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TITLE: Soil compaction at low moisture content-field trials in Sudan

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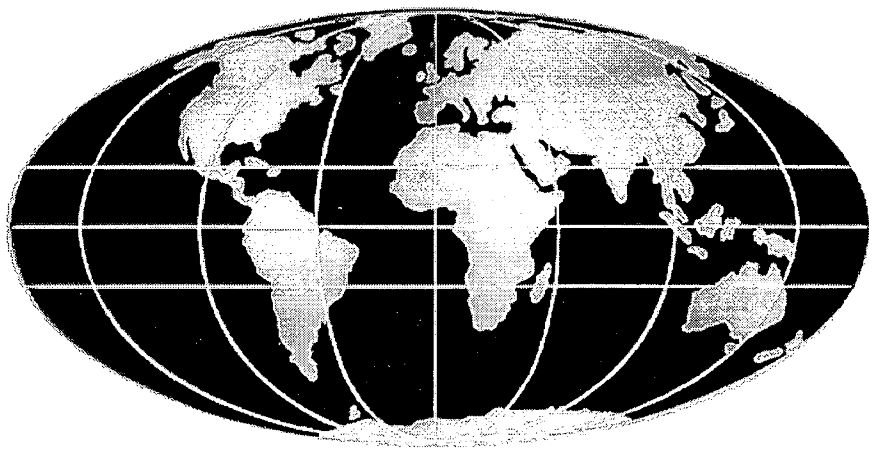

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Soil compaction at low moisture content
Field trials in Sudan

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SYNOPSIS. The difficulty of achieving optimum moisture content for the compaction of soils in arid areas is outlined, and past experience in soil compaction at low moisture contents is reviewed. The construction of a trial road embankment of a black silty clay in Sudan is described. The plasticity index of the fill material was 26-36 and it was compacted at its field moisture content, 20 per cent less than the Proctor optimum moisture content. Two types of rollers were used and densities ranging from 94 to 105 per cent of Proctor maximum dry density were achieved. In spite of the low moisture content at which it was compacted, this embankment has performed satisfactorily for a year and a half and the road it carries has suffered no ill effects. The implications are examined of using dry compaction for road construction on expansive clays in arid areas.

RESUME. Le rapport décrit la difficulté d'obtenir une teneur en eau optimale pour le compactage des sols et passe en revue les expériences déjà faites en matière de compactage des sols à teneurs en eau basses. La construction d'un remblai expérimental pour route en argile de limon noire, au Soudan, est décrite. L'indice de plasticité du matériau de remblai était de 26-36 et le compactage avait été effectué à la teneur en eau in situ, c'est à dire à 20 pour cent de moins que la teneur en eau optimale de Proctor. Deux types de rouleaux ont été utilisés, grâce auxquels on a atteint des densités allant de 94 à 105 pour cent de la densité sèche maximale Proctor. En dépit de la teneur en eau basse, à laquelle le compactage a été effectué, la performance du remblai s'est avérée satisfaisante pendant un an et demi et la route sur le remblai n'a souffert aucun effet nocif. L'auteur examine les implications pour la construction routière du compactage à sec des argiles expansives dans les zones arides.

1. INTRODUCTION

Traditionally, the student of compaction is taught that good construction practice requires unbound road materials and soils to be compacted at their optimum moisture content as determined in a suitable laboratory compaction test so that maximum density can be achieved with a given compactive effort. Where materials occur naturally at moisture contents close to this optimum value, or where water is cheaply available, this requirement presents few problems. However in arid areas water can be an expensive construction material, and in addition the mixing of large quantities of water into fine grained soils can present severe technical problems. Thus there are considerable economies available if it can be shown that adequate performance can be assured when materials are compacted without the addition of water, or with the addition of only a small amount.

2. DRY COMPACTION

Standard laboratory compaction tests give relationships of the type shown in Fig. 1. For a particular compactive effort increasing moisture contents yield increasing densities up to the optimum moisture content, but beyond this point the addition of further water leads to lower densities. As the compactive effort increases the dry density increases, but the optimum moisture content is reduced. Similarly with field compaction

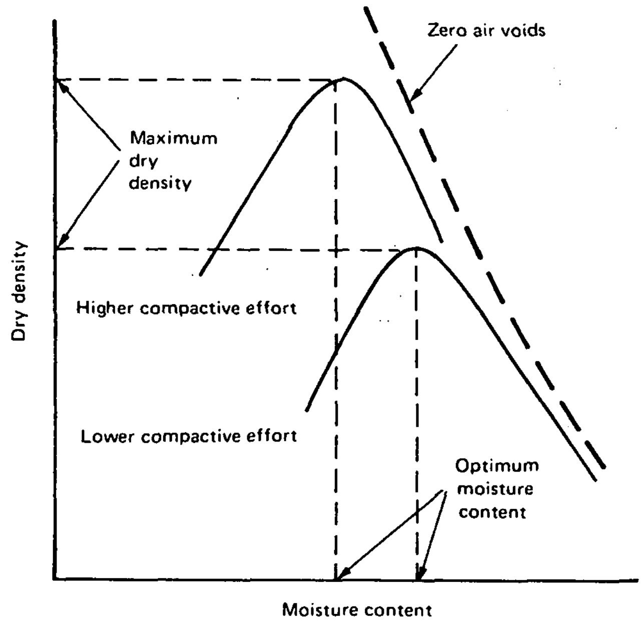


Fig. 1 Conventional compaction curves

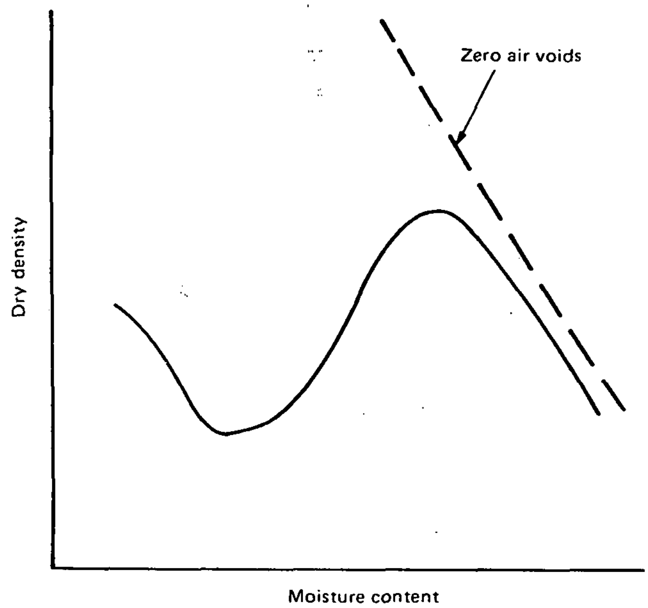


Fig. 2 Extended irregular compaction curve

plant on the same soil the heaviest rollers compact most effectively at lower moisture contents than the lighter rollers.

If compaction tests are carried out using a larger number of test points and a range of moisture contents extending towards zero, the resulting compaction curve can be irregular such as that indicated in Figure 2. The exact form of the curve depends on the type of the material, but it is not uncommon for the extended compaction curve to have a minimum value and a portion where density decreases as the moisture content is increased. Many examples of extended irregular compaction curves are reported in the literature (Morris 1975, Grace and Cocksedge 1978, Lee and Suedkamp 1972, Lee 1976, Lewis 1954, Lewis and Parsons 1961, Mtango 1979, Forssblad 1974). The shape of this 'dry end' of the compaction curve is particularly relevant to any study of 'dry' compaction. In the example of Fig. 2 there are certain values of dry density which can be achieved at three different moisture contents with the same compactive effort. It is necessary to know whether compaction at the driest moisture content is feasible in practice and how many materials have compaction curves with this feature.

Compaction is normally measured in terms of the dry density of the material. Whilst this is undoubtedly the most important parameter, there are other factors which need to be considered. High air voids contents and high soil suction values both have a potential for causing problems after construction, and the lack of cohesion in dry materials can cause severe construction difficulties.

3. AVAILABLE EXPERIENCE

3.1 Australia

A considerable amount of research on compaction was carried out during the years 1962-73 on a wide range of roller types and materials. The studies covered a wide range of moisture contents. A number of authors were concerned with this work, but a summary was prepared by the Australian Road Research Board as ARRB Report No. 35 (Morris 1975).

In current construction practice attention is paid to the scheduling of construction work such that dams may be built or bores drilled several seasons in advance of the work so that compaction water is available when required. In addition care is taken to make the best use of water by applying it at the time of day when it will have most effect eg at night or early morning when evaporation rates are low. Heavy rollers are normally employed in order to take advantage of their lower roller optimum moisture contents. Dry compaction of sub-grades is not uncommon in arid areas but pavement materials are normally compacted at or near roller optimum moisture content. In areas of expansive clays attempts are made to compact at the estimated ultimate equilibrium moisture content in order to minimise subsequent volume changes and consequent cracking.

3.2 South Africa

About 13 years ago the University of Pretoria completed a three part study of soil compaction in arid areas (Van Rooyen and Wessels 1967 a, b, c) which concentrated largely on the use of additives to assist compaction. This study was followed by a report on the uses of additives by NIRR (Todres 1970). Additives which are surface-active agents lower the surface tension of water and hence cause it to wet surfaces more effectively. The addition of these substances therefore improves the wetting of soil particles and improves the interparticle lubrication in the compaction process. Other additives create a flocculant effect whereby long chain molecules with two ionic groups latch onto soil particles and pull them together. In each case the overall effect is to lower the optimum moisture content for a particular level of compaction without significantly affecting the maximum dry density.

The development of the impact roller in South Africa was originally geared to the compaction of 'collapsing' soils but the roller has since been found to provide effective compaction to depths of 2 to 4 metres in uniform sands at low moisture contents (Clifford 1976).

3.3 North Africa

Trials carried out in Algeria (Republic Algérienne Democratique et Populaire 1977) on sands and gravels suggested that these particular materials were difficult to use for a dry compacted road. Tests in Morocco (Kabbaj 1979) using natural well graded gravels as fill material were reported to be successful but problems were experienced with dry sands.

Farther south in Mali, experiments with dry compaction on gravel roads are reported to have been particularly successful and the technique is now being used in other countries involved with the UNDP Sahelian feeder road project (International Road Federation 1978).

3.4 Europe

In the past a great deal of compaction research has been carried out in the United Kingdom by TRRL and in France by LCPC but naturally very little of it has been directly relevant to problems of dry compaction in arid areas. At TRRL early work (Lewis 1954) included tests with fairly low moisture contents but only recently has a research programme been started to look specifically at arid area construction techniques. Elsewhere investigations have been carried out into the dry compaction of sand (Grace and Cocksedge 1978). French work on crushed quartzite sands is of particular interest to students of dry compaction (Chaigne and Blivet 1971). The highest densities were achieved at zero moisture content and good results were obtained from a wide range of vibrating rollers.

More recently the Norwegian Road Research Laboratory have studied the dry compaction of a Kenyan gravel (Mtango 1979) and concluded that with this material successful dry compaction was only likely when natural moisture contents were very close to zero.

Most of the practical research on dry compaction carried out to date has been concerned with sand and gravel materials. Clearly many materials in this broad category can be compacted adequately without added water and give good road performance. However it is not clear what criteria should be adopted in the selection of materials or compaction techniques to ensure adequate performance. Dry compaction is not usually attempted for pavement materials on surfaced roads.

Published work on dry compaction of clays is virtually limited to the Australian experience where the main recommendation for expansive materials is to compact at moisture contents close to 'equilibrium'.

For all materials, vibrating rollers are generally favoured as the most effective type of plant for dry compaction.

4. DRY COMPACTION TRIAL IN SUDAN

4.1 Design of experiment and laboratory testing

A full-scale compaction trial has been

undertaken by TRRL in collaboration with the Sudanese Roads and Bridges Public Corporation. The trial, which was constructed in May/June 1978 on the Wad Medani-Sennar-Kosti road project, was designed to study the dry compaction of a black silty clay for use on a road embankment and subgrade. The experimental site is approximately 27 kilometres west of Sennar in an area where the average annual rainfall is 400-500 mm, all concentrated in the months June to September.

The expansive silty clay contains about 87 per cent of material passing the 75 µm sieve, is derived from igneous rocks, and contains clay minerals of the montmorillonite type. It is classified as MH on the Casagrade classification system with a Liquid Limit of 64-76 per cent, Plastic Limit of 38-42 per cent and a Plastic Index of 26-36 per cent.

At the trial site minor alterations to the vertical alignment of the road were approved in order that a standard embankment height of 1.2 metres could be maintained over the whole trial length. The experiment occupied a total length of 600 metres and was divided into 6 trial sections of 100 metres each (see Figure 3). It was decided that all sections would be constructed in 6 equal layers of 200 mm compacted thickness, and that the only variables would be the moisture content of the fill material and the type of roller. The moisture content for a particular section was controlled by permitting scrapers to excavate material only from between given depths in the borrow area. Hence with the soil moisture profile shown in Figure 4 material excavated from the surface to 300 mm had a moisture content range of 7-11 per cent; material from 300 mm to 600 mm had a range of 11-14 per cent; and material from below 600 mm had a moisture content greater than 14 per cent.

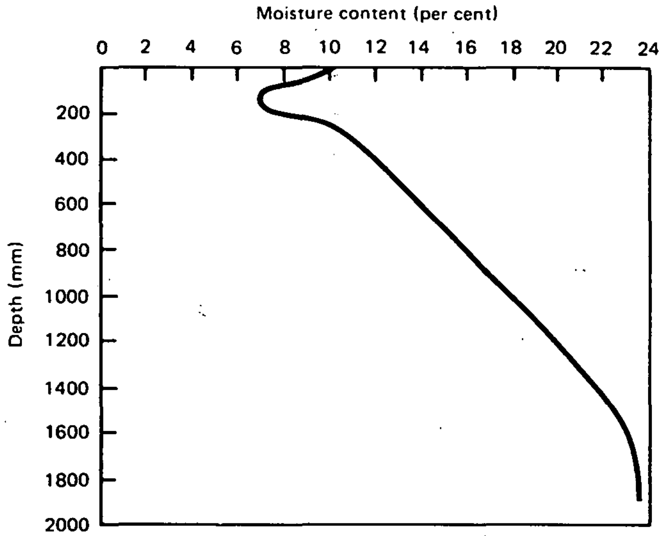


Fig. 4 Moisture content profile in natural ground – May 1978

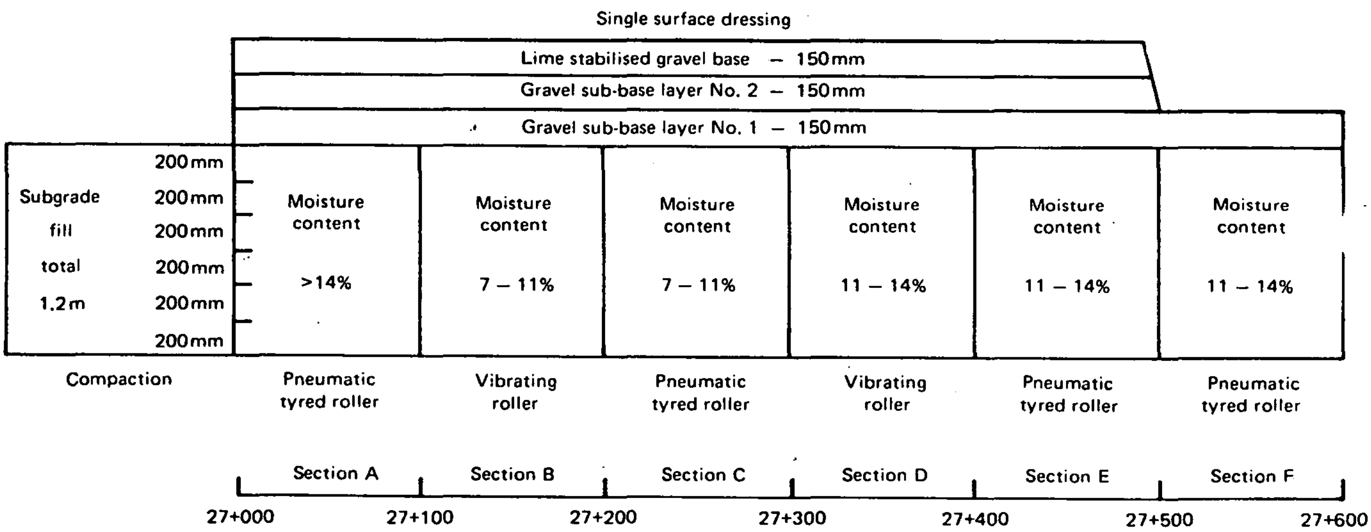


Fig. 3 Dry compaction trial: Sennar – Kosti road

The selection of rollers was limited to the two types of roller in common use on the project. One was a 10-tonne self propelled vibratory roller (Aveling Barford VS Vibra Victa), and the other was a 8-tonne pneumatic tyred roller (Aveling Barford PM20) which when fully ballasted operated at nearly 20 tonnes.

The five sections A, B, C, D and E were all covered with a pavement similar to that used elsewhere on the main project. This comprised two 150 mm sub-base layers of natural gravel, 150 mm layer of lime stabilised gravel base, a prime coat and a single surface dressing. The only difference between the pavement over the trial sections and the main project pavement was the substitution of a single surface dressing for the 50 mm asphaltic concrete surfacing. Section F only, had a pavement of one layer of natural gravel sub-base. It was intended that any subsequent settlement as a result of the dry compaction should be substantially over before the rest of the pavement was completed.

Laboratory compaction tests were carried out at different levels of compaction and yeilded the relationships shown in Figure 5. For the ordinary BS compaction test (British Standards Institution, 1975) the optimum moisture content was 29.5 per cent with a maximum dry density of 1.45 Mg/m^3 (90.7 lb/ft^3) compared with Heavy BS values of 22.3 per cent for optimum moisture content and 1.70 Mg/m^3 (106.2 lb/ft^3) for maximum dry density. As previously mentioned the irregular shaped compaction curves such as those shown in Figure 5 are particularly significant for the study of dry compaction. Although these curve shapes are not uncommon when compaction testing is extended to include very dry materials, many engineers are not familiar with this type of relationship. This is because normal compaction test procedure is only concerned with values close to the conventional optimum moisture content.

The laboratory compaction testing was carried out in 6 in. diameter moulds so that each specimen could be used for CBR testing also. Figure 6 gives the Iso-CBR chart which provides an indication of the sensitivity of the soil strength to moisture content and density.

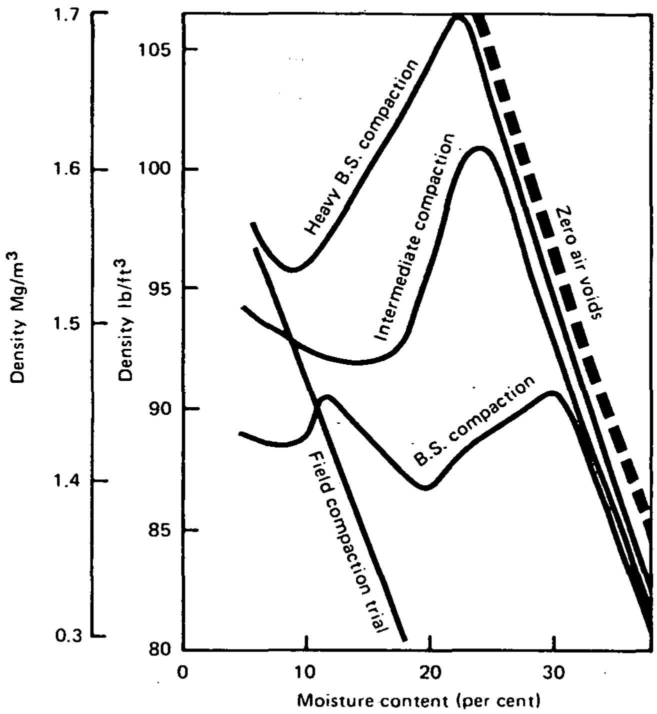


Fig. 5 Comparison of field and laboratory compaction

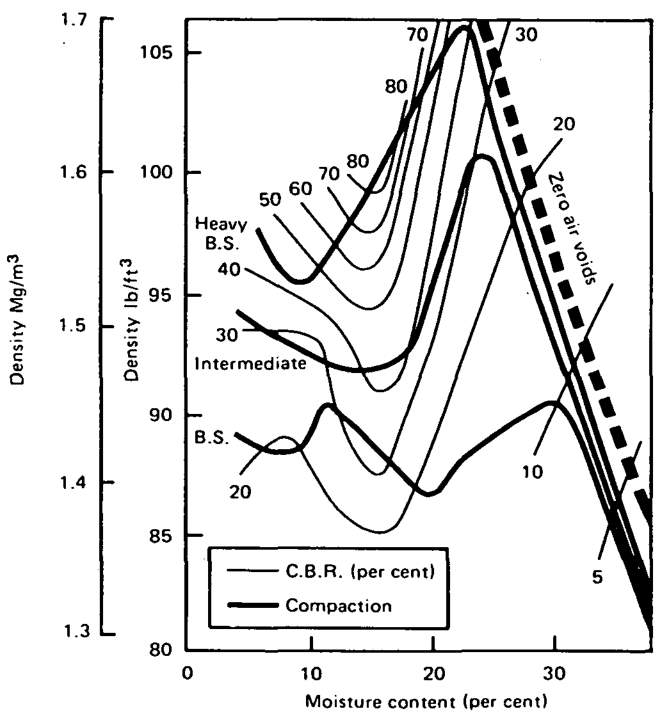


Fig. 6 ISO-CBR Chart – Laboratory compaction

4.2 Construction

The first construction operation was to install concrete monuments on each side of the road to mark the precise chainages of the beginning and end of each trial section and to act as temporary bench marks. Because of the expansive nature of the black silty clay these monuments were not adequate as permanent bench marks and therefore a suitable bench mark was installed on an adjacent 'Jebel' (rock outcrop).

The new road embankment was to be built on the line of the existing track but before construction started the whole area was cleared of vegetation and a grader used to carry out minor earthmoving operations. This operation was required so that the height of fill material would be identical for all six trial sections.

Apart from the moisture content of the fill material and the type of roller used for compaction, the construction and testing procedure was identical for each layer and each section. Fill material was excavated with scrapers from the appropriate depths in the borrow pit to ensure uniform moisture content and then transported and spread on the trial section. The loose material was shaped with a grader and levels checked before being rolled with 12 passes of the appropriate roller. Measurements were then made of dry density, moisture content and Impact Value (Clegg 1977) and optical levels were taken to provide cross section details.

Dry density measurements were made at six points per layer for each section using the sand replacement method. Average values were between 94 and 105 per cent of BS compaction test maximum and it is particularly significant that for both rollers the field density values decrease as the moisture content increases over the range of moisture contents studied. Because of the dry material there was considerable difficulty in making regular shaped density holes and this almost certainly contributed to fairly wide variations in the measured densities. The differences between the two rollers were not significant and therefore a single line is drawn to represent all field compaction (Figure 5).

The field density results over this limited range of moisture contents suggests that the field compaction curves have a similar shape to the laboratory compaction curves in as much as that they have a marked minimum density value.

Since field moisture conditions, in this case at least, are on the dry side of the moisture content corresponding to the minimum density it seems likely that some normal field compaction operations would permit the adding of insufficient water to reach the conventional optimum. This could encourage compaction to be carried out at or near the moisture content corresponding to the minimum dry density. In view of the known practical difficulties in adding and mixing large quantities of water particularly to clay soils, it appears in some cases that much of the effort employed in hauling water in arid areas could be counter productive in achieving high densities. Certainly the subject requires some detailed consideration before large compaction programmes are undertaken in arid areas.

Moisture contents and Impact Values were both measured at twenty points per layer for each trial section. The means of all test values for each trial section are given in Table 1.

On completion of the trial embankment the pavement layers were constructed in the same way as elsewhere on the Wad Medani-Sennar-Kosti project. No attempt was made to use dry compaction but construction quality was monitored in a similar way to the experimental sections. On completion of the surface dressing and opening to traffic, cross section levels were taken at 0.5 metre intervals across the road to provide a datum for comparison with subsequent levels.

4.3 Performance

The construction of the experimental sections was completed just before the 1978 wet season. Since that time there have been three detailed inspections of the road at which a visual assessment was made of the road condition together with a traffic survey and determination of cross section levels and moisture conditions in the embankment.

Moisture conditions were monitored by digging a hole through the pavement to the sub-grade and then augering to a depth of about 1 metre taking samples at 300 mm intervals. This operation was repeated 3 times at a selected chainage within each trial section such as to give values beneath the centre line and under each edge of the pavement. The selected chainage was different for each inspection. The moisture content profiles and their changes with time are indicated in Figure 7. These measurements have given no cause for concern for the performance of the trial sections.

Table 1. Mean test values - embankment.

	Section A	Section B	Section C	Section D	Section E	Section F
Dry density Mg/m^3	1.35	1.48	1.49	1.40	1.37	1.35
lb/ft^3	84.53	92.55	93.36	87.49	85.36	84.49
Moisture content - per cent	14.9	8.73	8.67	12.86	13.19	13.88
Impact Value (Clegg 1977)	13.2	10.6	11.6	12.8	12.1	12.1

Analysis of the cross section levels suggest that there has been negligible differential settlement since the completion of construction and there is no deterioration of the road surface shape which can be attributed to any effect of the dry compaction procedures adopted during construction.

The visual assessments carried out at each inspection have yielded only minor signs of road deterioration. At the first inspection only one small crack was identified. At the second inspection a few additional cracks had appeared but they were sealed with hot bitumen and chippings. At the third inspection no further cracks could be identified. The nature of the cracks suggest that they were related to the stabilised base rather than the dry compaction of the subgrade and fill materials. At the edge of the embankment there are occasional erosion channels which need to be rectified before the next wet season.

Traffic counts made since the completion of construction suggest that in the dry season the average daily traffic is about 200 vehicles in both directions but falling to about 100 vehicles per day in the wet season. No doubt this fluctuation will even out once an all-weather route is completed to Kosti. Commercial vehicles form about 80 per cent of the total traffic.

4.4 Conclusions from Sudan experiment

From the results of the experiment so far it appears that compaction of clay embankments without added water may be a perfectly acceptable construction technique for use in this part of Sudan. However the satisfactory performance of these trial sections only proves that dry compaction is effective under the particular conditions of the experiment and further investigations are required into the sensitivity of road performance to different levels of supervision or variations in thickness of compacted layers, number of roller passes and material characteristics.

Field dry density values of between 94 and 105 per cent of BS maximum dry density were generally higher than expected, but in part this may have been due to the expansive nature of the soil in that the shrinkage of the material at low moisture contents makes it easier to pack more material into a given volume.

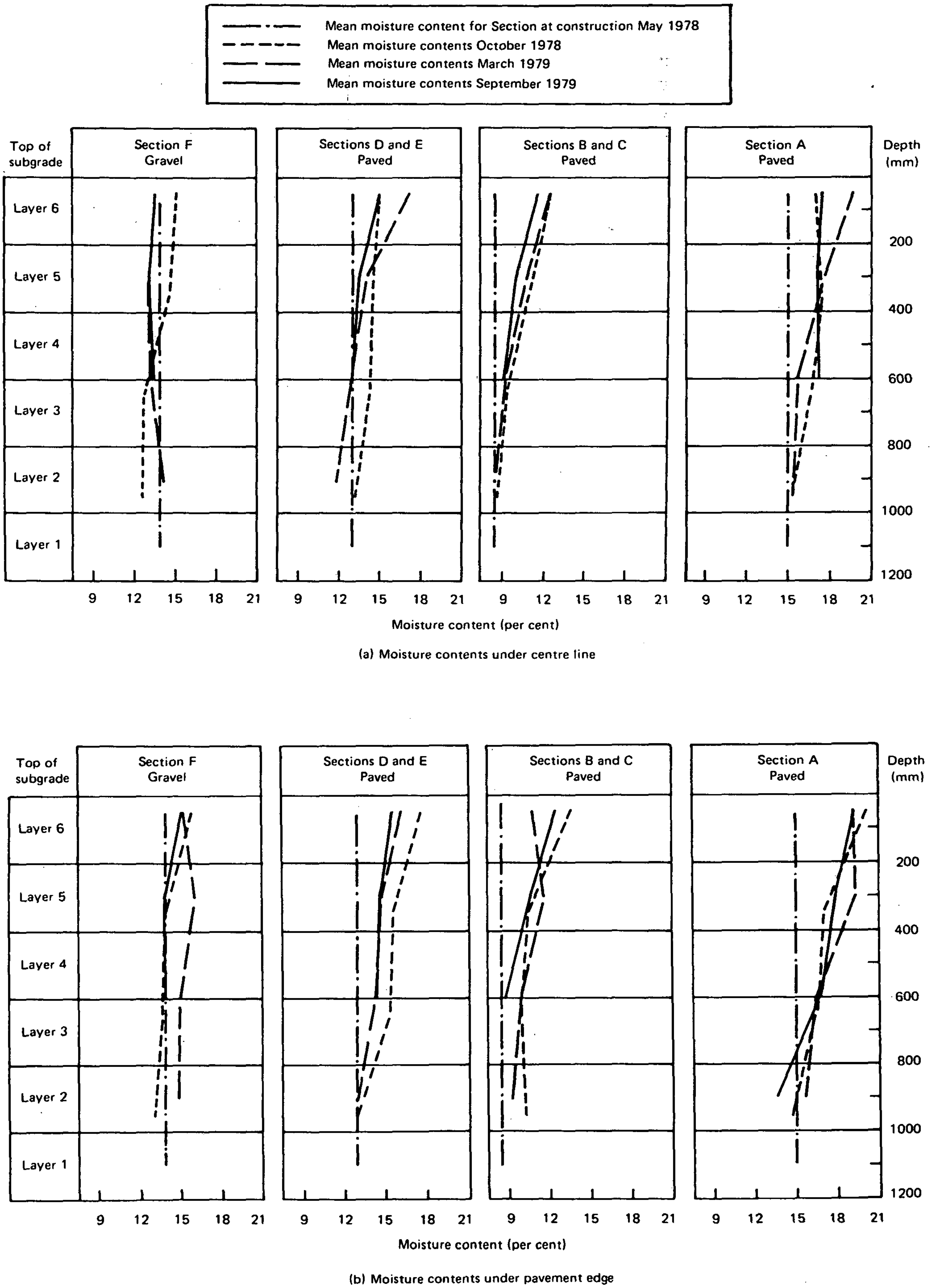
The differences in performance between the pneumatic tyred roller and the vibrating smooth wheel roller were negligible under the conditions of this trial. This does not necessarily mean that both rollers are equally efficient. One roller may be capable of achieving the final density with a smaller number of passes than the other. It is also possible that one roller was more effective at producing additional compaction at depths below the top layer. Such an effect would not have been identified by the density testing procedure adopted during this trial. However many engineers would expect the vibrating roller to be more effective than the pneumatic tyred roller in both these respects.

In most situations dry density is the most important parameter in assessing the performance of dry compaction. However in dry conditions high densities will also be associated with high air voids and these could lead to problems if the embankment wetted up too quickly. The moisture measurements made during this trial gave no indication that soil moisture changes are creating any problems.

5. IMPLICATIONS FOR ROAD CONSTRUCTION ON EXPANSIVE CLAYS IN ARID AREAS.

5.1 Subgrade strength

Because the relationship between moisture content and suction exhibits hysteresis between the wetting and drying curves, it can be shown that a dry compacted subgrade will attain a lower equilibrium moisture



(a) Moisture contents under centre line

(b) Moisture contents under pavement edge

Fig. 7 Changes in moisture content since construction

content than one that has been compacted at a moisture content wetter than the ultimate equilibrium value. This lower moisture content results in higher subgrade strength and hence increases the life of the road. In addition the greater stiffness of the stronger subgrades provides a better platform for the compaction of subsequent layers thus helping to obtain the best possible performance from the pavement. Alternatively it can be argued that thinner pavements are required for the same performance. Although not related specifically to the question of dry compaction of expansive clay fills, the principles relating to the prediction of the strength of clay fill subgrades and its relation to road performance have been discussed by Black and Lister (Black and Lister 1978).

5.2 Volume changes and cracking

Wet expansive clay will shrink and crack when the moisture content is reduced causing cracks to appear in the road pavement above. These cracks subsequently permit water to enter the structure and create a weakness which eventually causes complete road failure. This failure mechanism is only too familiar to highway engineers and others working with expansive clays. Dry compaction is one way in which the adverse effects of expansive clays can be minimised since materials compacted dry may be expected to gradually wet up to equilibrium moisture content without cracking. In the absence of cracking subsequent wet and dry cycles will have a minimum effect on a road pavement. If compaction is carried out at the equilibrium moisture condition then in theory there should be no cracking and no volume change.

5.3 Differential swelling and settlement

When water is added to clay materials it is very difficult to obtain good mixing and even distribution of moisture. This means that different parts of the soil mass will expand or shrink by different degrees as equilibrium values are approached and potentially this can cause differential movements and possibly cracking in the road pavement. However at naturally occurring moisture contents the distribution of water throughout the material is very even and therefore changes in moisture content towards equilibrium values are more likely to be accompanied by uniform movements within the soil mass, thus reducing the chances of pavement deformation and cracking.

5.4 Collapse settlements

The size distribution of individual fragments or clods of dry clay will undoubtedly affect the compaction and performance characteristics of a clay material. Depending on the plasticity, the clods will have different resistance to the breaking down action of construction plant. Dry compacted clays will usually have high air voids which could permit moisture changes to take place quite rapidly. The points of contact between the dry clay fragments or clods are highly stressed and the addition of water may allow softening at the points of contact with consequent collapse settlement.

5.5 Compacted densities

Laboratory compaction trials do not necessarily give the same relationships between density and moisture content as field compaction and therefore it is important to select the laboratory test which best reproduces field conditions. Where the use of dry compaction is anticipated laboratory vibrating hammer density tests should be considered in addition to the normal falling hammer tests.

If the natural moisture content is less than that corresponding to any minimum density value on the relevant compaction curve, adding water in insufficient quantities may lead to compacted densities lower than could be obtained without added water.

The factors discussed above consider some of the main implications of adopting dry compaction of expansive clays in arid areas. Compared with traditional compaction methods at optimum moisture content, dry compaction offers the possibility of increased subgrade strength, reduced cracking, reduced differential movements and reduced costs. Dry densities are likely to be lower than those to be expected at optimum conditions but possibly higher than those often achieved in practice. It is essential that realistic relationships between density, moisture content and compactive effort are derived for each new material before dry compaction is attempted on a major project.

The major disadvantages relating to dry compaction appear to be related to the high air voids and the risks of collapse settlement.

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