4	–1	99**	99	0
	2.8	8	–2	99**	106	–7
			Average difference (Scheme No. 2):			–2.4
	4.12	39†	–3	105	105	0
	4.13	39†	–2	106	107	–1
	4.14	31†	–3	101	105	–4
	4.15	70†	–4	106	102	+4
	4.16	55†	–4	104	102	+2
	4.17	48†	–2	104	107	–3
	4.18	53†	–1	99	104	–5
	4.19	53†	–1	104	104	0
			Average difference (Scheme No. 4):			–0.9
	7.6	4	–2	95	100	–5
	7.7	8	–2	97	104	–7
	7.8	16	–2	101	106	–5
			Average difference (Scheme No. 7):			–5.7
Pneumatic-tyred roller	2.11	4	–2	94**	95	–1
	2.12	8	–1	95**	98	–3
			Average difference (Scheme No. 2):			–2.0
Sheepsfoot roller	4.20	10	–1	90	88	+2

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

** Values in top 10 cm (4 in) of compacted base.

† Considered to be the state of compaction to refusal.

TABLE 11

Comparison of the states of compaction produced by pneumatic-tyred rollers on friable red clays in East Africa and on heavy clay, sandy clay and gravel-sand-clay soils in the full-scale trials at the Road Research Laboratory[6]

Approx. average shear stress in top 152 mm (6 in)		Ref. No.	Number of applications of load	Field moisture content minus optimum moisture content of B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (per cent)	Relative compaction* (per cent)				
					Field, on friable red clay soils	Estimated from full-scale plant trials on			Average difference
(N/cm^2)	(lb/in^2)					Heavy clay	Sandy clay	Gravel-sand-clay	
15.9	23	1.14	4	−9	87	90	88	–	− 2
		1.5	8	−9	87	94	91	–	− 5
		1.8	4	−1	90	96	100	–	− 8
11.0	16	9.8	4	0	90	95	99	97	− 7
		9.10	16	−2	88	101	102	102	−14
		9.5	4	+3	97	99	100	97	− 2
		9.7	16	+2	100	100	101	98	0
8.3	12	10.7	4	−3	79	91	91	91	−12
		10.9	16	−5	79	92	91	92	−13

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

TABLE 12

Comparison of the state of compaction produced in trials by the U.S. Army Corps of Engineers and in East Africa by pneumatic-tyred scrapers compacting 23 cm (9 in) loose layers[25-27]

Location	Wheel load		Tyre inflation pressure		Number of passes	Plant optimum moisture content minus optimum moisture content of B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (per cent)	Maximum relative compaction* (per cent)	Soil type
	(Mg)	(tons)	(N/cm^2)	(lb/in^2)				
U.S.A.	9	9	38	55	4	+ 1	100†	Clayey sand SC
					6	+ 2	103†	Silty clay CI
East Africa	9 (approx)	9 (approx)	34	50	4	+ 2	98	Friable red clay MH – CH

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

† Compaction tests carried out in 15 cm (6 in) diameter moulds using 5 layers, each compacted by 12 blows of a 4.5 kg (10 lb) hammer falling 0.5 m (18 in).

TABLE 13

Comparison of the states of compaction produced in trials in the U.S.A., India and East Africa by smooth-wheeled rollers[25,29-31]

Location	Details of compaction plant	Average number of passes	Loose layer thickness (cm)	Loose layer thickness (in)	Average relative compaction* (per cent)	Field moisture content minus optimum moisture content of B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (per cent)	Soil classification	Remarks
Indiana, U.S.A.	10 Mg (10 ton) roller load per cam (in) width on rear rolls: 62.5 kg (350 lb)	2 to 2.5	15 to 30	6 to 12	105 to 93†	−1 to +3	C2	Soil compacted in a series of lifts. Bottom 2-4 lifts omitted from calculations of relative compaction
Ohio, U.S.A.	10 Mg (10 ton) roller. Load per cam (in width on rear rolls: 58.0 kg (325 lb)	2.6 to 4.1	15 to 20	6 to 8	105 to 101	−2	CL-CI-CH	Soil compacted in 28-35 lifts
India[30]	7 Mg (7 ton) roller. Load per cm (in) width on rear rolls: 52.5 kg (294 lb)	64	23	9	Max. 99	−2	CL	Soil compacted on a bed of 152 mm (6 in) compacted soil resting on the natural soil.
India[31]	6 Mg (6 ton) roller	64	23	9	Max. 98	−2	CL	Soil compacted on a bed of 305 mm (12 in) compacted soil resting on the natural soil.
Scheme No. 4 East Africa	8-12 Mg (8-12 ton) smooth-wheeled rollers	50 (approx.)	23	9	Max. 106	−3	GC	Lime-stabilized soil compacted on subgrade where compaction operations were controlled.
Scheme No. 7 East Africa	10-12 Mg (10-12 ton) roller. Load per cm (in) width on rear rolls: 71.4 kg (400 lb)	16	23	9	101	−2	GC	Soil compacted on rolled sub-grade
Scheme No. 9 East Africa	10-12 Mg (10-12 ton) roller. Load per cam (in) width on rear rolls: 85.7 kg (480 lb)	16	23	9	Max. 100	+2	CH	Soil compacted on rolled sub-grade

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

† Laboratory test carried out using a fresh sample for each point.

TABLE 14

Compaction data from three construction schemes in Kenya[16,32,33]

Construction scheme	Details of compaction process	Soil type	Average field moisture content minus optimum moisture content of B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (per cent)	Average relative compaction* (per cent)
Sasuma Dam[16]	Heavy pneumatic-tyred (tyre inflation pressures up to 102 N/cm^2 (150 lb/in^2) and sheepsfoot rollers: 152-178 mm (6-7 in) loose layers	Frieable red clay MH–CH	0	101
Experimental stabilized-soil road, Makuyu[32]	Pneumatic-tyred and smooth-wheeled rollers, moisture control by visual inspection	Cement-stabilized gravel GC	Data not available	93
		Cement-stabilized friable red clay CH		101
		Lime-stabilized friable red clay CH		99
		Dye-stabilized friable red clay CH		100
Road embankment at Embakasi[33]	50 Mg (50 ton) pneumatic-tyred roller and construction traffic	Heavy black clay (Black cotton soil) CH	–3	103

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

TABLE 15

States of compaction achieved during the construction of embankments on six major road construction schemes in Great Britain[34]

Construction scheme	Compaction plant used	Soil type	Average dry density		Average compaction relative to B.S. Compaction tests (per cent)	
			(Mg/m^3)	(lb/ft^3)	2.5 kg (5.5 lb) rammer method	4.5 kg (10 lb) rammer method
Maidenhead By-pass (Berkshire section)	3-wheeled 8 Mg (8 ton) smooth-wheeled rollers Tandem 8 Mg (8 ton) smooth-wheeled rollers Grid roller (ballasted to about 9 Mg (9 tons))	Hoggin GC	2.13	133	103	99
Maidenhead By-pass (Buckinghamshire section)	8 Mg (8 ton) smooth wheeled rollers (3 wheeled and tandem) 1.5 Mg (30 cwt) towed vibrating rollers 1.25 Mg (25 cwt) tandem vibrating rollers	Hoggin GC	2.23	139	106	101
Slough By-pass	15 Mg (15 ton) self-propelled pneumatic-tyred roller 22 Mg (22 ton) self-propelled pneumatic-tyred roller 12 Mg (12 ton) towed pneumatic-tyred roller 3.5 Mg (3½ ton) towed vibrating roller 3-wheeled 8 Mg (8 ton) smooth-wheeled roller	Hoggin GC	2.08	130	97	93
		Sandy clay CL	1.79	112	96	87
Oxford Southern and Western By-pass	1.5 Mg (30 cwt) towed vibrating rollers Grid roller (ballasted to 13.5 Mg (13½ tons)) 3-wheeled 8 Mg (8 ton) smooth-wheeled roller	Sandy gravel GW	2.19	137	103	99
Biggleswade By-pass	8 Mg (8 ton) smooth-wheeled rollers (3-wheeled and tandem)	Sandy gravel GW	2.13	133	98	96
	3-wheeled 8 Mg (8 ton) smooth-wheeled roller	Stony silty clay CI	1.78	111	96	85
		Silty clay CI	1.67	104	93	83
	1 Mg (19½ cwt) tandem vibrating roller	Fly ash SC	1.20	75	89	83
South Mimms By-pass	No specialized compaction plant. Compaction achieved by earthmoving plant	Heavy clay CH	1.51	94	94	81

TABLE 16

States of compaction specified and achieved on two road tests in the U.S.A.

Location	Pavement layer	Material	Relative compaction* (per cent)		Percentage of values	
			Specified	Averaged obtained	Above specification	Below specification
WASHO	Subgrade	Silty clay loam ML – MI	91–95	92–96	Data not given	
	Sub-base	Crushed gravel (51 mm (2 in) max. size)	–	100–103		
	Base	Crushed gravel (19 mm (¾ in) max. size)				
AASHO Road Test[36]	Subgrade	Sandy Clay CL	95–100	97–99	11	8
	Sub-base	Gravel	100–105	101–102	3	11
	Base	Gravel	100–105	104	26	3
		Cement-treated gravel	Not less than field max. dry density minus 80 kg/m^3 (5 lb/ft^3)	Field max. dry density plus 16 kg/m^3 (1 lb/ft^3)	–	1.5

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

TABLE 17

States of compaction achieved on six earth dams of friable red clay in Brazil[37]

Dam	Average relative compaction* (per cent)	Field moisture content minus optimum moisture content of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method (per cent)	Liquid limit (per cent)	Plasticity index (per cent)
Limoeiro	96.3 ± 3.2	−1.1 ± 2.4	32 – 55	10 – 25
Euclides de Cunha	101.0 ± 2.2	−0.8 ± 0.9	25 – 75	5 – 35
Graminha	101.5 ± 2.0	−0.4 ± 0.5	26 – 72	5 – 30
Bariri	99.5 ± 2.7	−0.6 ± 0.7	28 – 45	12 – 28
Jurumirim	101.6 ± 2.6	−2.1 ± 1.2	42 – 56	15 – 27
Juria (left wing)	98.9 ± 2.1	−0.6 ± 0.4	16 – 38	5 – 18

* Based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method

TABLE 18

Comparison of the states of relative compaction attained in East Africa with the requirements of AASHO *Guide specifications for highway construction*[18]

Description of pavement layer	Lime-stabilized base[a]	Cement-stabilized base[a]	Earthworks and subgrades
Attainable relative compaction[b] (per cent) from data at ten road construction schemes in East Africa.	100	90[c]	95 (with moisture control) 85 (without moisutre control)
Requirements of AASHO *Guide specifications for highway construction*	100[d]	95[e]	95 (for designated layers below formation level)

a) With moisture control

b) Relative compaction $= \dfrac{\text{Field dry density x 100}}{\text{maximum dry density of B.S. Compaction test, 2.5 kg (5.5 lb) rammer method}}$ (per cent)

c) Specimens compacted immediately after mixing in laboratory compaction test.

d) Aggregate base

e) Laboratory compaction test AASHO Designation T134

TABLE 19

Maximum relative compaction achieved in the full-scale compaction plant trial of the Road Research Laboratory

Compaction plant	Maximum relative compaction achieved – per cent						
	Heavy clay CH	Sandy clay CL	Well-graded sand, SW	Gravel-sand clay GW	Uniformly graded sand, SU	Wet mix. limestone	Wet mix. slag
2.75 Mg (2¾ ton) smooth-wheeled roller	*97 ; 83†	103 ; 89	108 ; 101	106 ; 99	– –	103 ; 102	103 ; 102
8 Mg (8 ton) smooth-wheeled roller	105 ; 90	106 ; 92	109 ; 102	107 ; 100	– –	104 ; 103	104 ; 103
13.5 Mg (13½ ton) grid roller	107 ; 91	106 ; 92	110 ; 102	105 ; 98	102 : 100	– –	– –
5 Mg (5 ton) club-foot sheepsfoot roller	108 ; 92	108 ; 94	– –	101 ; 94	– –	– –	– –
4.5Mg (4½ ton) taper-foot sheepsfoot roller	108 ; 92	108 ; 94	– –	99 ; 93	– –	– –	– –
12 Mg (12 ton) pneumatic-tyred roller	102 ; 87	102 ; 88	105 ; 98	102 ; 96	– –	– –	–
20 Mg (20 ton) pneumatic-tyred roller	107 ; 91	107 ; 93	106 ; 98	108 ; 101	– –	– –	– –
45 Mg (45 ton) pneumatic-tyred roller	112 ; 96	110 ; 95	108 ; 101	108 ; 101	– –	– –	– –
102 kg (2 cwt) power rammer	111 ; 95	109 ; 94	107 ; 99	106 ; 99	– –	– –	– –
607 kg (12 cwt) frog rammer	107 ; 91	104 ; 90	106 ; 98	105 ; 99	– –	– –	– –
203 kg (4 cwt) vibrating roller	– –	– –	102 ; 93	95 ; 89	– –	– –	– –
343 kg (6¾ cwt) vibrating roller	93 ; 79	92 ; 79	105 ; 98	102 ; 96	100 ; 98	104 ; 103	106 ; 105
991 kg (19½ cwt) tandem vibrating roller	– –	94 ; 81	107 ; 99	105 ; 98	– –	105 ; 103	106 ; 105
3.75 Mg (3¾ ton) towed vibrating roller	107 ; 91	109 ; 94	113 ; 105	112 ; 105	100 ; 98	– –	– –
3.75 Mg (3¾ ton) tandem vibrating roller	108 ; 92	107 ; 93	115 ; 107	110 ; 103	– –	– –	– –
8.5 Mg (8½ ton) towed vibrating roller	109 ; 93	110 ; 95	114 ; 106	111 ; 104	103 ; 101	– –	– –
4.25 Mg (4¼ ton) vibrating sheepsfoot roller	107 ; 91	108 ; 94	107 ; 99	103 ; 96	103 ; 101	– –	– –
5 Mg (5 ton) vibrating sheepsfoot roller	110 ; 94	– –	– –	– –	– –	– –	– –
203 kg (4 cwt) vibrating plate compactor	– –	– –	106 ; 98	98 ; 92	– –	– –	– –
660 kg (13 cwt) vibrating plate compactor	104 ; 89	106 ; 92	112 ; 104	109 ; 102	101 ; 99	105 ; 103	104 ; 103
711 kg (14 cwt) vibrating plate compactor	88 ; 75	105 ; 90	107 ; 99	106 ; 99	– –	104 ; 103	103 ; 102
1.5 Mg (1½ ton) vibrating plate compactor	– –	– –	107 ; 99	105 ; 98	– –	– –	– –
2 Mg (2 ton) vibrating plate compactor	99 ; 84	– –	106 ; 98	106 ; 99	– –	– –	– –

* Relative compaction based on the maximum dry density of the B.S. Compaction test, 2.5 kg (5.5 lb) rammer method.

† Relative compaction based on the maximum dry density of the B.S. Compaction test, 4.5 kg (10 lb) rammer method.

TABLE 20

Estimation of standard deviation from mean sample range[44]

Sample size	d
2	1.128
3	1.693
4	2.059
5	2.326
6	2.534
7	2.704
8	2.847
9	2.970
10	3.078

TABLE 21

Calculation of limits of true mean value[43]

Sample size	Factor 'a'		
	9 chances in 10	19 chances in 20	99 chances in 100
3	1.686	2.484	5.730
4	1.176	1.591	2.920
5	0.953	1.241	2.059
6	0.823	1.050	1.646
7	0.734	0.925	1.401
8	0.670	0.836	1.237
9	0.620	0.769	1.118
10	0.580	0.715	1.028
11	0.546	0.672	0.955
12	0.518	0.635	0.897
13	0.494	0.604	0.847
14	0.473	0.577	0.805
15	0.455	0.554	0.769
16	0.438	0.533	0.737
17	0.423	0.514	0.708
18	0.410	0.497	0.683
19	0.398	0.482	0.660
20	0.387	0.468	0.640
21	0.376	0.455	0.621
22	0.367	0.443	0.604
23	0.358	0.432	0.588
24	0.350	0.422	0.573
25	0.342	0.413	0.559
n greater than 25	$a = \frac{1.645}{\sqrt{n-2}}$ approx.	$a = \frac{1.960}{\sqrt{n-2}}$ approx.	$a = \frac{2.576}{\sqrt{n-2}}$ approx.

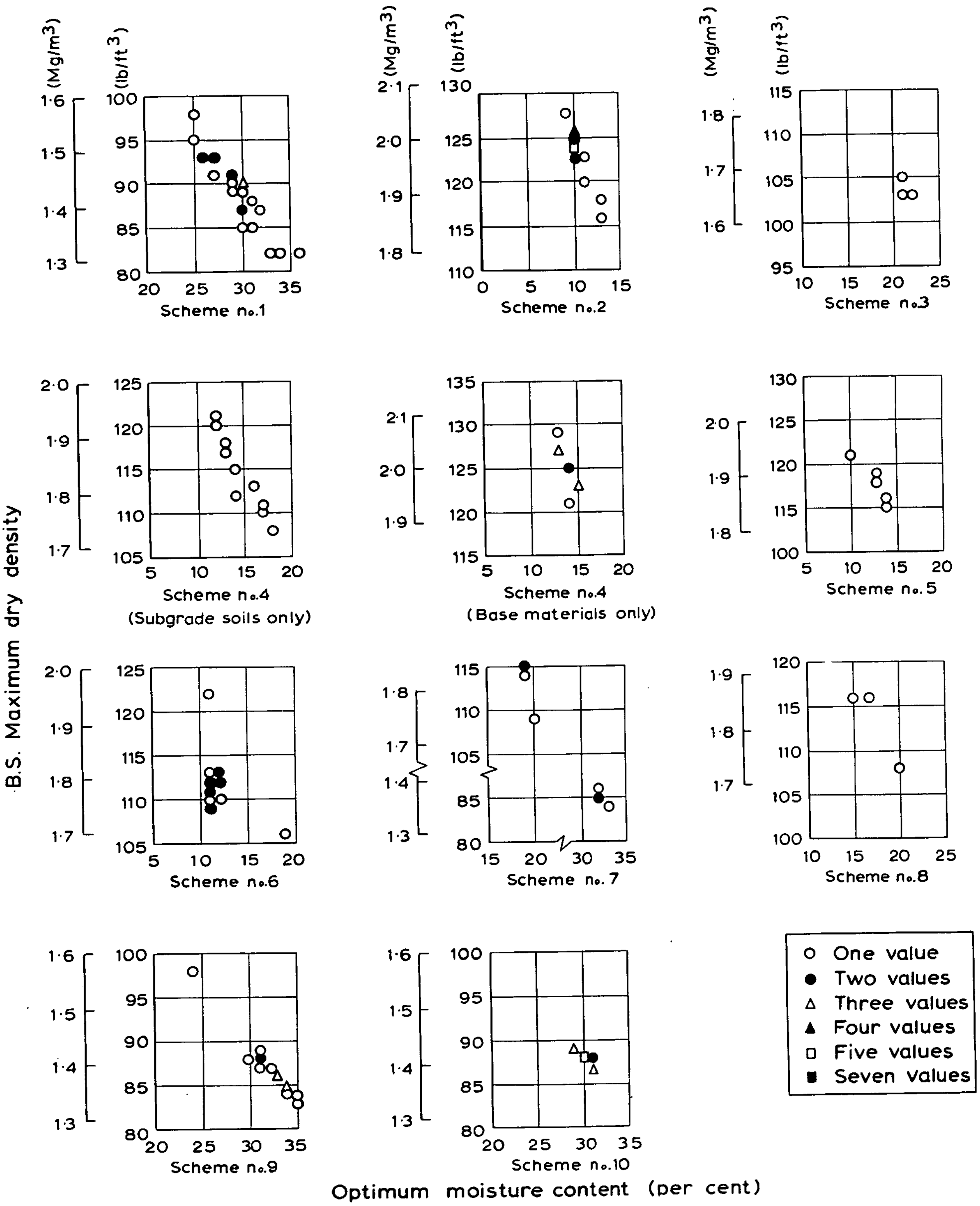
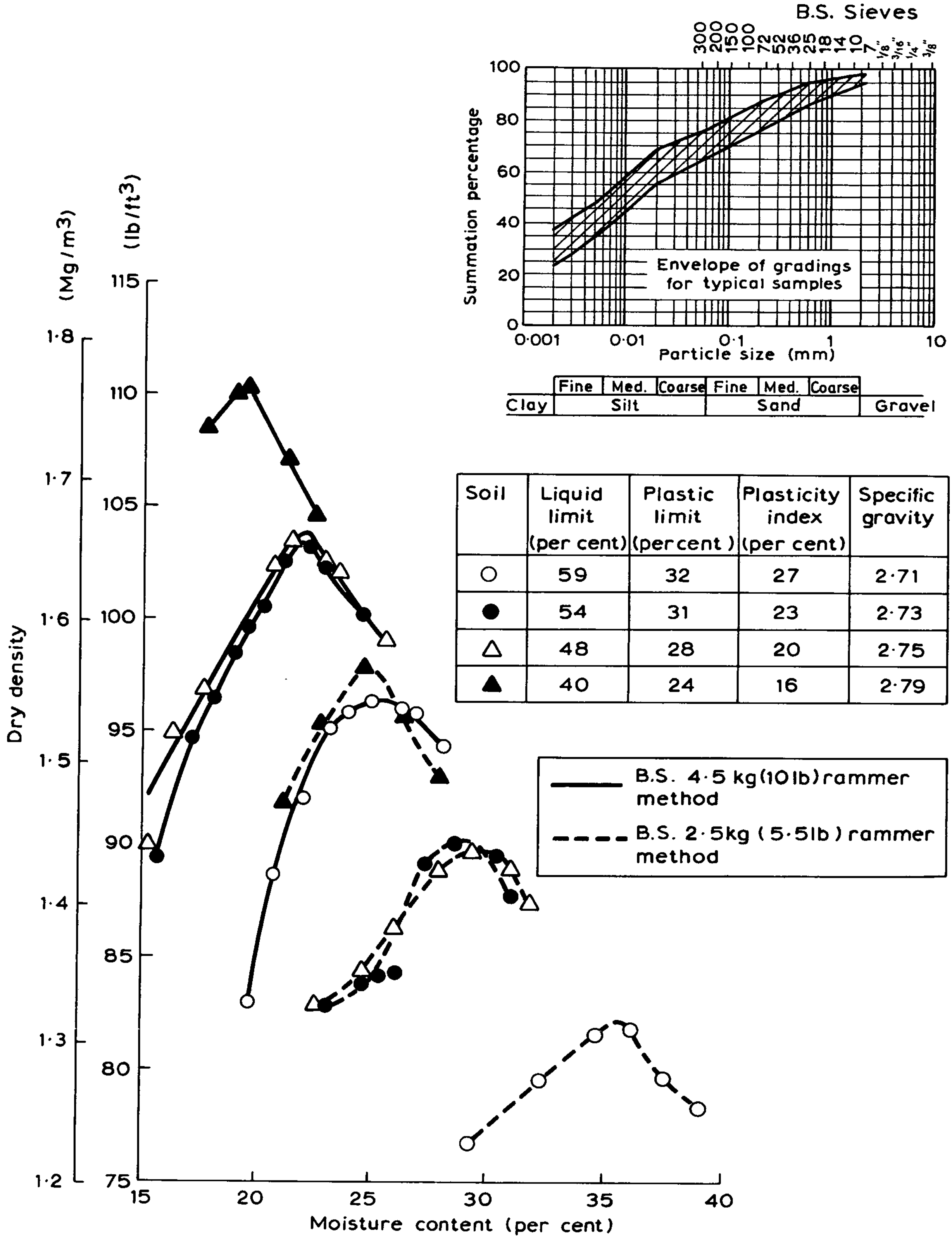
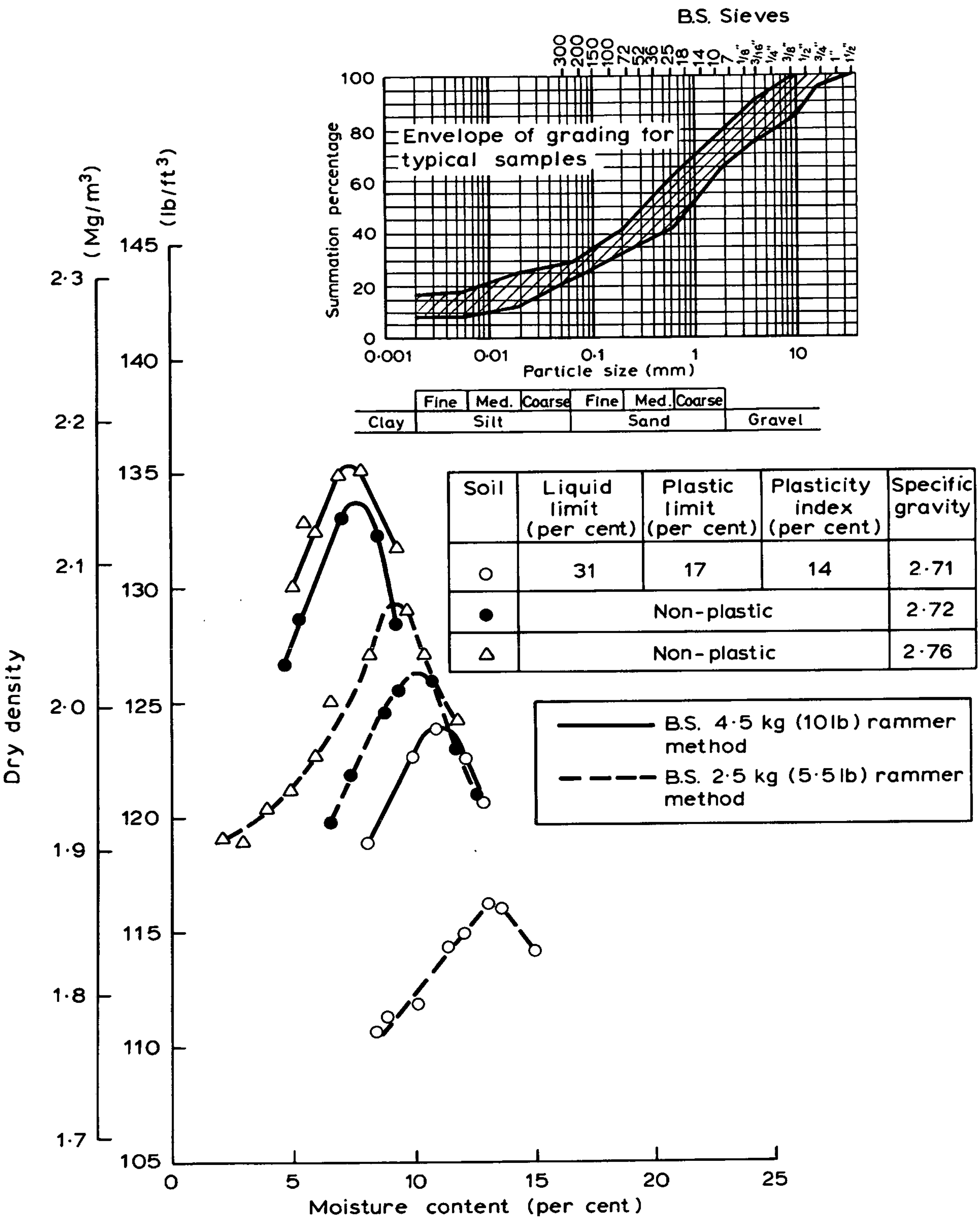


Fig.1. B.S. COMPACTION TEST DATA. (2·5 kg (5·5 lb) RAMMER METHOD)



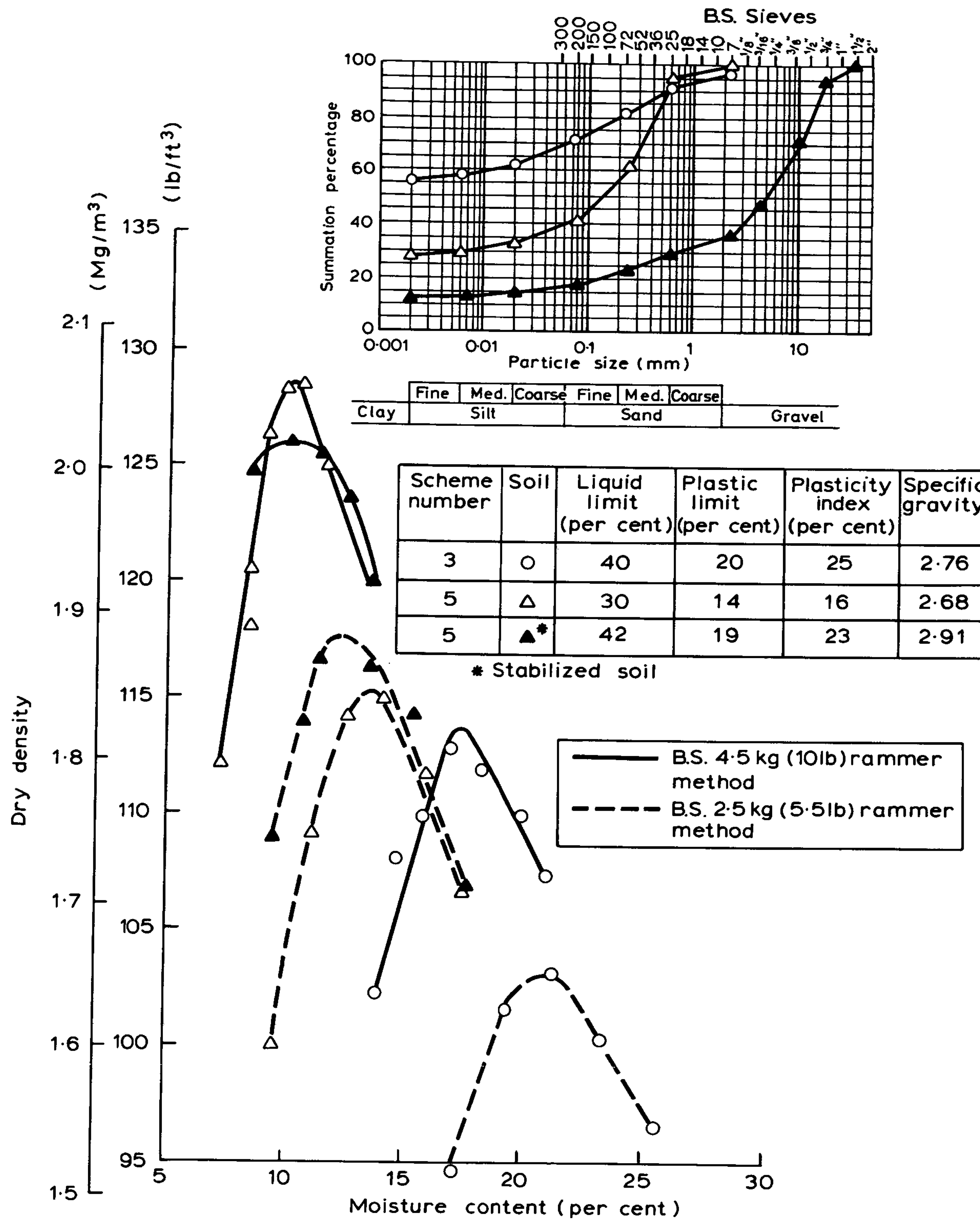
Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	59	32	27	2·71
●	54	31	23	2·73
△	48	28	20	2·75
▲	40	24	16	2·79

Fig. 2. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEME No. 1



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	31	17	14	2·71
●	Non-plastic			2·72
△	Non-plastic			2·76

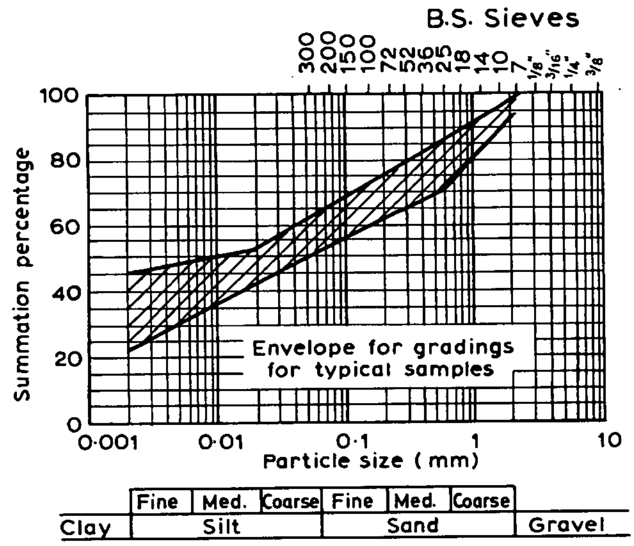
Fig. 3. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL STABILIZED SOIL SAMPLES FROM SCHEME No. 2



Scheme number	Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
3	○	40	20	25	2·76
5	△	30	14	16	2·68
5	▲*	42	19	23	2·91

* Stabilized soil

Fig. 4 CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEMES Nos. 3 AND 5



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	56	23	33	2·70
●	49	22	27	2·70
△	25	13	12	2·70

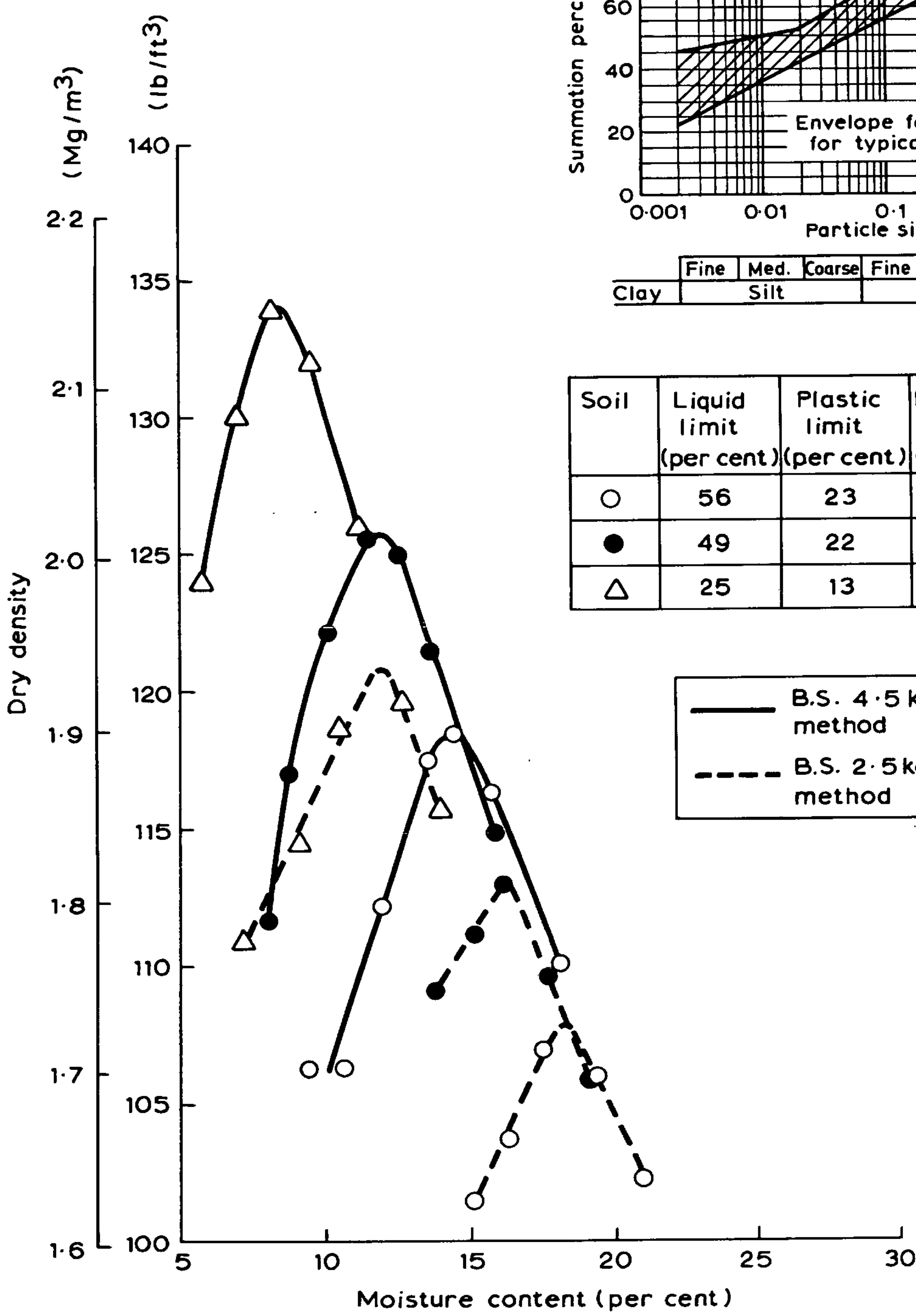
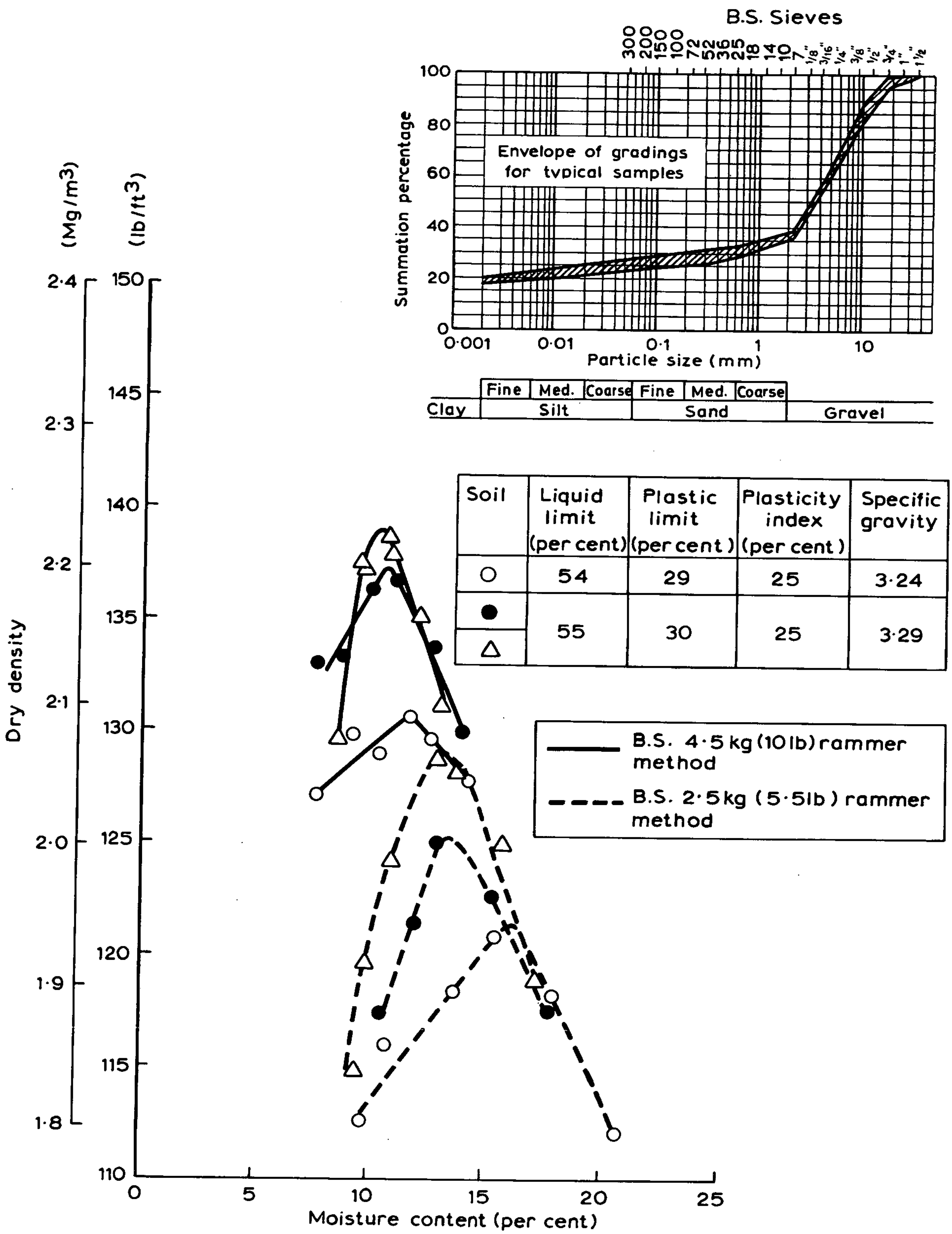
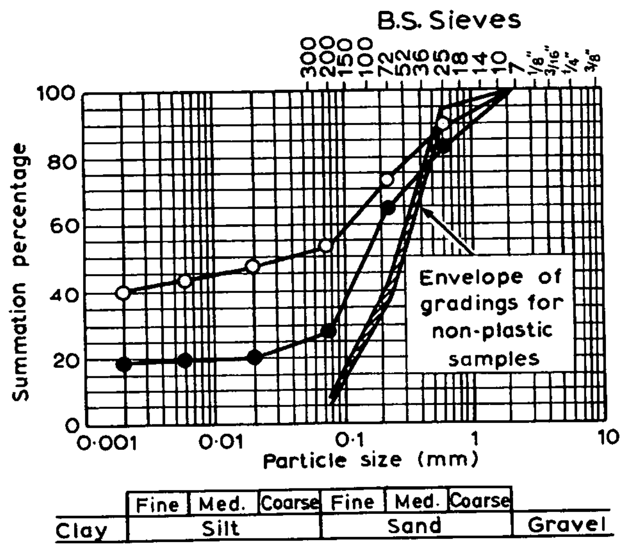


Fig. 5. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SUBGRADE SOIL SAMPLES FROM SCHEME No. 4



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	54	29	25	3·24
●	55	30	25	3·29
△				

Fig. 6. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL STABILIZED SOIL SAMPLES FROM SCHEME No. 4



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	47	18	29	2·70
●	25	11	14	2·69
△	Non-plastic			2·65
▲	Non-plastic			2·66
□	Non-plastic			2·65

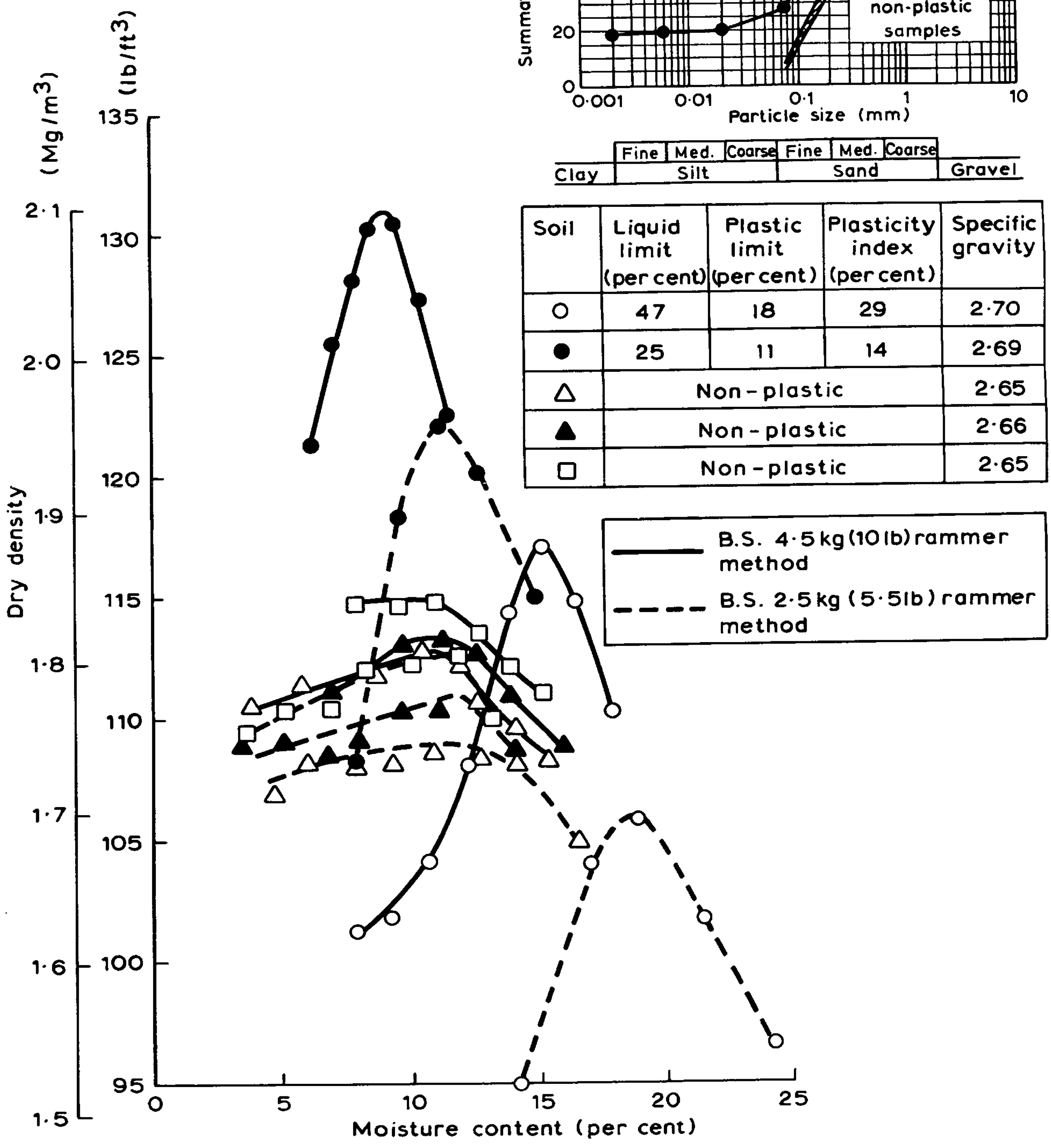
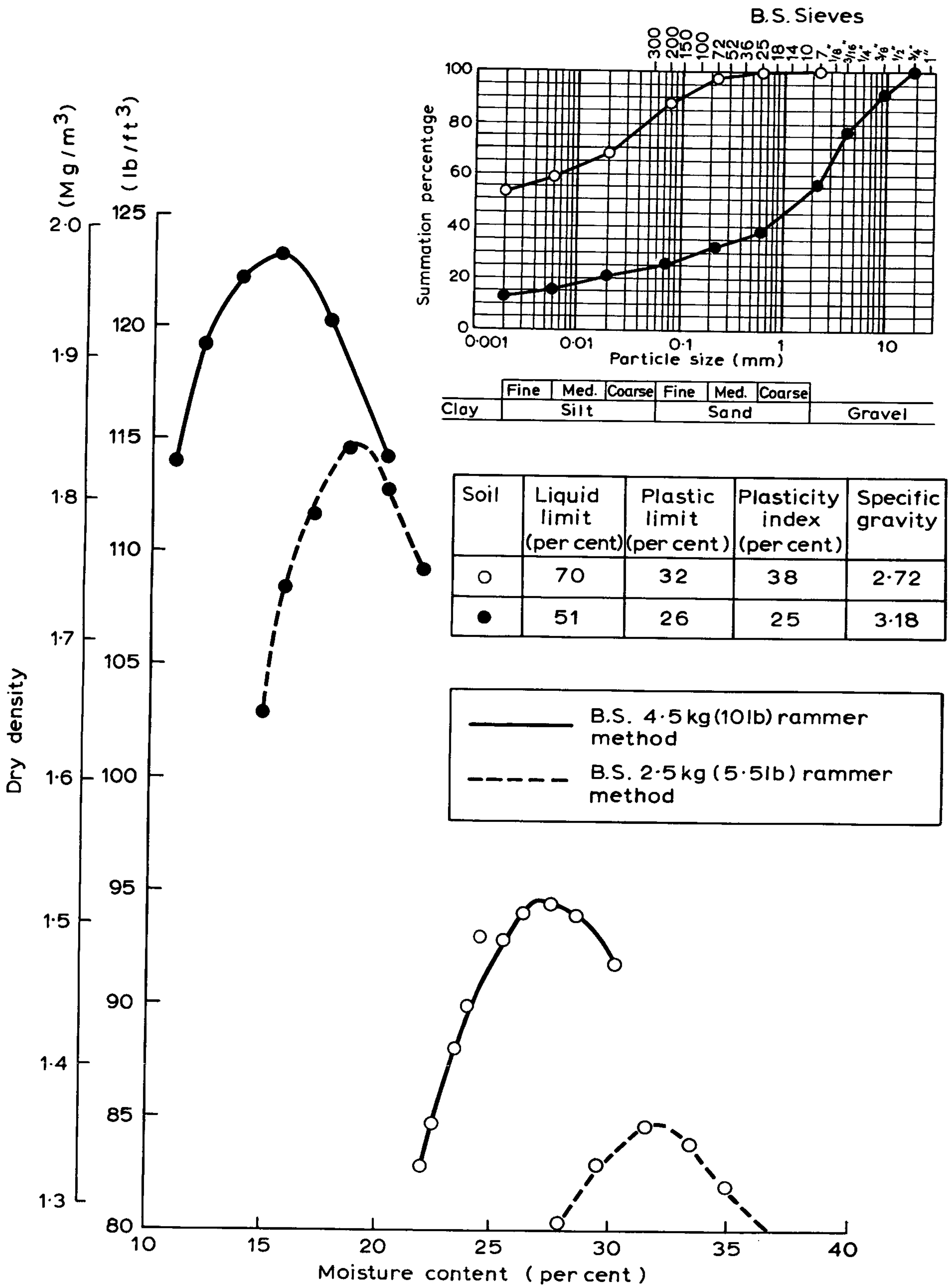
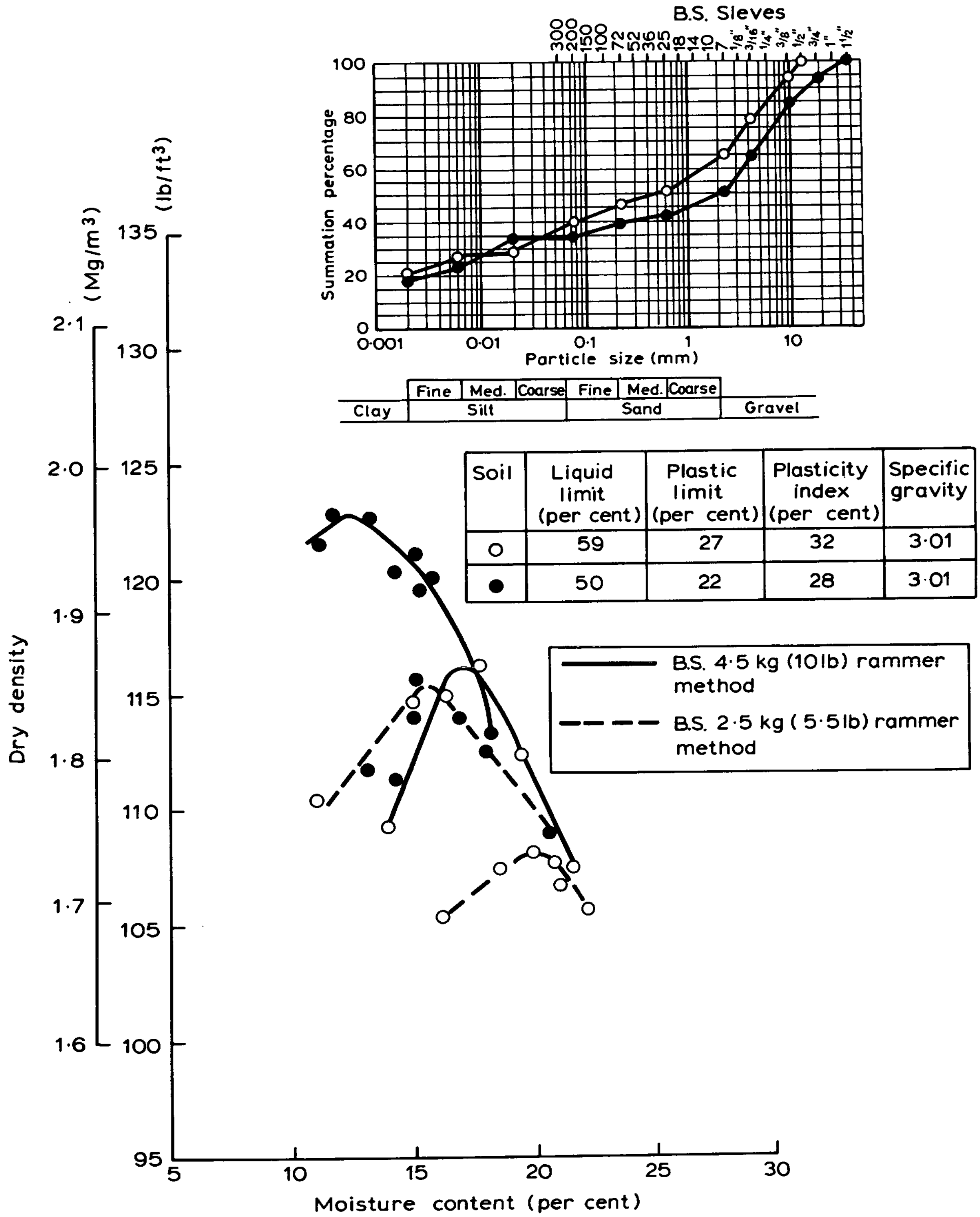


Fig. 7. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEME No. 6



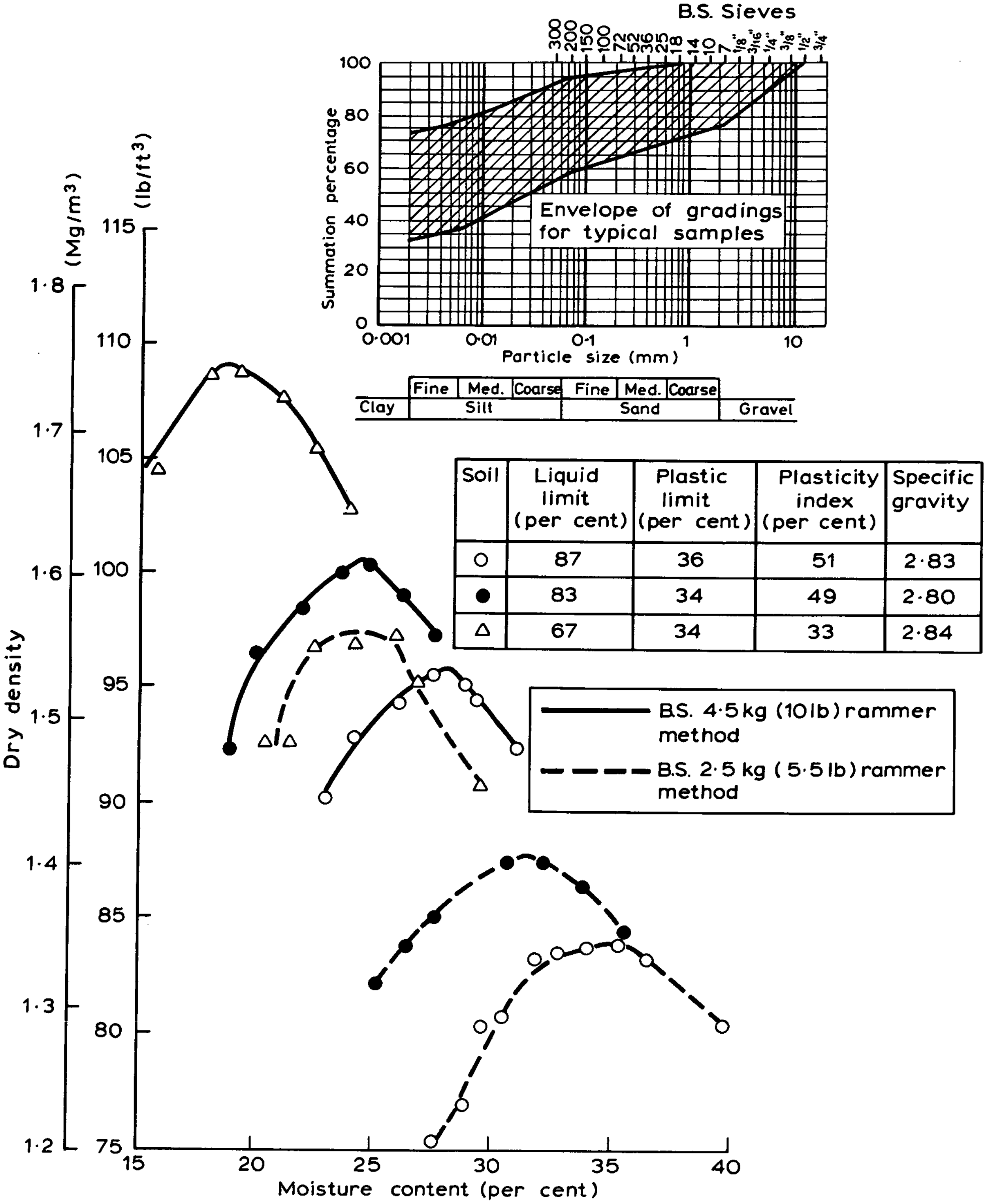
Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	70	32	38	2·72
●	51	26	25	3·18

Fig. 8. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEME No. 7



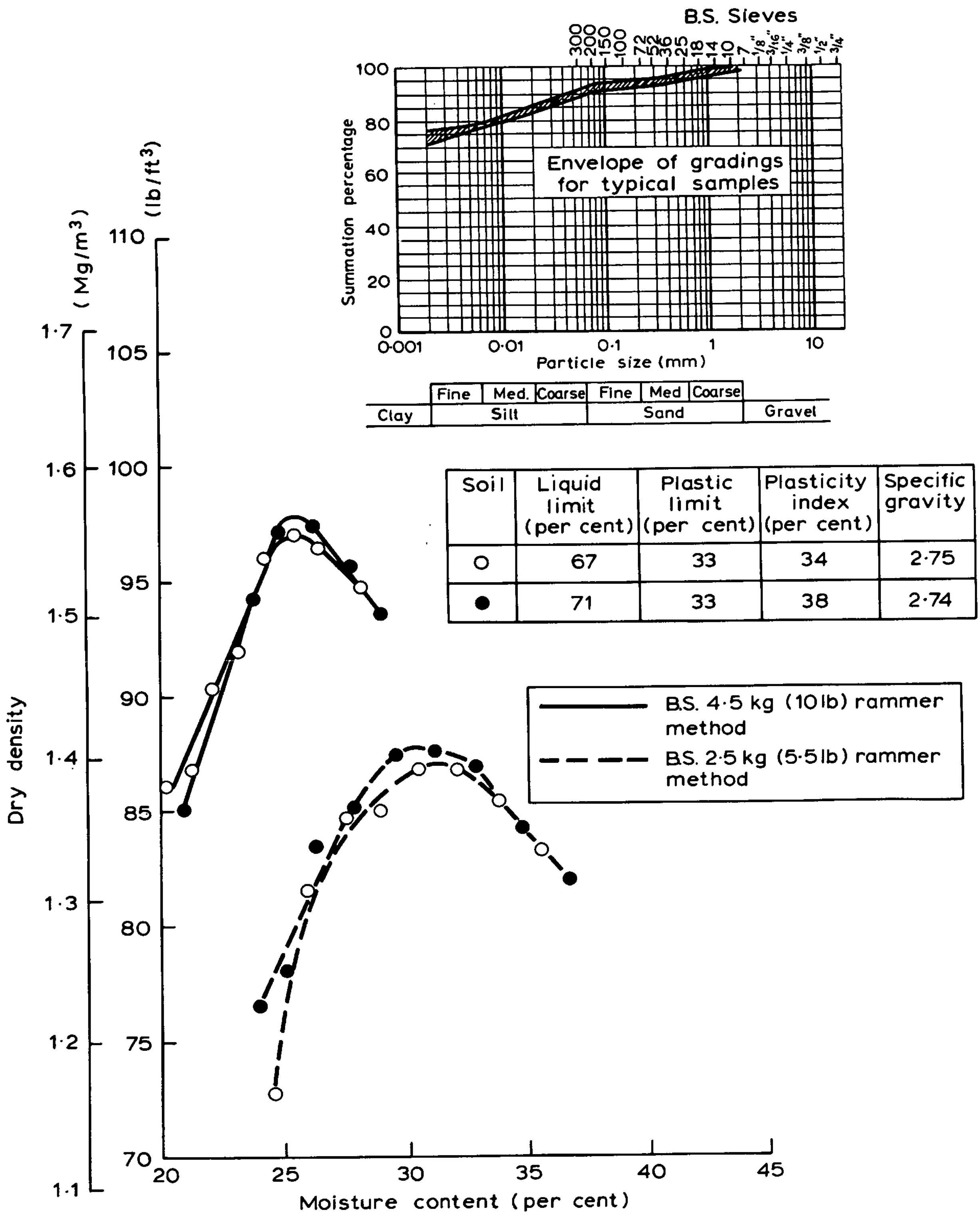
Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	59	27	32	3·01
●	50	22	28	3·01

Fig. 9 CLASSIFICATION AND COMPACTION DATA FOR TYPICAL STABILIZED SOIL SAMPLES FROM SCHEME No 8



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	87	36	51	2·83
●	83	34	49	2·80
△	67	34	33	2·84

Fig. 10. CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEME No. 9



Soil	Liquid limit (per cent)	Plastic limit (per cent)	Plasticity index (per cent)	Specific gravity
○	67	33	34	2·75
●	71	33	38	2·74

Fig. 11 CLASSIFICATION AND COMPACTION DATA FOR TYPICAL SOIL SAMPLES FROM SCHEME No. 10

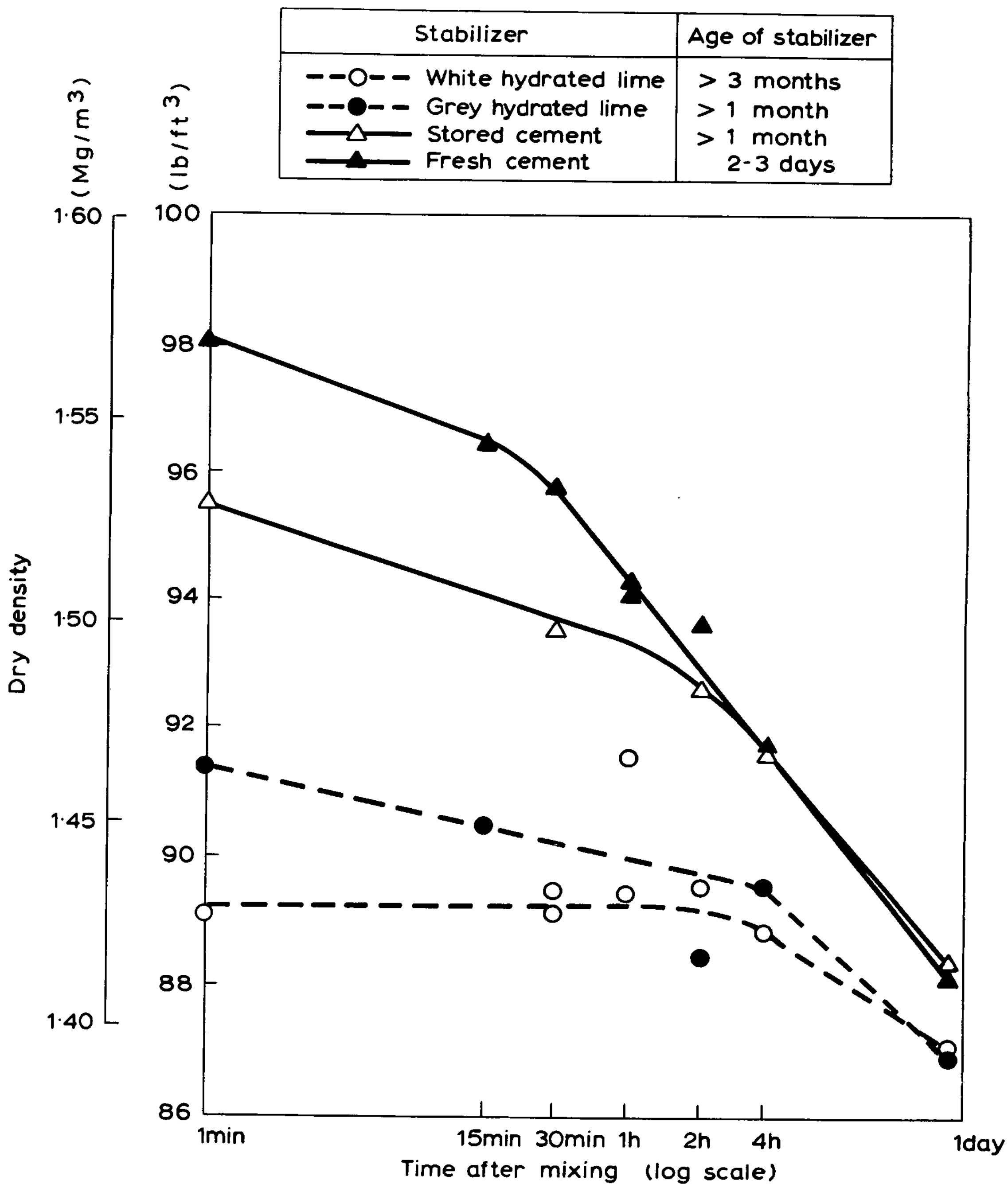
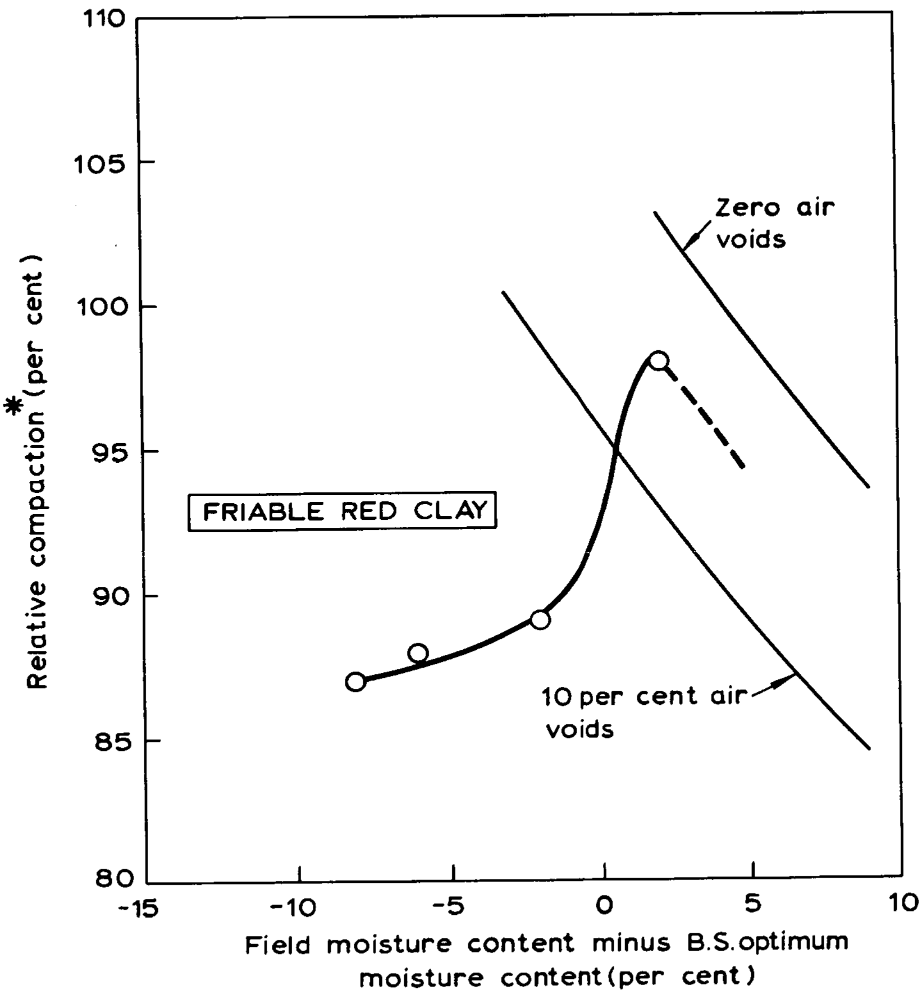


Fig. 12. THE EFFECT OF A LAPSE OF TIME BETWEEN MIXING AND COMPACTION ON THE DRY DENSITY ATTAINED FOR SOIL FROM SCHEME No. 8 WITH 5 PER CENT STABILIZER

Wheel load	:	9 Mg (9 tons) approx
Tyre inflation pressure	:	34 N/cm^2 (50 lb/in^2)
Loose layer thickness	:	23 - 25 cm (9–10 in)

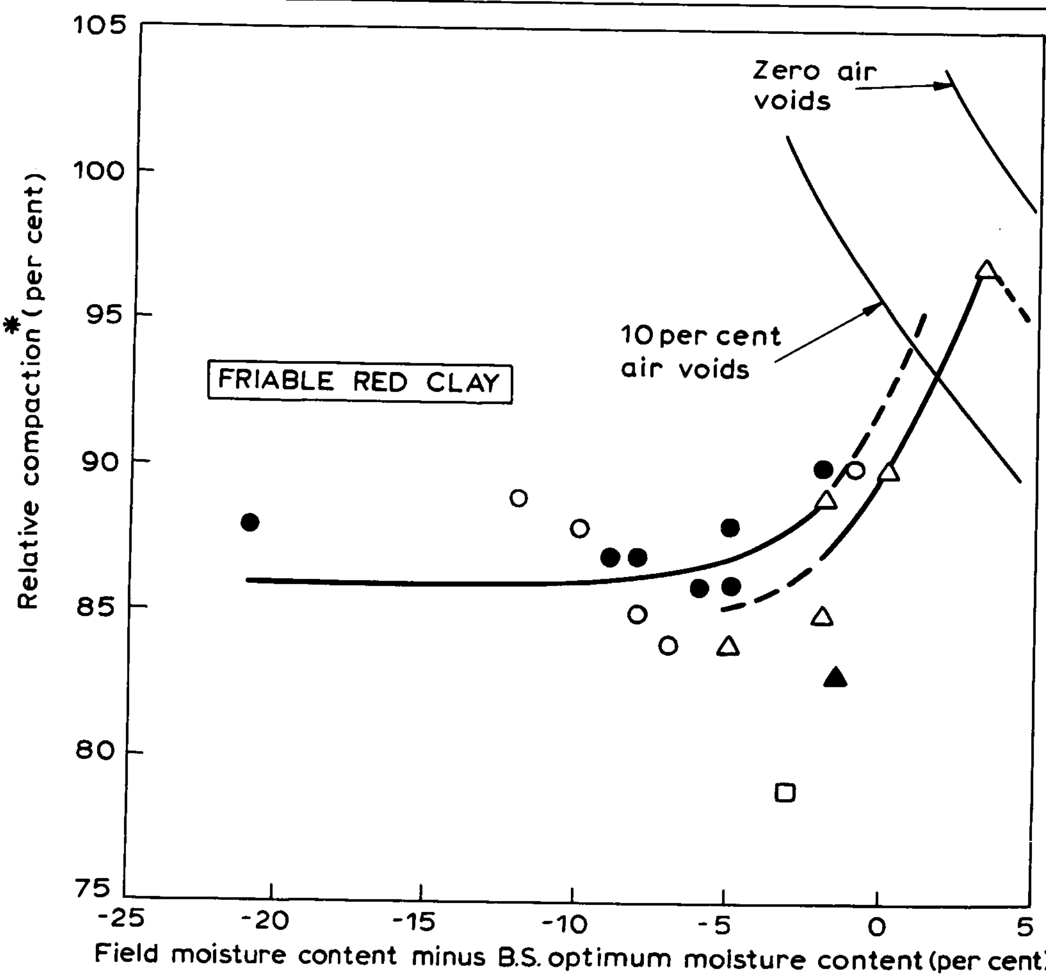
4 passes scraper equals 8 passes conventional pneumatic-tyred roller



*Relative compaction = $\frac{\text{Field dry density} \times 100}{\text{Maximum dry density of B.S. compaction test 2·5 kg (5·5 lb) rammer method}}$ per cent

Fig. 13. RELATION BETWEEN RELATIVE COMPACTION AND MOISTURE CONDITIONS FOR THE TOP 15 cm (6 in) OF COMPACTED SOIL FOR 4 PASSES OF A LOADED 13·8 m^3 (18 yd^3) MOTORIZED PNEUMATIC-TYRED SCRAPER ON FRIABLE RED CLAY SOILS AT SCHEMES Nos. 1 AND 9

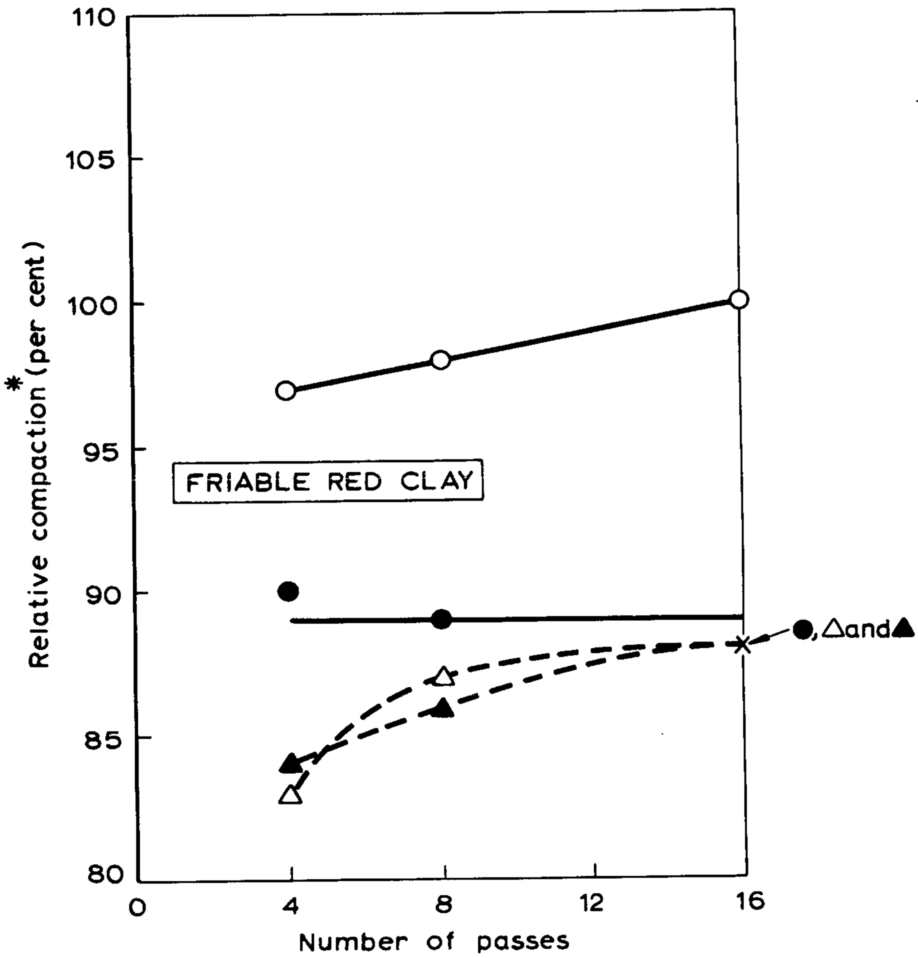
Type of plant	Wheel load and tyre inflation pressure	Approx shear stress in top 152cm (6in)		Symbol
		(N/cm²)	(lb/in²)	
Towed pneumatic-tyred roller	12Mg (12 tons) and 55N/cm² (80lb/in²)	17·3	25	○
	7Mg (7 tons) and 45N/cm² (65lb/in²)	14·5	21	●
Motorized scraper	9Mg (9 tons) and 34N/cm² (50lb/in²)	11·0	16	△
Self-propelled pneumatic-tyred roller	1·3Mg (1·3 tons) and 72N/cm² (105lb/in²)	15·9	23	▲
Towed scraper	2Mg (2tons) and 26N/cm² (38lb/in²)	8·3	12	□
Loose layer thickness varied from 15 to 43cm (6-17in) but dry density only determined in top 15cm (6in) of compacted soil				



*Relative compaction - as defined on Fig. 13

Fig. 14. RELATION BETWEEN RELATIVE COMPACTION AND MOISTURE CONDITIONS FOR THE TOP 15cm (6in) OF COMPACTED SOIL FOR 4 PASSES OF PNEUMATIC-TYRED WHEELS ON FRIABLE RED CLAY SOILS AT SCHEMES Nos 1,7, 9 AND 10

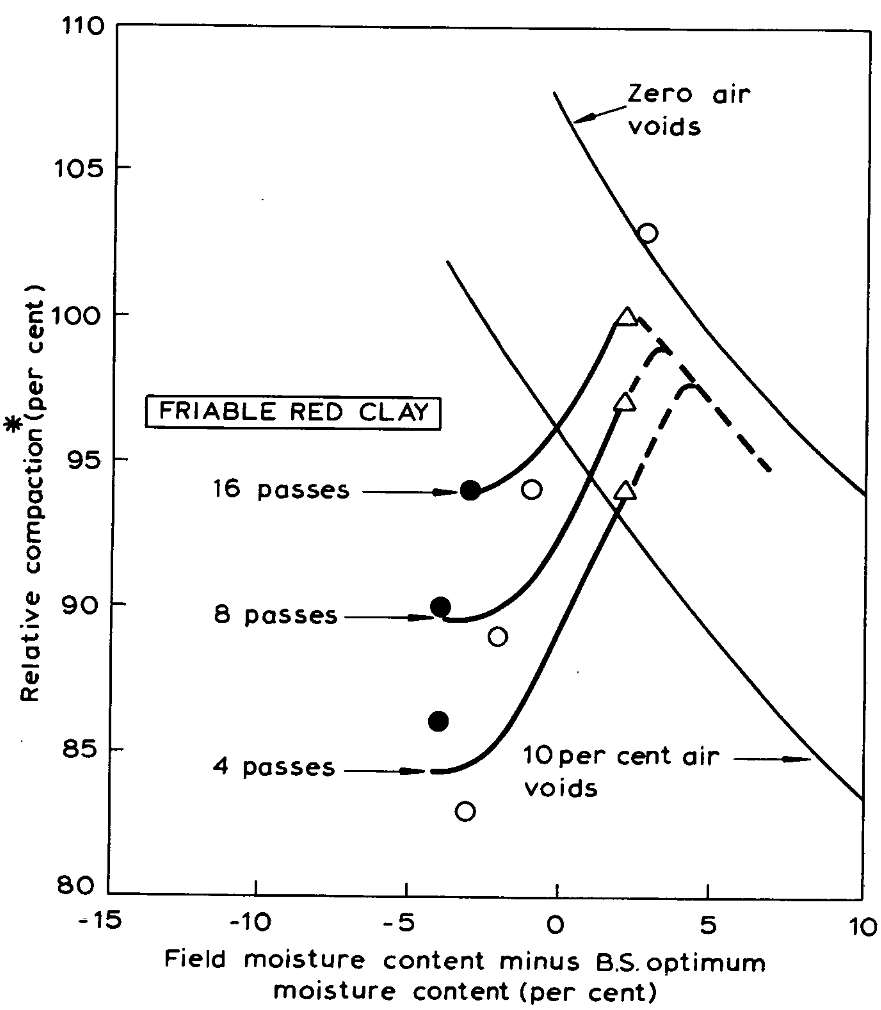
Type of plant	Wheel load and tyre inflation pressure	Field m.c. minus B.S. optimum m.c. (per cent)	Loose layer thickness (cm)	Loose layer thickness (in)	Symbol
Motorized scraper	9Mg (9 tons) and 34 N/cm^2 (50lb/in^2)	+2	23	9	○
		-2	23	9	●
Self-propelled roller	1·3 Mg (1·3 tons) and 72 N/cm^2 (105lb/in^2)	-2	23	9	△
		-4	15	6	▲



* Relative compaction - as defined on Fig. 13

Fig. 15. RELATION BETWEEN RELATIVE COMPACTION, LOOSE LAYER THICKNESS NUMBER OF PASSES OF PNEUMATIC-TYRED PLANT AT DIFFERENT MOISTURE CONDITIONS ON FRIABLE RED CLAY SOILS AT SCHEMES Nos. 9 AND 10

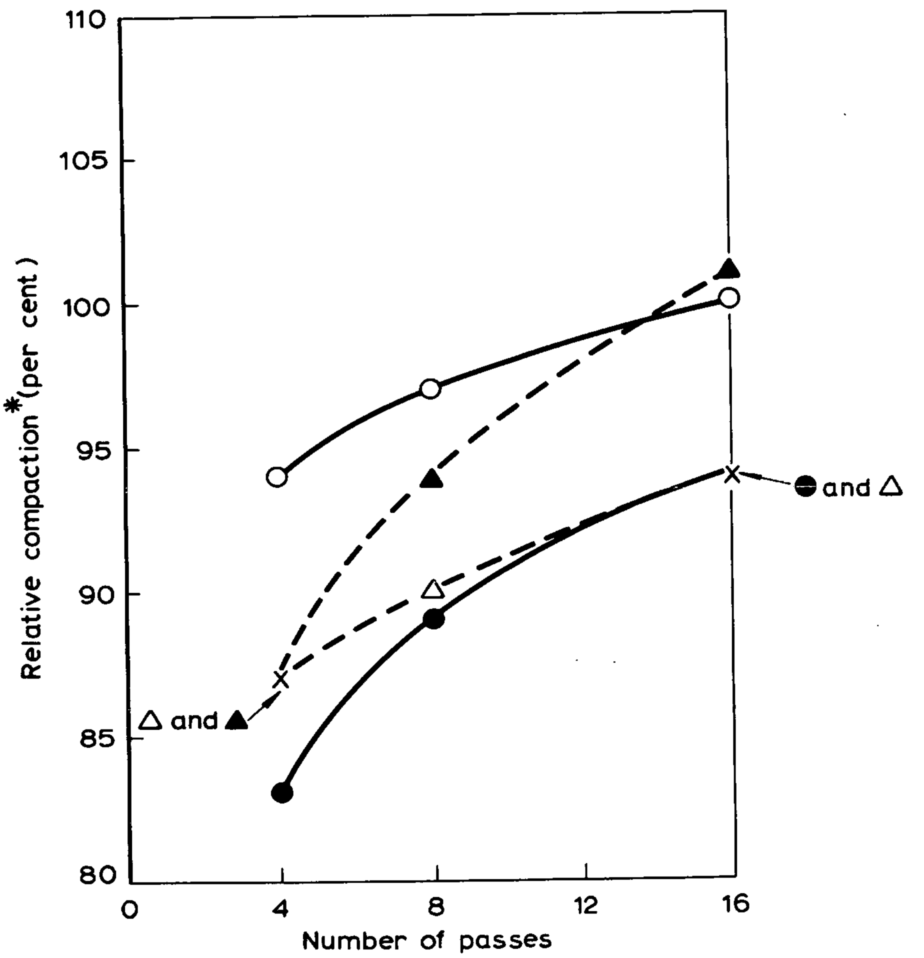
Smooth-wheeled roller	Load per unit width on rear rolls	
	(kg/cm)	(lb/in)
○	71·4	400
●	82·1	460
△	85·7	480
Loose layer thickness : 23cm(9in)		



*Relative compaction - as defined on Fig. 13

Fig.16. RELATION BETWEEN RELATIVE COMPACTION, AND MOISTURE CONDITIONS FOR THE TOP 15cm (6in) OF COMPACTED SOIL FOR 4,8 AND 16 PASSES OF SMOOTH-WHEELED ROLLERS ON FRIABLE RED CLAY SOILS AT SCHEMES Nos.9 AND 10

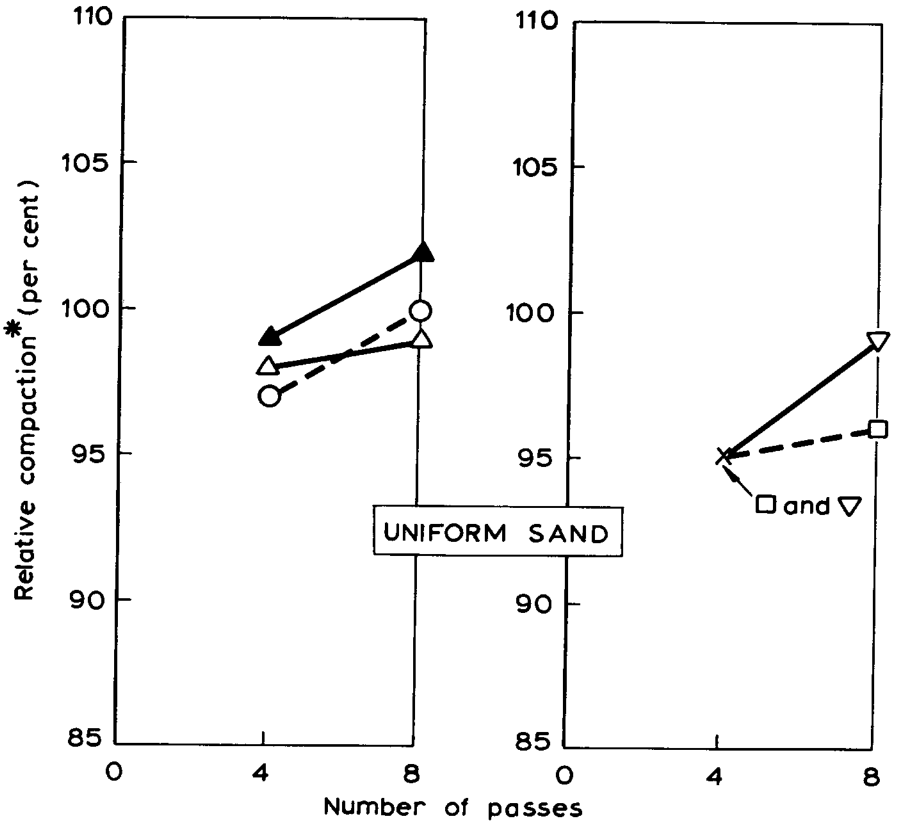
Load per unit width on rear rolls		Field m.c. minus B.S. optimum m.c. (per cent)	Loose layer thickness		Symbol
(kg/cm)	(lb/in)		(cm)	(in)	
85·7	480	+2	23	9	○
71·4	400	-2	23	9	●
82·1	460	-4	23	9	△
			15	6	▲



* Relative compaction - as defined on Fig. 13

Fig. 17. RELATION BETWEEN RELATIVE COMPACTION, LOOSE LAYER THICKNESS AND NUMBER OF PASSES OF SMOOTH-WHEELED ROLLERS AT DIFFERENT MOISTURE CONDITIONS ON FRIABLE RED CLAY SOILS AT SCHEMES Nos.9 AND 10

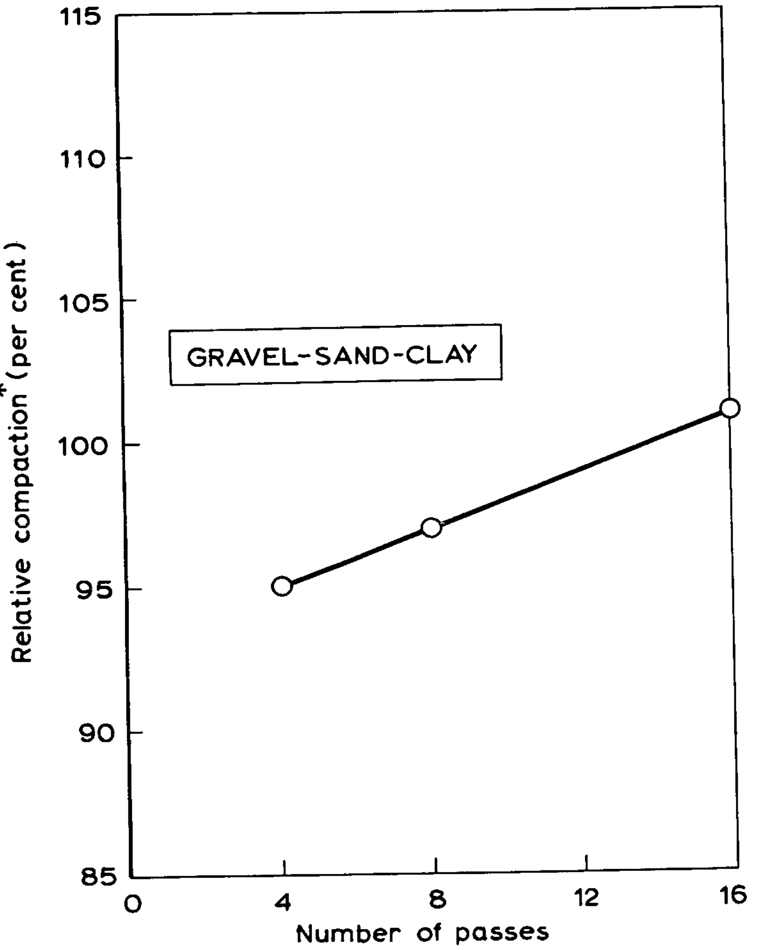
Type and details of plant	Field m.c. minus B.S. optimum m.c. (per cent)	Symbol
Pneumatic-tyred roller. Wheel load 0·7Mg (0·7tons) Tyre inflation pressure 21N/cm^2 (30lb/in^2)	-3	○
Vibrating roller. Load per unit width: 21·4 kg/cm (120 lb/in)	-4	△
	-2	▲
Smooth-wheeled roller. Load per unit width on rear rolls : 57·1kg/cm (320lb/in)	-3	□
Tracked tractor. Contact pressure 4·8N/cm^2 (7lb/in^2)	-2	▽



*Relative compaction - as defined on Fig. 13

Fig. 18. RELATION BETWEEN RELATIVE COMPACTION, AND NUMBER OF PASSES OF COMPACTION PLANT FOR A 23cm (9in) LOOSE LAYER THICKNESS ON UNIFORM SAND SOIL AT SCHEME No.6

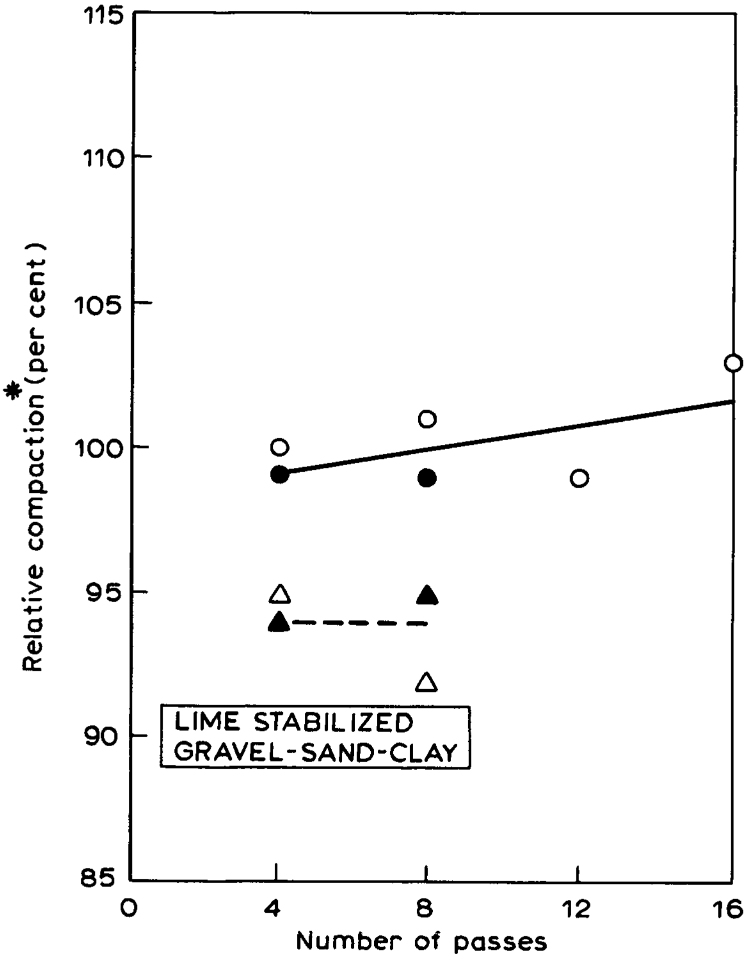
Load per unit width on rear rolls		Field m.c. minus B.S. optimum m.c. (per cent)	Loose layer thickness	
(kg/cm)	(lb/in)		(cm)	(in)
71·4	400	-2	23	9



*Relative compaction - as defined on Fig. 13

Fig. 19. RELATION BETWEEN RELATIVE COMPACTION, AND NUMBER OF PASSES OF A SMOOTH-WHEELED ROLLER FOR A 23cm (9in) LOOSE LAYER THICKNESS ON GRAVEL-SAND-CLAY SOIL AT SCHEME No.7

Type of plant	Tyre inflation pressure		Field m.c. minus B.S. optimum m.c. (per cent)	Symbol
	(N/cm^2)	(lb/in^2)		
Smooth-wheeled roller. Load per unit width on rear rolls: 55·4kg/cm (310 lb/in)	–		-1	○
			-2	●
Pneumatic-tyred roller. Wheel load: 1·4 Mg (1·4 tons)	10	15	-2	△
	23	34	-1	▲
Loose layer thickness : all 19 cm (7 1/2 in)				



*Relative compaction - as defined on Fig. 13

Fig. 20. RELATION BETWEEN RELATIVE COMPACTION AND NUMBER OF PASSES OF SMOOTH WHEELED AND PNEUMATIC TYRED ROLLERS FOR THE TOP 10cm (4in) OF COMPACTED MATERIAL ON STABILIZED GRAVEL-SAND-CLAY SOIL AT SCHEME No. 2

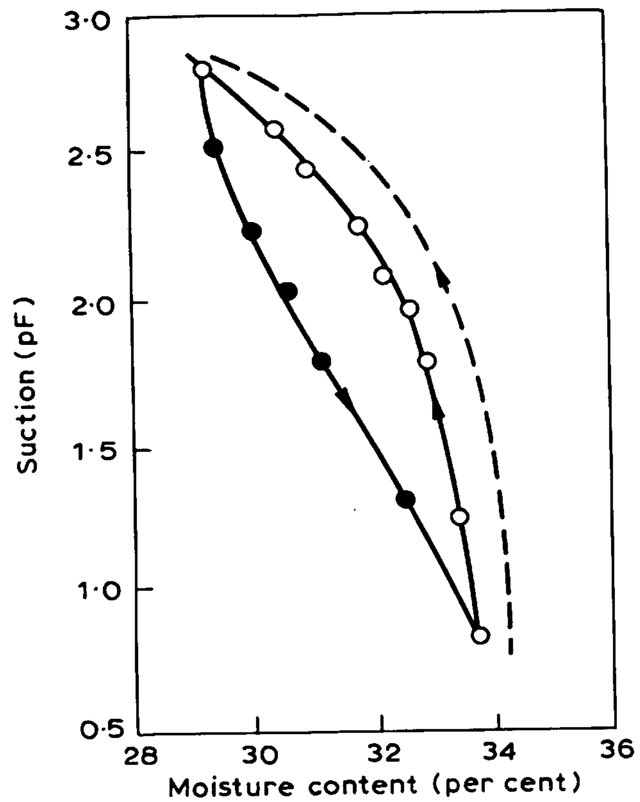


Fig. 21. SUCTION/MOISTURE CONTENT RELATION FOR HEAVY CLAY SOIL

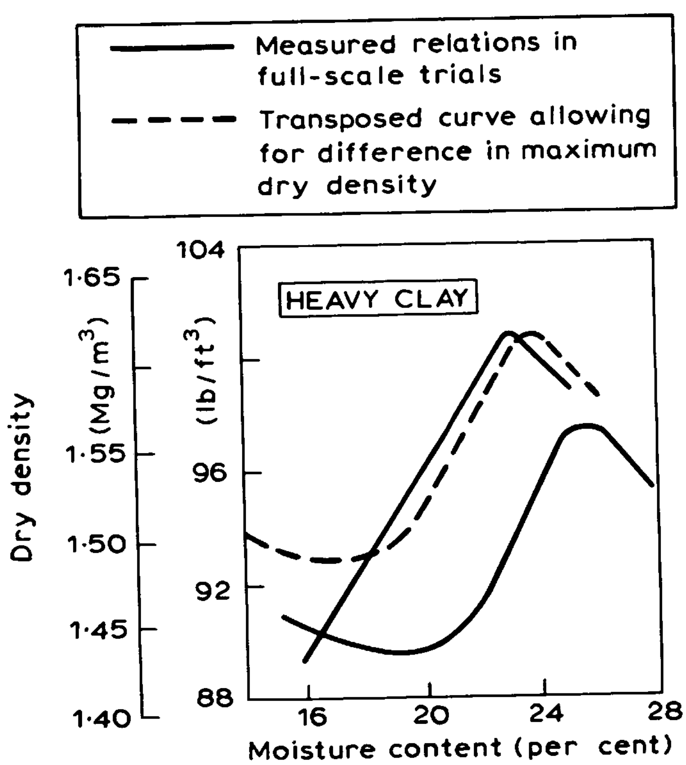


Fig. 22. TWO DRY DENSITY/MOISTURE CONTENT RELATIONS FOR A 12 Mg (12 tons) PNEUMATIC-TYRED ROLLER COMPACTING 23 cm (9 in) LOOSE LAYERS OF HEAVY CLAY SOIL

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ABSTRACT

The compaction of soils and stabilized bases on roads in East Africa: M.P. O'REILLY, ME, C.Eng., MICE, MIEI, Am.Inst.He. Department of the Environment, TRRL Report LR 600: Crowthorne, 1974 (Transport and Road Research Laboratory). As part of a study of aspects of normal road-building practice in tropical countries, the states of compaction achieved in road bases and earthworks were investigated at ten road construction schemes in East Africa. In addition, where possible, controlled compaction trials were carried out.

The most significant conclusion from the investigation is that the states of compaction achieved in the field correspond quite closely with those obtained in full-scale compaction tests carried out at the Transport and Road Research Laboratory. The relation between compactive effort, moisture content and the dry density obtained in the field followed accepted patterns; overstressing was noted on a uniform sand soil. The optimum moisture condition for compaction in the field was close to the optimum moisture content in the B.S. Compaction test 2.5 Kg (5.5 lb) rammer method and simple and rapid methods of appraising the moisture conditions were effective in maintaining the moisture contents within an acceptable range.

The study showed that the states of compaction commonly specified for tropical roads can be attained under normal working conditions.

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