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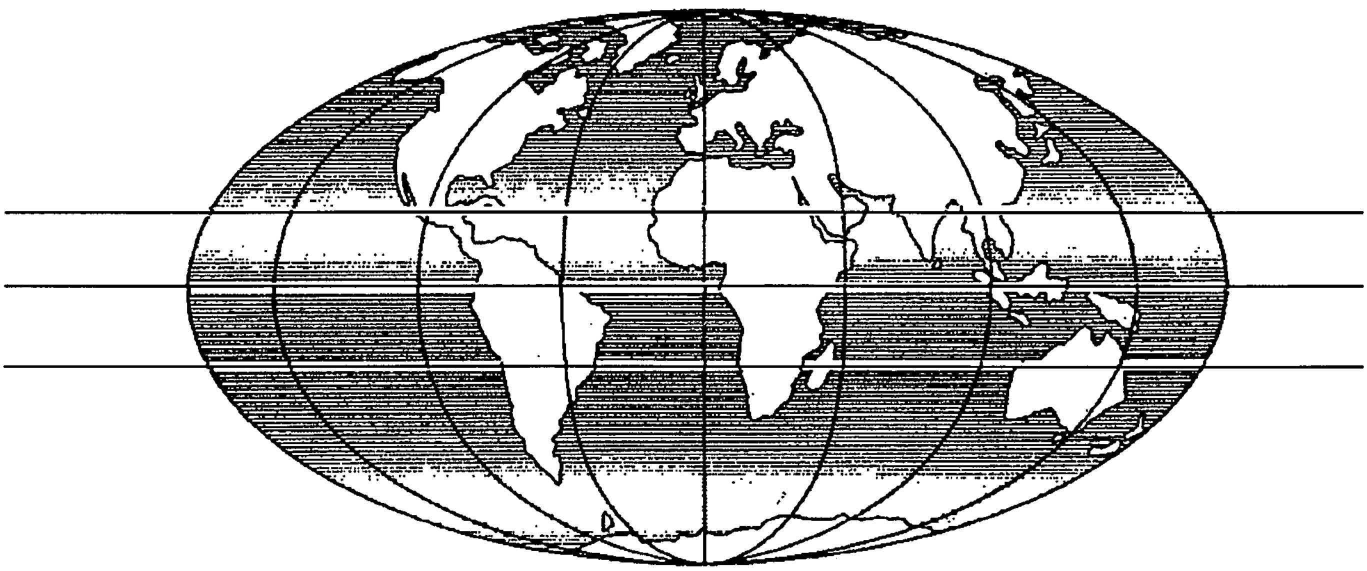
TITLE **Soil compaction at low moisture contents in Kenya**

by **M J O'Connell, et al**



Overseas Centre
Transport Research Laboratory
Crowthorne Berkshire United Kingdom

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SOIL COMPACTION AT LOW MOISTURE CONTENTS IN DRY AREAS IN KENYA

M J O'CONNELL*, J H G WAMBURA** AND D NEWILL*

* Transport and Road Research Laboratory, United Kingdom

** Ministry of Transport and Communications, Kenya

ABSTRACT: A joint research project between the Ministry of Transport and Communications, Kenya and the Transport and Road Research Laboratory, UK is a study of soil compaction at low moisture contents in arid areas. This paper describes part of the study in which an investigation has been carried out on a well-graded clayey gravel designated as a road base material for a road project in NW Kenya. The investigation comprised laboratory testing, pilot and full-scale trials to examine the density and strength characteristics of the material at low moisture contents. The results were compared with those obtained when compaction was carried out under normal requirements at optimum moisture content.

It was shown that high densities were achieved at low moisture contents both in laboratory tests and in the field trials and that vibrating compaction methods were preferred. Conventional construction plant and operating techniques were successfully applied and specifications for compaction in Kenya were readily exceeded. Field CBR measurements for the base constructed at low moisture contents were lower than those obtained in the laboratory. Analysis of pavement strength parameters including deflection, radius of curvature and structural number showed that the trial sections were different but indicate that the designs were adequate for a life of 0.5 million equivalent standard axles. The road trials constructed with bases at different initial moisture contents have performed equally well for two years but further information on the longer term performance is required before final recommendations can be made on the use of dry compaction.

1. INTRODUCTION

Soil compaction at constant compactive effort and different moisture contents generally produces a dry density-moisture content relation with a well-defined maximum dry density and optimum moisture content similar to that shown in Fig 1. At very low moisture contents and at constant compactive effort the density of many soil types will increase in a way shown in Fig 2. For most cases the natural moisture contents of soils are close enough to the optimum for only relatively small adjustments to be required in order for maximum density to be achieved. In hot dry climates, however, this is not so and problems often occur if large quantitites of water have to be added in areas where it is both scarce and expensive. The fact that high densities can be achieved at low moisture contents and that this has only rarely been exploited, has led to a joint research project being set up between the Transport and Road Research Laboratory, UK, and the Ministry of Transport and Communications, Kenya. It was appropriate to undertake the work in Kenya as approximately fifty five per cent of the country has an annual rainfall of between 500 and 250mm a year and for a further twenty per cent the rainfall is less than 250mm. Also in these areas a number of major road projects were planned where water for construction purposes was known to be a severe problem.

The research project has involved studies of fine-grained soils typical of those used in road embankments and subgrades, and of coarse-grained gravelly soils used in sub-bases and bases. This paper describes an investigation of one material, a well-graded clay gravel, designated as base material for the road that was being upgraded from gravel to

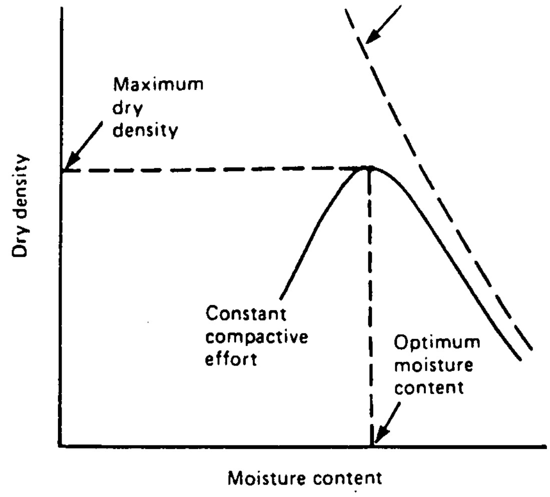

Fig. 1 Conventional compaction curve

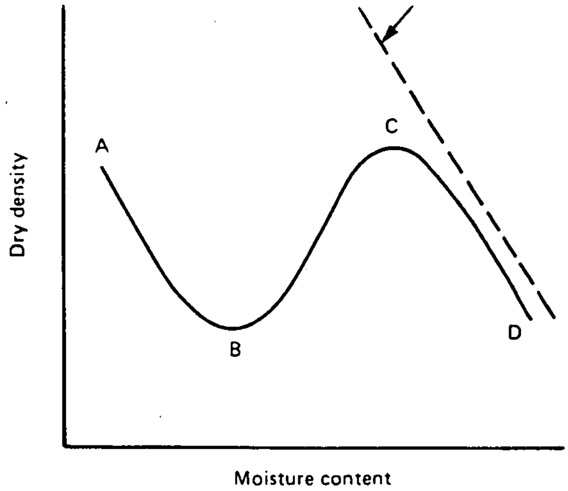

Fig. 2 Extended compaction curve for low moisture contents

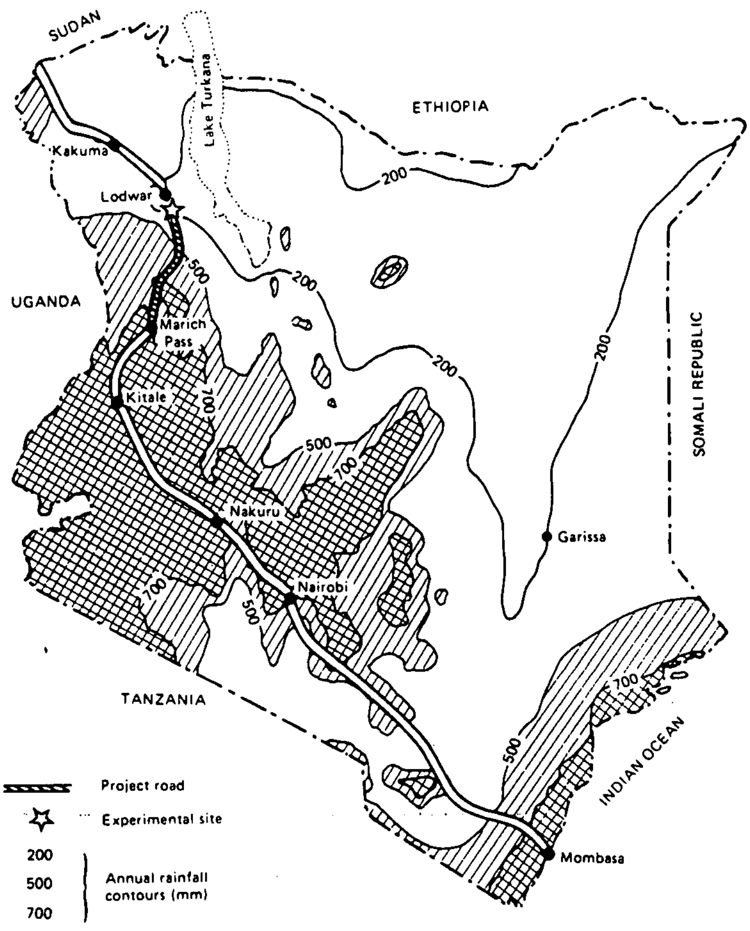

Fig. 3 Trial location and rainfall map of Kenya

bitumen surfaced standard from Marich Pass to Lodwar in north-western Kenya. The 200 km route passed through the arid or semi-arid region of the Rift Valley (see Fig 3). The study of the material was carried out in three stages. These were:-

i) Laboratory tests to determine dry density-moisture content relations obtained by different compaction methods to see if high densities could be obtained at low moisture contents.
ii) Pilot-scale compaction trials to determine the most effective type of roller for the material especially at low moisture contents and to see if laboratory compaction results predicted field behaviour.
iii) Full-scale road trials to compare the performance of the road base material compacted at a range of moisture contents under the influence of traffic and climatic conditions during the life of the road.

The performance of the full-scale trials has been monitored so far for two years and results are presented of surface and sub-surface measurements made at and since construction. These have comprised visual inspections, surface deformation, pavement deflection including radius of curvature, pavement strength and moisture conditions of the pavement layers. Some of the factors associated with compaction at low moisture contents are also described.

2. MATERIALS USED IN THE STUDY

2.1 Description and classification

The materials used in the study were alluvial quartzitic clayey gravels assigned for use in the road base of the 200 km long Marich Pass to Lodwar road. According to the British Soils Classification System they are described as well-graded clayey gravels with the symbols GWC (BSI 1981). The material used for the initial laboratory tests and for the pilot-scale compaction trials was from the southern end of the road project, from a borrow pit at km 25 from Marich Pass. That used for the full-scale road trials was from a borrow pit at km 19 from Lodwar at the northern end of the project.

The gradings and plasticities of the materials from the different sources are shown in Fig 4 and indicate that the materials have a similar classification. They were generally the same as the materials used for the road base throughout the project.

2.2 Density-moisture content relations from laboratory tests

Initial dry density-moisture content relations were determined using the material from km 25 from Marich Pass. Tests were carried out according to British Standard methods (BSI 1975) using three different levels of compaction, the 2.5 kg and 4.5 kg rammer dynamic compaction methods and the vibrating hammer method. The range of moisture contents extended from the very dry natural moisture content of the soil of between 1 and 2 per cent to the saturated condition of about 11 per cent. The results shown in Fig 5 clearly indicated the potential for achieving high dry densities at low moisture contents. For the vibrating hammer and 4.5 kg rammer methods the results were at least equal to 95 per cent of the maximum dry density achieved in the 4.5kg rammer method at the optimum moisture content, which is the specification for field compaction in Kenya. It was because of this that a decision was made to proceed with the pilot-scale compaction trials. Further laboratory tests were carried out on samples from the other borrow pit at km 19 from Lodwar that was to provide material for the full-scale road trials. The results of these tests are discussed later in the paper.

3. PILOT-SCALE COMPACTION TRIALS

The purpose of the pilot-scale trials was; to assess the performance of different compaction plant, to compare the dry density-moisture content relations obtained with the results of the laboratory tests, and to determine whether full-scale trials should be conducted. The types of plant, designated as compactors 1 to 4, were two vibrating and two pneumatic tyred rollers and these are specified in accordance with normal practice either by mass per metre width or mass per wheel in Table 1. (Department of Transport 1986). The clayey gravel material was prepared at a range of moisture contents from between 1 and 2 per cent to a maximum of 8.5 per cent. At each moisture content a section 150mm thick was laid and subdivided into four compaction bays. Each bay was then compacted with six passes of one of the rollers. After compaction the dry density

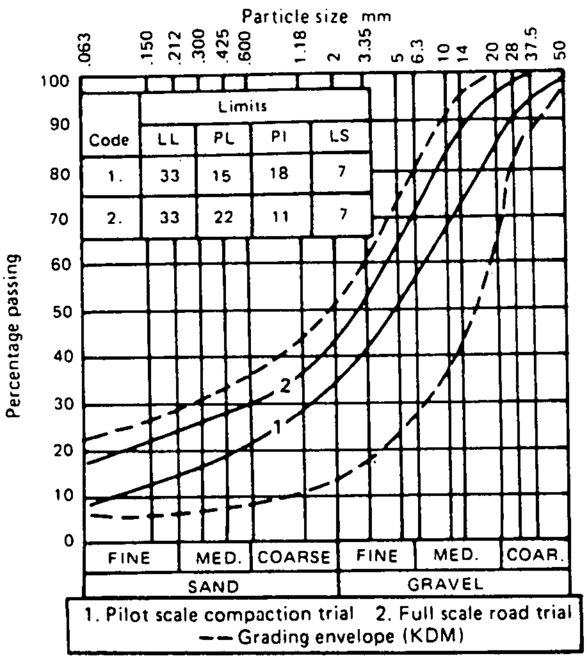

Fig. 4 Road base : particle size distribution and limits

was determined by the sand replacement method (BSI 1975). The best overall performance throughout the moisture range was obtained by compactor No 1, the vibrating roller, which had the greatest mass per metre width. The dry density-moisture content relation obtained for this roller is shown in Fig 6 where it is compared with the laboratory compaction curves. It can be seen that the normally specified density for road bases is achieved at both the lowest moisture content and the optimum moisture content.

Table 1. Compactors used in pilot-scale trials

Compactor type	Static mass/ metre width Mgs	Mass/ wheel Mgs
1.Vibratory	3.4	-
2.Vibratory	2.4	-
3.Pneumatic	-	1.3
4.Pneumatic	-	3.5

4. FULL-SCALE ROAD TRIALS

The aim of the trial was to examine the performance of the road base, compacted at different moisture contents, under the traffic and climatic conditions of the region. A site for the trials was located at Km six south of Lodwar (see Fig 3) on the Marich Pass to Lodwar road. At Lodwar the average annual rainfall is approximately 200 mm and the average daily maximum and minimum temperatures are 35°C and 24°C. The water table is not near the surface.

4.1 Design and layout of the trial

The results of the laboratory tests and the pilot-scale trials provided the basis for planning and designing the full-scale trials. The recommendations of the Kenya Design Manual (MOTC 1981) were generally followed for pavement design and were similar to that being used for the construction of the upgraded Marich Pass to Lodwar road. The subgrade material was a medium-fine non-plastic silty sand, BSCS group symbol SM, which had a design CBR strength in excess of 30 per cent at the specified density of 100 per cent of the density obtained in the 2.5 kg rammer method of compaction. The Kenya Design Manual subgrade classification was S6. The estimated traffic was within the Design Manual category T5 of 0.5 million equivalent standard axles during a 15 year design life so that pavement structure type 1 was appropriate. This permitted a sub-base of natural material and a natural gravel base with a double surface dressing. The strength of the subgrade meant that a sub-base was not required.

The clayey gravel used for road base construction and selected for the trial did not satisfy the Kenya Design Manual specification of soaked CBR of 80 per cent at the specified density. However in dry areas with good drainage the Manual does permit a lower specification for road base materials if they have less than 35 per cent passing the 75 micron sieve, a plasticity index of less than 20 per cent and a soaked CBR of greater than 50 per cent. The clayey gravel met these requirements.

The road trial was designed to have three sections each 100 m long with their road bases constructed at different moisture contents. These were the natural moisture content of 1.7 per cent, the optimum moisture content of 6.7 per cent and an intermediate moisture content of 3.5 per cent which was the moisture content of the lowest density achieved in the laboratory and pilot-scale trial. In all other aspects the design of the sections was the same. The section at optimum moisture content, which represented normal construction practice, was the control against which the other two sections were

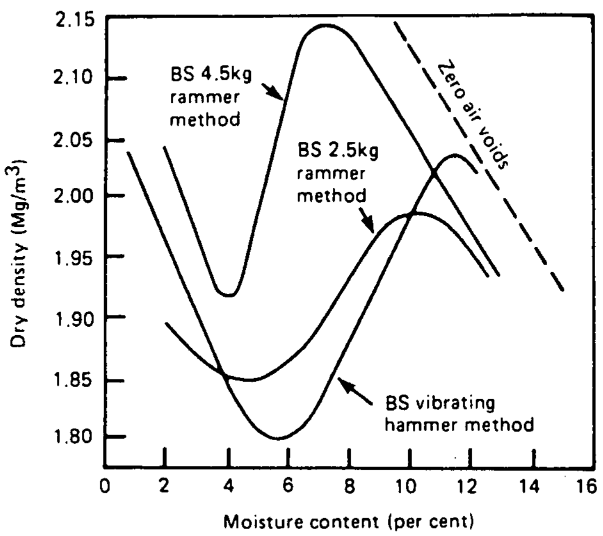

Fig. 5 Dry density/moisture content relationship for road base gravel (pilot scale trials)

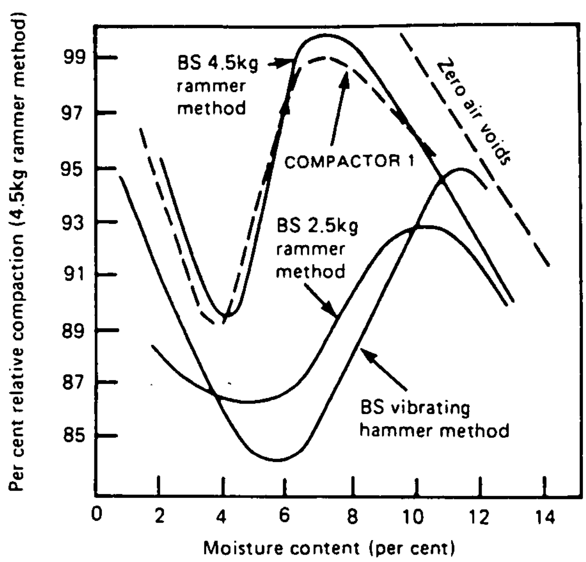

Fig.6 Field dry density/moisture content relationship relative to laboratory methods,for compactor 1.

to be compared. The section compacted at the intermediate moisture content provided the opportunity to asses the behaviour of soils whose natural moisture contents are such that it may be difficult to achieve the density specified for construction.

In the paper the section at optimum is described as Section A, the section at the intermediate moisture content as Section B and the dry section as Section C.

The lay-out of the experiment and the cross-section design is shown in Fig 7.

4.2 Construction of the full-scale trial

4.2.1 The subgrade

In the preparation of the sand subgrade the residual gravel from the old gravel surfaced road was removed. During reshaping of the subgrade which was at a natural moisture content of two per cent some shearing occurred. Further compaction in this dry condition was carried out with a vibrating roller operating in the vibrating and non-vibrating mode. Although specified densities were achieved it was clear that the sheared area remained looser and weaker than adjacent unsheared areas. It was decided to rely on the confinement of the overlying base layer to ensure that the specified design of CBR greater than 30 per cent would be obtained. This was confirmed during subsequent field testing (see Fig 8). The particle-size distribution of the silty sand subgrade material is shown in Fig 9.

4.2.2 The road base and surfacing

The clayey gravel base material was hauled to the site and dumped by tipper trucks. Spreading was carried out by motor grader and in the case of the sections at the intermediate and optimum moisture content water was added from a water tanker fitted with a spray bar. Water losses by evaporation during the mixing process were 30 per cent of the total volume added so that, for the section prepared at optimum moisture content, 30,000 litres were required. Half of this amount was added to the section at the intermediate moisture content.

The road base was compacted in a single layer to give a minimum thickness of 150 mm. Nine passes of a vibrating roller of static mass 2.3 Mg/m width were applied based on the results of the pilot scale trials and recommendations given in the UK Specifications for Highway Works (Department of Transport 1986).

The sections were sealed with a double

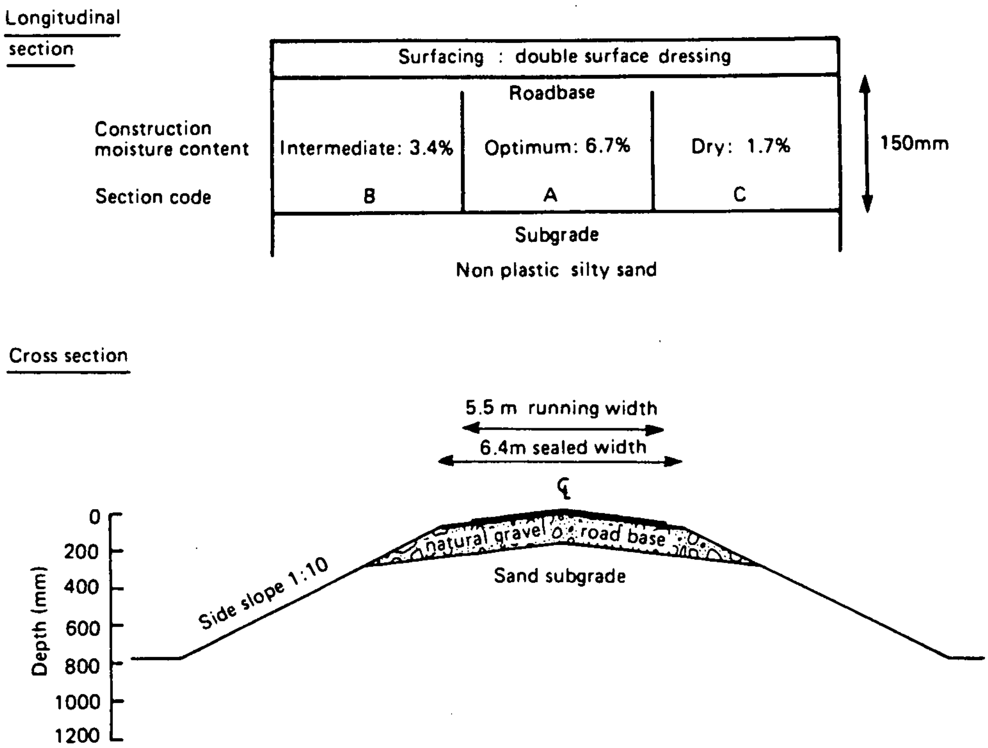

Fig. 7 Layout of full scale trials

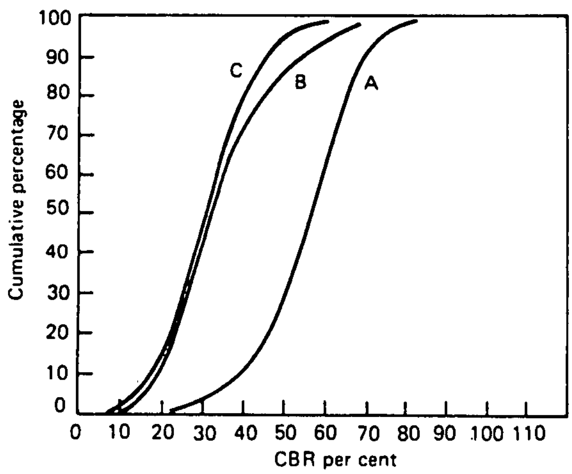

Fig. 8 Distribution of subgrade CBR's (DCP method)

surface dressing using a bituminous binder MC 3000 sprayed at a rate of 1.7 l/m^2 for the first layer and 1.1 l/m^2 for the second layer. The higher application rate of the first seal was because no prime coat was applied to the base before surface dressing. A continuously graded basalt aggregate was used as chippings for both seals each with the same maximum size of 18 mm. The seal was effectively an 'Ottadekke' type which has been used on a number of lightly trafficked roads in Kenya (Thurmann-Moe and Ruistuen 1983).

4.3 Construction control

4.3.1 Density and moisture content measurements

After compaction of the base, for each section, eleven dry density determinations using the sand replacement method and five moisture content measurements were made. The results are shown in Table 2. The distribution of density results relative to the maximum achieved in the 4.5 kg rammer method is shown in Fig 10. The mean density and moisture content results for each section are shown in

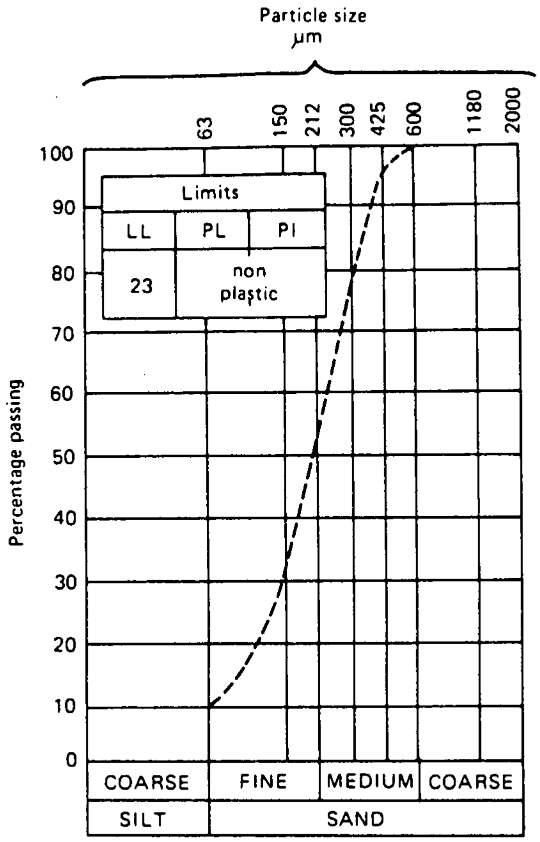

Fig. 9 Particle size distribution of subgrade material

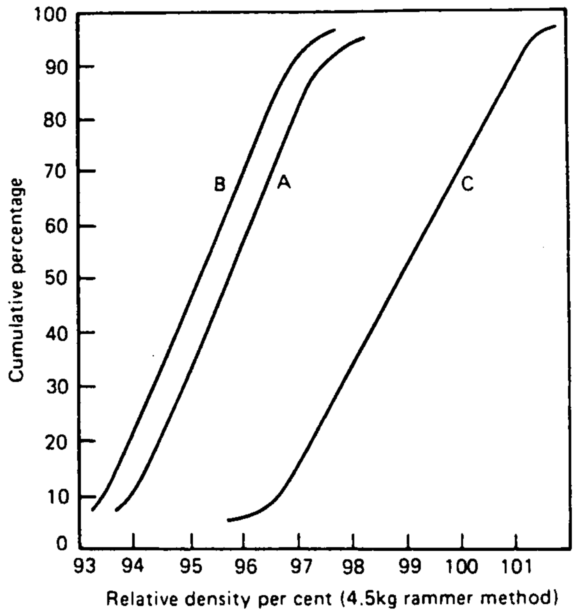

Fig.10 Distribution of field densities at construction

Table 2. Dry densities and moisture contents of full-scale trials

Section	Dry Density Mg/m^3		Moisture Content per cent	
	Mean	SD	Mean	SD
A	2.054	0.03	6.7	0.4
B	2.045	0.03	3.6	0.5
C	2.125	0.03	1.7	0.2

Fig 11 together with the CBR and dry density/moisture content relations from four laboratory compaction tests. The density/moisture content relations were prepared from the material used for the full scale trials and the series of iso-CBR lines were derived from unsoaked CBR tests carried out on the samples compacted in the laboratory.

The results show that the highest field densities were achieved for Section C with mean values of 100 per cent relative compaction whereas the other two sections had mean values just exceeding the minimum specified value.

4.3.2 In-situ bearing strength measurements

Although the highest density was obtained in the dry compacted Section C it was important to obtain information about the strength of the different bases. A rapid test with the Clegg Impact Hammer (Clegg 1976) was used which gave values that could be correlated with CBR. Tests were carried out at intervals during compaction after 3,5 and 7 passes and on completion of compaction at 9 passes. The results are shown in terms of CBR in Table 3 where each value is the median of 25 tests. The distribution of the results of tests made on completion of compaction is shown in Fig 12. Table 3 shows that the strength increased with the number of passes of the roller but was considerably lower for the dry compacted section.

4.3.3 Base thickness measurements

The thickness of the road base was determined from optical level measurements taken before and after the base material was placed and compacted. More than 55

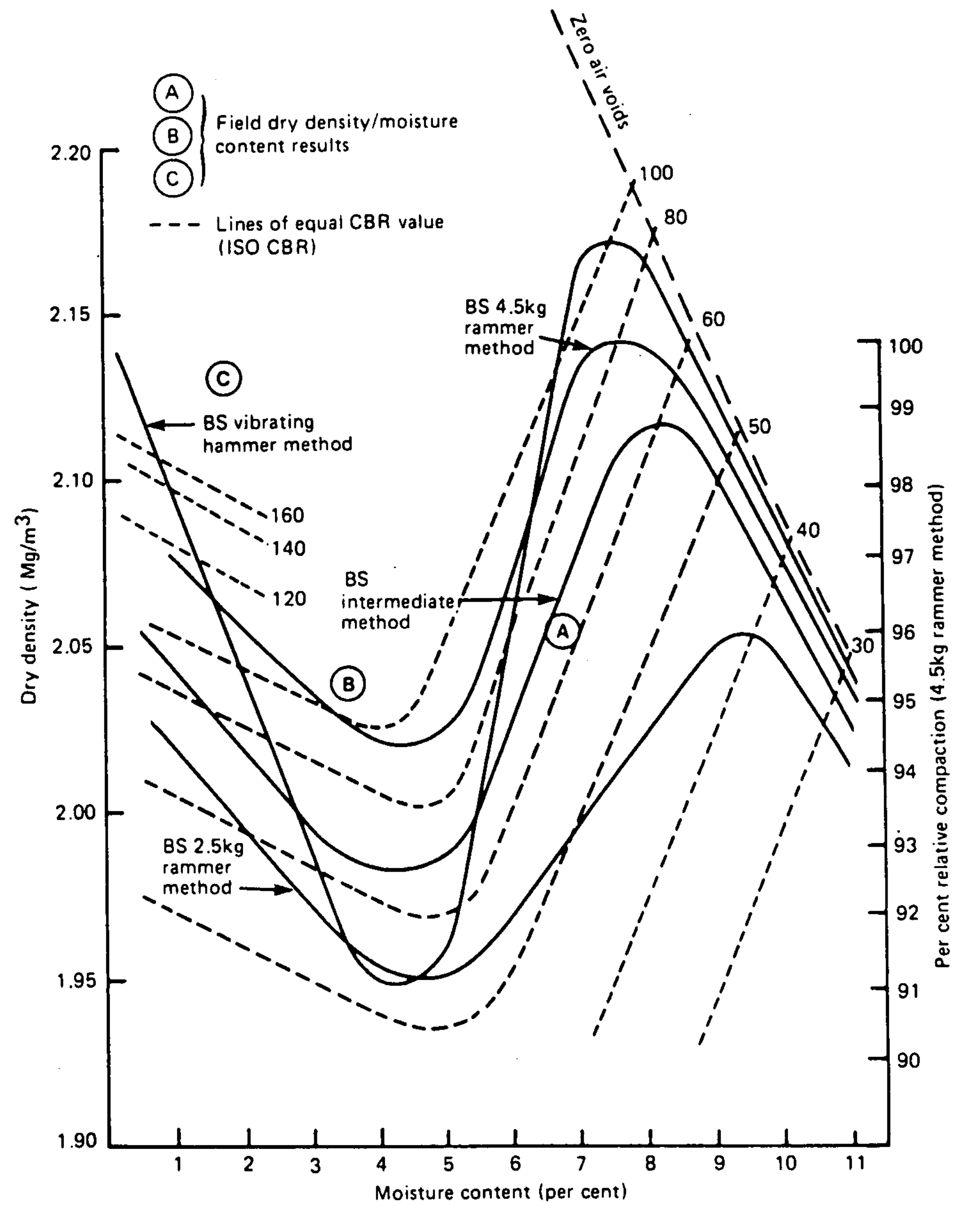

Fig. 11 Laboratory CBR/dry density/moisture content relationship for road base gravel (full scale trial) with field results

Table 3. Relation between increasing compaction and CBR

Compaction No. of passes	Median CBR value % (Clegg Impact Hammer)		
	SECTION		
	A	B	C
3	40	47	23
5	42	50	28
7	-	52	30
9	78	66	44

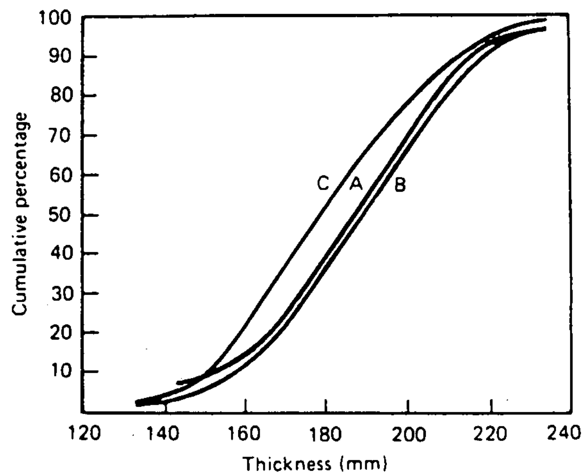

Fig. 13 Distribution of roadbase thickness

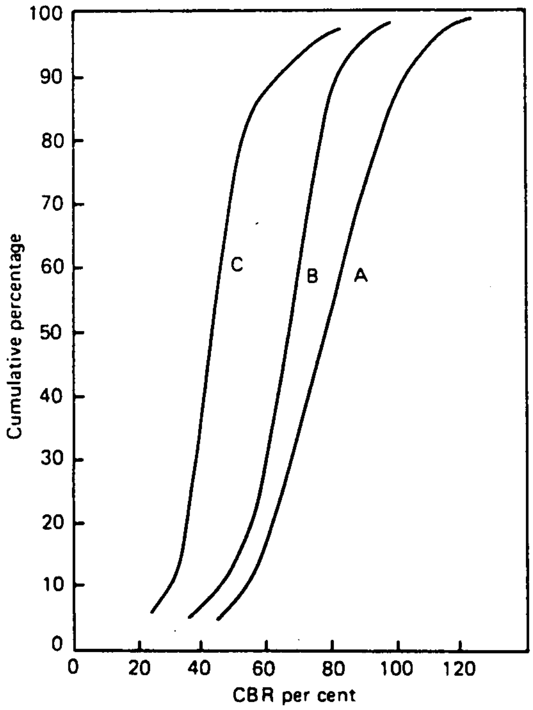

Fig. 12 Distribution of roadbase strength at construction (Clegg Impact Hammer)

values were obtained for each section and the distribution of road base thickness measurements is shown in Fig 13. The median values for the sections were between 177 and 187 mm and more than 90 per cent of values were equal to or greater than the minimum 150 mm thickness required in the design.

5. MONITORING PROGRAMME

The monitoring programme to assess the performance of the trials has included measurements of:-

i) Moisture contents of the road base, subgrade, shoulders and open ground adjacent to the trial sections. The measurements were made by test pitting or by profiling to a depth of 1.5 m below the surface.
ii) Pavement strength in terms of CBR, using a dynamic cone penetrometer, to a depth of 0.8 m below the surface (Kleyn and Savage 1982). Some insitu CBR measurements have been made which confirmed the correlation between DCP and CBR.
iii) Transient deflection tests using the Benkelman Beam and measurements of radius of curvature using the TRRL 'line of influence' apparatus (Smith and Jones 1982) to give information on the structural strength.
iv) Surface condition in the form of surface deformation by cross-sectional and longitudinal levelling surveys, rut depths and cracking. Longitudinal level surveys have also been made with a modified Abay beam (Abaynayaka 1984) which also provided information on road roughness.
v) Traffic counts by 12 hour manual classified counts supported by automatic counter readings.
vi) Rainfall and climatic data obtained from the meteorological station at Lodwar. Average conditions for the past 30 years were also obtained from Lodwar.

6. RESULTS OF THE MONITORING PROGRAMME

6.1 Moisture contents

Moisture content measurements of the road-base which were generally taken from the centre-line and edges of the pavement showed that Sections A and B have dried to the same value as Section C which had remained unchanged since construction. The subgrade moisture contents have remained constant at between 1 and 2 per cent to a depth of at least 1.3 m below the top of the subgrade. Moisture contents measured in open ground have varied seasonally from maximum values of 25 per cent at depth of 0.8 m in the wet season to 2 per cent in the dry season. The largest seasonal fluctuations occur at a depth of one metre as shown in Fig 14. They are however strongly influenced by local variations in topography.

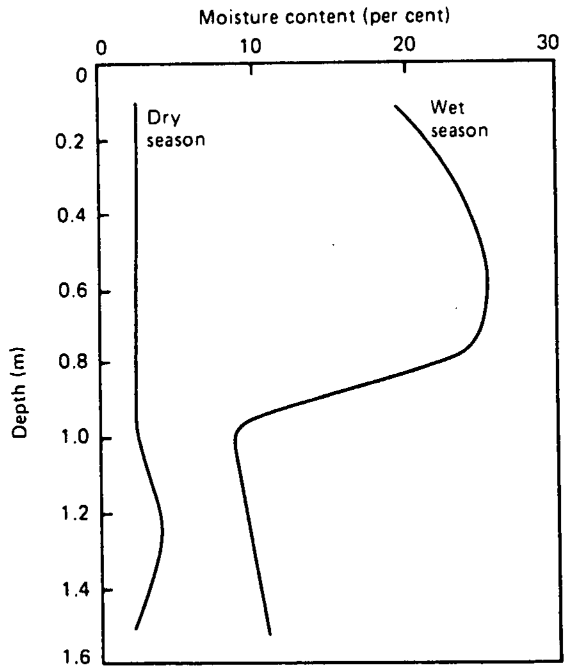

Fig. 14 Open ground moisture content profile

6.2 Pavement and subgrade strength

6.2.1 Subgrade

The median values of a series of DCP measurements showed that the CBR of Section A was 59 per cent, the CBR of Sections B and C were 29 per cent and 31 per cent respectively. In considering the subgrade support strength using the modified structural number approach to assess pavement strength (Hodges et al 1975) the differences for subgrades with CBR greater than 30 per cent are small. This can be illustrated by considering the design structural number for the road which, including the contribution from the subgrade, is 3.0. The proportion of this value contributed by the subgrade is 63 per cent and 64 per cent for Sections B and C respectively and 69 per cent for Section A. The modified structural number values obtained from actual measurements are dealt with later in the discussion of results.

6.2.2 Road base

Measurements in terms of CBR from the DCP test are given in Table 4. They show that Section A had the highest strengths and that they had increased since construction from a mean value of 61 per cent to greater than 100 per cent. This increase coincided with the section drying from the optimum moisture content to 2 per cent. Sections B and C, have remained constant since construction. The results of Section A correlate well with predictions from iso-CBR lines obtained from the laboratory tests (see Fig 11). The fact that Section C did not correlate with predicted values is discussed later in the paper.

6.3 Pavement deflection and radius of curvature

Pavement deflections were measured in the verge-side and offside wheeltracks of both lanes at 10 chainages within each trial section. The results of two series of tests, one shortly after construction and the other two years later, are given in Table 5 and show that generally there was no change between consecutive measurements apart from Section B in the lane towards Lodwar which had increased. Section A had the lowest deflections and the other two sections were approximately the same.

Whereas deflection measurements give information related to the whole pavement structure the radius of curvature, by measuring the shape of the deflection bowl, is known to be more discriminating in terms of road base behaviour. One series of tests was carried out two years after construction at the same locations

Table 4. In-Situ CBR (DCP Method) for roadbases

Section	Year	CBR per cent			
		No. of Values	Mean	SD	Range
A	0	12	61	8	51-79
	1	3	79	14	63-89
	2	14	166 (1)	114 (1)	70-450 (1)
B	0	12	40	10	21-55
	1	3	45	4	41-47
	2	14	41	9	29-60
C	0	9	37	6	27-44
	1	3	37	3	34-39
	2	14	47	8	32-61

(1) Inferred values of CBR greater than 100% exceed the calibrated range of DCP and are regarded as estimates.

Table 5. Mean Deflections

Section	Year	Transient Deflection (mm x 10^{-2})			
		Towards Marich Pass		Towards Lodwar	
		V/S	O/S	O/S	V/S
A	0	34	31	37	45
	2	33	32	34	40
B	0	42	48	49	51
	2	45	48	58	63
C	0	44	48	50	55
	2	45	48	49	53

as per deflection tests. The results given in Table 6 indicate that as for the deflection tests Section A is the stronger with the highest radius of curvature values. Another reason for measuring radius of curvature and deflection of the pavement is to analyse the simple two layer system of the pavement structure using multi-layer elastic theory. Fig 15 shows the relation between radius of curvature and deflection based on different moduli of elasticity for the two layers. E_1 represents the road base and E_2 the subgrade. Plotted on the graph are the mean values of each of the trial sections that were measured two years after construction. The results show that the modulus of elasticity for the subgrade is high for all sections and that Section A is different from Sections B and C. Also Section A originally compacted at optimum moisture content has the highest value of E_1. These differences between the layers of each section and between the sections are consistent with those obtained from other measurements such as the direct strengths of the pavement layers.

Table 6. Mean radii of curvature

Section	Year	Radius of Curvature (m)			
		Towards Marich Pass		Towards Lodwar	
		V/S	O/S	O/S	V/S
A	2	80	83	80	66
B	2	40	36	44	42
C	2	50	46	52	43

This method of structural analysis has shown that it should be possible to distinguish between the behaviour of the two component layers in each of the three sections as historical data is built up.

6.4 Surface condition

Measurements of rut depth using a 2 m straightedge, deformation from cross-section and longitudinal section profiles and inspections for cracking have shown no deterioration of the road surface since construction. The rut depths are shown in Table 7. The higher values recorded in the offside wheel-track of the Marich Pass lane which persist through all 3 sections were the result of a small ridge caused during construction by an overlap of the surface dressing close to the centre line. The use of the Abay beam for measuring surface irregularity in the wheel-tracks has enabled road roughness values to be obtained using a correlation between Abay beam measurements (Abaynayaka 1984) and the Towed Fifth Wheel Bump Integrator. The values which were between 2,000 and 2,500 mm/km are consistent with normal results for a new road with a granular base and sealed with a surface dressing.

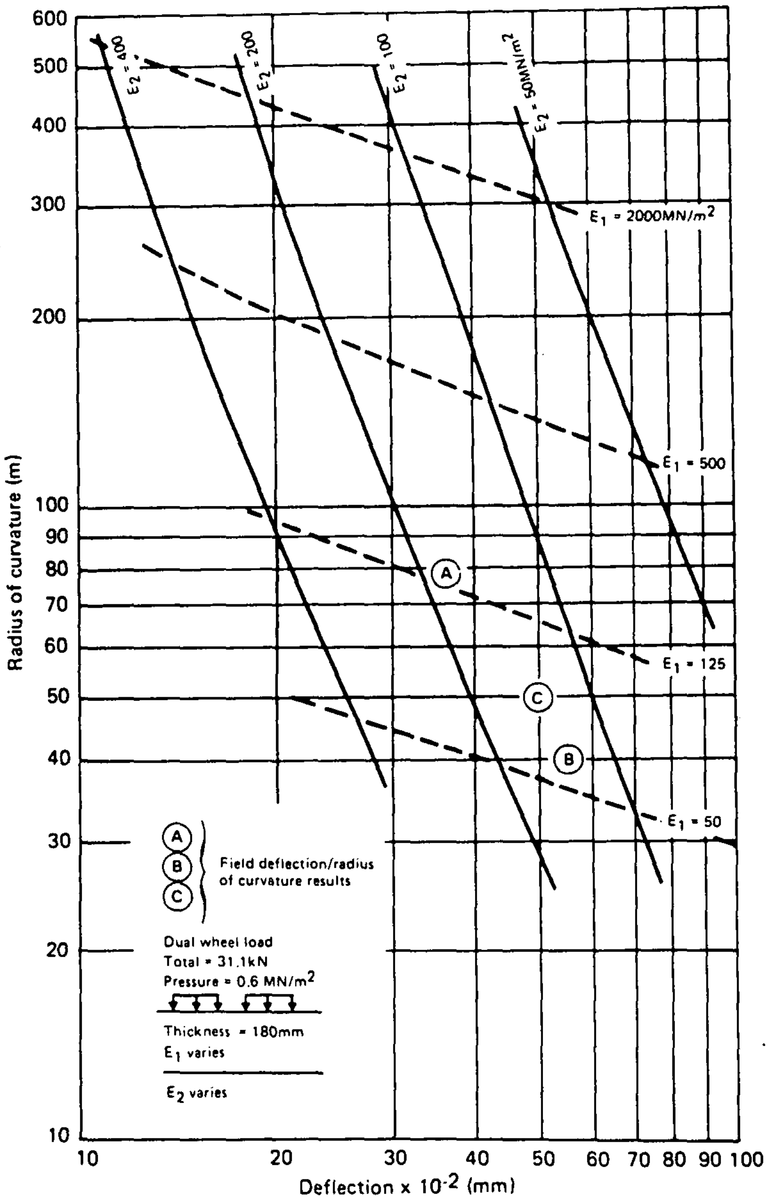

Fig. 15 Relationship between radius of curvature and deflection

6.5 Traffic volume and traffic loading

Manual classified traffic counts have been conducted annually since construction. The results of these surveys have been supported by automatic traffic counter readings and have shown that the ADT is 72 with 52 per cent in the medium goods and 3 per cent in the heavy goods category. Axle loads have not been measured but using the Kenya Design Manual guide of one equivalent standard axle per vehicle for medium goods type and four e.s.a for heavy goods vehicles it is estimated that a total of 20,000 e.s.a. have been carried in each direction in the two years since construction.

7. DISCUSSION

Quality control of compaction during road construction requires that certain specifications are met. In Kenya, like

Table 7. Mean rut depths

Section	Year	Mean Rut Depth (mm)			
		Towards Marich Pass		Towards Lodwar	
		V/S	O/S	O/S	V/S
A	0	3	6	4	2
	1	2	5	4	2
	2	3	6	2	2
B	0	2	4	0	1
	1	2	5	2	3
	2	3	6	1	1
C	0	2	8	3	2
	1	2	6	2	2
	2	4	5	1	3

many other countries, the requirement for road bases is related to the laboratory 4.5 kg rammer test. (Kenya specifies a relative density of 95 per cent of the maximum dry density at optimum moisture content). When compaction is carried out at low moisture contents it is doubtful whether the existing specifications are appropriate. This discussion therefore considers the results of the study and how they might be applied to enable dry compaction to be used more widely in arid areas.

7.1 Laboratory compaction at low moisture contents

Both dynamic rammer and vibrating hammer methods were used in the laboratory compaction tests. At low moisture contents more variable and lower densities were obtained in the dynamic rammer test because the action of the falling rammer on the unconfined surface in the mould was to disturb the soil as well as compact it. In the vibrating hammer test the soil is confined by the hammer's foot which is just less than the diameter of the mould and more consistently high densities were obtained. It is for this reason that the vibrating hammer should be the preferred method of laboratory compaction at low moisture contents.

7.2 Comparison of laboratory and field compaction

The overall comparison of laboratory and field densities is shown in Figs 6 and 11. Fig 6 gives the results of the pilot-scale trial and Fig 11 the full-scale trial. The difference between the laboratory results in the two figures is mainly because the soils used were from two different sources although they were both classified as well-graded plastic gravels. The comparison of laboratory and field densities showed that at the lowest moisture content of 2 per cent in the pilot-scale and full-scale trials relative densities of 97 per cent and 100 per cent respectively were obtained. The specification density, therefore, was readily achieved and exceeded. In road construction practice at low moisture contents it is important to achieve the highest density possible to ensure that no further compaction subsequently occurs under the action of traffic. Specifications related to the vibrating hammer test therefore, may be better for compaction at low moisture contents or alternatively field compaction trials to assess the performance of the plant should be carried out to determine a 'method' specification.

At the intermediate moisture content the relative densities achieved in the two trials were 89 per cent in the pilot-scale and 96 per cent in the full-scale. In the full-scale trial, therefore, the density passed the specification despite being in the moisture content zone where densities are normally expected to be at their lowest. This was probably because the material used in the full-scale trial was more rounded and would be expected to be easier to compact. Although the laboratory vibrating hammer test predicted the trend of the changing densities between low and intermediate moisture contents it further confirmed the need for compaction trials to ensure that maximum density is achieved in construction practice.

At optimum moisture content the relative field densities, as expected, exceeded the specified density, being 96 per cent and 99 per cent for the full-scale and pilot scale trials respectively. The difference in these results was probably because of differences in the two materials and in the two vibrating rollers that were used. The densities achieved, therefore, would be dependent on the field moisture contents and number of passes of the roller.

7.3 Laboratory and field CBR

The CBR results of Section A at construction compared well with those predicted in the laboratory tests. Because the road base has dried from 6.7 per cent to 2 per cent since construction an increase in strength occurred which was also similar to that predicted (see Fig 11). Section B has shown no change in strength mainly because the moisture content has changed much less, from 3.5 per cent to 2 per cent. Section C has also not changed in strength since construction which is as expected as the moisture content has not changed. The field CBR of Section C however was significantly different from that predicted from the laboratory with values of the order of 40 per cent measured in the field and greater than 100 per cent predicted in the laboratory. The higher laboratory value is partly because of the lateral confinement provided by the mould in the laboratory test which is not present in the field. Studies elsewhere have shown that at low moisture contents the low strengths measured at the completion of construction of a layer have subsequently increased when confining pressures have been applied from the construction of overlying layers. This did not occur in the full-scale trial with the road base covered only by a thin surface dressing.

The higher strength of Section A both at construction and during the monitoring period is considered to have been because of the type of material and the effect of moisture. The clayey gravel road base compacted at the optimum moisture content and then dried produced a very hard material because increasing suctional forces bind the soil particles together. This could only have occurred to a limited extent in the 'intermediate' section (Section B) and not at all in the dry section (Section C) where the plastic fines in the dry condition only behaved as an inert filler. In the dry section, therefore, frictional forces alone provided the stability whereas at the other extreme, in the wetter condition, strength was attributed to cohesive forces and then increasing suction as the soil dried as well as frictional forces. It should be noted that soil suction would not normally be a contributory factor in road bases because specifications prohibit or severely limit the amount of plastic fines that are allowed.

The results of the trials so far support the Kenya Design Manual which permits higher limits of plastic fines for construction in arid areas. If normal specifications were applied the addition of lime could be used to modify the plasticity of the soil. In such a case the behaviour would be similar to that found in Section C where inter-particle friction is primarily responsible for the soil strength.

7.4 Field strength measurements and pavement design

Values of pavement deflection are considered to be satisfactory for the type of construction used although Section A was significantly different from Sections B and C. The difference between the sections is also shown in the radius of curvature measurements where Section A has the highest and most satisfactory value. Because the difference is shown up in both deflection and radius of curvature results it can be deduced that this is because of differences in the performance of the road base and not the subgrade.

Modified structural number can also be used to demonstrate that the pavement strength is adequate. When the method of analysis is applied to the design recommendations in Road Note 31 (TRRL 1977) a structural number of 3.0 can be calculated and considered adequate for a pavement designed to carry 0.5 million equivalent standard axles. The calculated values for the trial sections are 3.7 for Section A and 3.1 for Sections B and C. This demonstrates further that all of the sections should be sufficiently strong for the designed traffic loading. However, a major feature of the monitoring programme is to examine the performance of the road bases. The relatively low strengths of the bases in Sections B and C might indicate a risk of shear failure under the action of traffic and if this does occur it would be expected to be the result of a few excessively heavy axle loads rather than the cumulative effect of traffic within the legal limits.

7.5 Construction methods

In the trials conventional methods of using construction plant were generally successful when dealing with materials at low moisture content. Segregation of particles is normally a problem when handling dry materials but in this case spreading was easily carried out with a motor grader. The reason was mainly because the maximum size is 20 mm and not 40 mm which is more common for crushed stone base materials.

Compaction of the dry material was carried out with medium weight vibrating rollers. A method of rolling from the outer edges of the layer towards the centre was adopted to give better confinement of the material. The pilot scale trial indicated that other types of roller could be used for compaction but it was concluded that vibrating rollers were more efficient throughout the range of moisture contents.

Considerable difficulties occur when mixing very dry materials with water especially in hot dry climates when allowance has to be made for high losses caused by evaporation. The quantities of water required in conventional construction practice to raise the moisture content to the optimum for compaction, when it may be scarce and involve long haul distances, can seriously affect productivity.

7.6 Mechanism of compaction

The results of the study have shown clearly that for the well-graded clayey gravel high densities were obtained at low moisture contents. The mechanism to explain this behaviour is still being investigated but in normal compaction the addition of water to lubricate soil particles to achieve higher density is well understood; so is the effect of excess water when saturation is reached when individual particles are pushed apart. With reference to Fig 2 this covers the part of the graph in the dry density-moisture content relation represented by BC and CD. As moisture contents fall below the value of B in the figure, inreases in density occur probably because surface tension between particles is reduced as the soil approaches the dry condition. A further explanation of the increase in density as soils become drier from B to A is that with compaction soil particles will occupy the volume that would have been occupied by water in a wetter condition and the high specific gravity of the soil particles compared with water will obviously result in a higher overall density. It could also be expected that at constant compactive effort closer packing of soil particles can occur in the dry condition by the reorientation encouraged by vibrating compaction.

8. CONCLUSIONS

The main conclusions arising from the study of compaction at low moisture content were:

1. The vibrating hammer test is the preferred method of carrying out laboratory compaction at low moisture contents.
2. High densitites were obtained at low moisture contents in both laboratory and field compaction and could exceed current specifications.
3. The vibrating hammer test predicted the performance of the vibratory rollers over a range of low moisture contents.
4. Compaction trials were important to establish a method of compaction that will ensure that maximum density is achieved in the field.
5. For the dry compacted material in the field trials the in-situ CBR results derived from DCP tests were much lower than those predicted by laboratory tests.
6. The use of deflection and radius of curvature measurements and the determination of the elastic moduli of the pavement layers appears to provide a satisfactory method of monitoring trial sections and comparing the performance of dry compacted road bases with those constructed conventionally.
7. Construction plant and conventional operating techniques were successfully applied when using materials at low moisture contents.
8. Road trials constructed with bases at different initial moisture contents have performed equally well for two years although traffic levels have been low (20,000 e.s.a.). Further information on the longer term performance is clearly required before final recommendations can be made.
9. There is a need to extend studies of dry compaction to a wider range of materials used in different parts of the road pavements and to determine the limiting climatic conditions where dry compaction can be used.

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