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TITLE: The Location and Engineering Properties of Volcanic Cinder Gravels in Ethiopia

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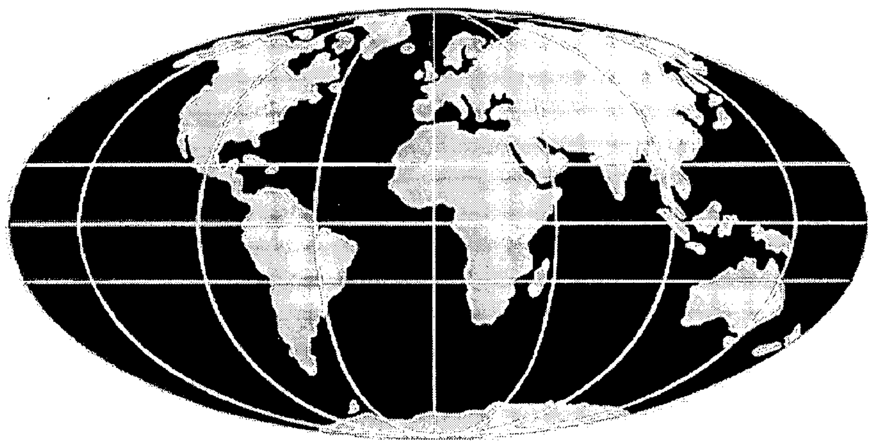

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The location and engineering properties of volcanic cinder gravels in Ethiopia

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Volcanic cinder gravels occur extensively in Ethiopia, but in the past they have been used for road construction only to a limited extent, even though their use would substantially reduce road construction costs in many instances. As part of a joint research project undertaken by the Ethiopian Road Authority and the United Kingdom Transport and Road Research Laboratory, research has been carried out to provide information on the occurrence and properties of the volcanic cinders with the object of encouraging their wider use in future road construction.

This paper describes the procedures used to map the occurrence of cinder gravels in Ethiopia, reports the results of laboratory tests made on a range of the materials, and gives details of an investigation of an existing cinder gravel road.

With the aid of aerial photographs a map was prepared showing the distribution of cinder gravels throughout Ethiopia. The laboratory investigation showed that cinder gravels, which typically have weak particles and are deficient in fine material, are improved by compaction in that some breakdown of the larger particles occurs, producing a better grading and higher strength. It was also found that the addition of fines improves the strength and density of the compacted cinder gravels. The road examination confirmed that the action of traffic produces the same breakdown effect in gravel roads as was observed in the laboratory compaction tests.

RESUME L'Ethiopie contient des quantités considérables de graviers de scories volcaniques, mais, même si leur utilisation peut, dans de nombreux cas, produire une réduction substantielle des coûts de construction routière, ils n'ont été utilisés que de façon limitée dans la construction des routes. Dans le cadre d'un projet de recherche entrepris conjointement par les Autorités des Routes d'Éthiopie et le Transport and Road Research Laboratory du Royaume-Uni, des recherches ont été effectuées pour fournir des informations sur la présence et les propriétés des scories volcaniques, en vue d'encourager dans l'avenir une utilisation plus large de ces dernières en construction routière.

Ce rapport decrit les procédés utilisés pour produire des cartes montrant l'em placement des scories volcaniques en Ethiopie, présente les résultats d'essais en laboratoire effectués sur un certain nombre de ces matériaux et donne des détails sur des recherches faites sur une route déja construite contenant du gravier de scories volcaniques.

Des photos aériennes ont été employées pour préparer une carte montrant la distribution des graviers de scories dans toute l'Ethiopie. Les recherches en laboratoire ont prouvé que les graviers de scories, qui, typiquement, contiennent des grains de résistance faible et une quantité insuffisante de matériaux fins, sont améliorés par compactage, du fait que les grains les plus larges sont partiellement brisés en morceaux plus petits, produisant ainsi une granularité améliorée et une résistance plus élevée. Les essais ont aussi montré que l'addition d'élements fins améliore la résistance et la densité des graviers de scories compactés. Les observations faites sur la route ont confirmé que l'action du trafic produit dans les routes en gravier le même effet de fragmentation que celui observé dans les essais de compactage en laboratoire.

1 INTRODUCTION

In 1975 a joint research project was commenced in Ethiopia by the Ethiopian Road Authority and Transport and Road Research Laboratory (UK). One of the objectives of the research programme was to establish guidelines to enable highway engineers to make fuller use of locally-available materials for road construction. This was considered to be particularly relevant in Ethiopia as, in common with many other developing countries, an extensive programme of rural road construction is in progress which is expected to continue for a number of years.

For rural roads, which generally carry low volumes of traffic, earth or gravel roads are usually an adequate form of construction. In the case of gravel roads an important factor in helping to reduce costs is to make the best use of locally-available materials. Uusally these materials are natural gravels which will often vary in quality from one deposit to another. The engineer requires guidance in the selection of natural gravels for road construction, and specifications for their use appropriate to the types of materials available, and the service conditions anticipated in the road. This paper describes an investigation of one type of material, volcanic cinder gravel, which, although widespread in Ethiopia has been used for road construction only to a limited extent. One reason for the limited use of volcanic cinder gravels up to the present is that they are generally deficient of fine material and do not conform with the grading specifications for conventional crushed rock bases. Another reason is that they have a reputation for being difficult to compact.

The study, aimed at a full assessment of cinder gravels for road construction in Ethiopia comprised the following stages:

i) A field survey to locate and identify cinder gravels and to obtain samples for laboratory testing. The survey also included the examination of aerial photographs and photo-mosaics and the preparation of a map showing the distribution of cinder deposits throughout Ethiopia.

ii) A laboratory investigation to determine their physical and engineering properties.

iii) An examination of existing cinder gravel roads to compare the performance of the materials under trafficking with the results of the laboratory investigations.

iv) Compaction trials to determine the most suitable plant for practical use.

v) A full-scale experiment to examine the behaviour of different cinder gravels under controlled conditions in relation to traffic and climate. This paper describes the first three stages of the investigation.

2 DEFINITION OF VOLCANIC CINDERS

Volcanic cinders are pyroclastic materials associated with recent volcanic activity. They occur in characteristically straight-sided cone-shaped hills which frequently have large concave depressions in their tops or sides where mixtures of solids and gases were released during the formation of the cone. Cinders vary in colour often within the same cone and may be red, brown, grey or black. The cinder particles also vary in size from large irregularly shaped lumps 50 cm in size, to sand and silt sizes. In some cones, however, particles may be more uniform with the largest size not exceeding 3 cm in diameter. Other characteristic features of cinders are their light weight, their rough vesicular surface and their high porosity. Usually they are weak enough to be crushed under the heel.

An advantage of cinders as a road construction material is the relative ease with which they can be dug from the quarry; a mechanical shovel or hand tools are usually adequate for their extraction although occasionally a bulldozer may be required to open up a working face.

3 FIELD SURVEY

Field visits in connection with the survey were all carried out within a distance 150 km of Addis Ababa. They were concentrated in areas near to Debrezeit, Nazaret, Zwai, Butajira and Giyon (see Fig 1). Approximately 70 cones were visited and more than 90 samples were collected for laboratory examination. Samples were obtained either from existing borrow pits from which material had previously been extracted or by digging pits where cinder cones had not been disturbed. Existing borrow pits provided the opportunity to obtain deeper profile samples which were more representative of the cone as a whole.

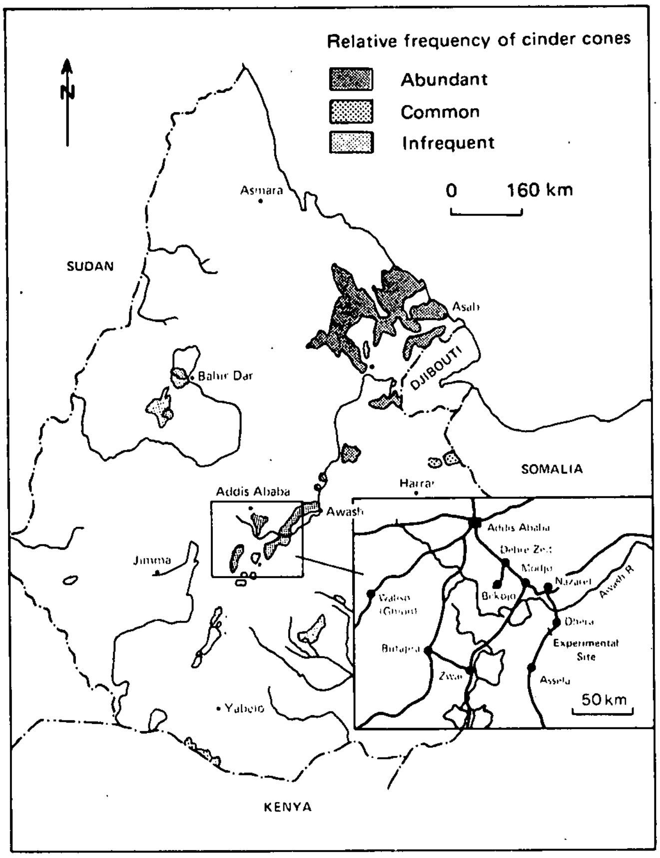

Fig. 1 Cinder cone distribution in Ethiopia, survey area enlarged

Cinder cones rarely support any vegetation other than grasses and examination of the exposed profiles showed that the depth of soil cover was not more than a few centimetres. A weathered cinder zone, however, usually extended down to a depth of about two metres. In some cones deposits of calcium carbonate coated the cinder gravels; these did not persist throughout the cones but in thin white bands parallel to and usually close to the surface.

The size of cinder cones vary but they do not normally exceed 100 metres in height and side-slopes are generally of the order of 20° - 23°. The largest cones would be expected to contain cinder deposits of about one million cubic metres. Occasionally cones occur singly but more commonly they are found in clusters in a linear arrangement associated with geological faults and recent lava flows.

The distinctive shape of the cinder cones made them easily identifiable on aerial photographs and photographs were used both to plan the survey and subsequently in the field work. The examination of air-photos and print lay-downs was extended to cover the whole of Ethiopia and from these and a study of areas of recent (Quaternary) volcanics on the geological map, a preliminary map was compiled showing the occurrence of cones throughout the country (see Fig 1). They were mostly concentrated in the Rift Valley which extends from Tanzania and Kenya and bisects the country in a SSW-NNE direction; an indication of their frequency for each of the areas that were identified has been given.

During the survey data sheets were used to make a comprehensive record of all the relevant information that related to each site. This included descriptions of soil profiles and samples that were collected, the geology, topography, vegetation and climate of the area. The data together with the subsequent test information that was obtained was used as an input to a data storage system for engineering materials which was developed as another part of the ERA/TRRL Joint Road Research Project[1]. It is hoped that the data storage and retrieval system, when fully established, will be a valuable aid to highway engineers concerned with road planning and construction in Ethiopia.

4 LABORATORY INVESTIGATION

Observations made during the field survey indicated that the two most important factors likely to affect the engineering behaviour of the cinder gravels were the grading and the strength of the gravel particles. The aims of the laboratory investigation on the cinder gravels, therefore, were to determine:

i) the most appropriate methods for classifying and evaluating the engineering properties.

ii) the variability of cinder gravels from different deposits and within the same deposit.

iii) their strengths and densities at different levels of compaction.

iv) the effect of compaction on the grading.

v) the effect of moisture on engineering properties, and

vi) the effect of adding locally available volcanic ash to make up for the deficiency of fine material (< 75 μm diameter) in the grading of cinders.

The test methods used in the materials investigation were generally those given in the appropriate British Standard [2,3].

4.1 Classification tests

4.1.1 Particle-size distribution. Particle-size analyses were carried out on 53 of the samples that were collected during the field survey. Although the zone of weathering varied in different profiles it was clear that this did not extend beyond depths of two metres as, below this level, there was little fine material present. Out of 40 samples from below two metres that were tested only one, from a cone near to km 130 on the Nazareth to Assela road, had more than 4 per cent passing the 75 µm sieve.

The thirteen samples tested from the top two metres had a far wider range in the finer fraction with as much as 30 per cent passing the 75 µm sieve in a number of the profiles examined (see Fig 2). In some cases the fine fraction was plastic.

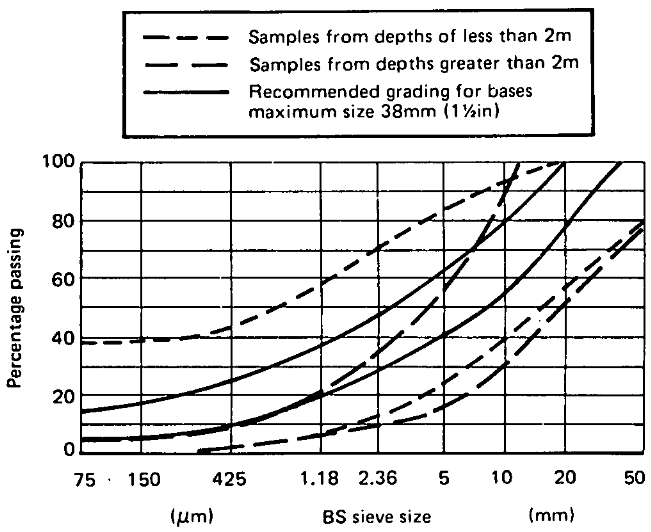

Fig. 2 Gradings of samples obtained during the survey compared with a recommended grading envelope

For practical purposes, it was the material below the weathered zone that was representative of cinder cones as a whole and although there was much similarity in the small amounts of fine material that they contained there was considerable variation in the size of the coarser material. The maximum size in some cones was no more than 2-3 cm whereas in others lumps up to 30 cm or 50 cm were present. Oversize material could be removed by screening or by crushing to produce smaller sizes but even so because of the deficiency in the fraction less the 75 µm the gradings did not conform to the recommended limits for road base materials[4] (see Fig 2).

From the results of particle-size distribution it is clear that in order to obtain representative samples of cinder cones the material should be taken from below the weathered zone.

4.1.2 Modified aggregate impact test. The strength of the cinder gravel particles was measured by the aggregate impact test using the modified procedure for weak aggregates[5]. The modified procedure is essentially a reduction in the standard number of blows of the falling weight that is applied to the sample and so avoids the problem of 'over-crushing' and compacting samples when weak materials are tested.

The test proved to be very suitable for the work on cinders with a number of advantages over the Los Angeles abrasion test which is more commonly used in materials laboratories. The apparatus was portable and hand-operated and used relatively small quantities (about 300 g.) of material which could be tested in both the dry and soaked condition. A further advantage was the shorter time taken to complete the test.

The modified aggregate impact values of 23 of the samples collected during the survey ranged from 46 to 177 (values expressed as that percentage of the original material which passes the BS No 2.36 sieve at the end of the test) and showed the wide range of strengths of the cinder particles (see Table 1). Even so they were all rated as weak when compared with the recommended values of less than 35 for aggregates used in the wearing course of bituminous road surfacings.

Nine of the samples were also tested after a period of 48 hours immersed in water. The results showed that despite their porous nature there was no loss of strength except for one sample.

From the description of the cinder gravel samples given in Table 1 it could also be seen that there was no correlation between colour and strength. This differs from the study by Hendrickson and Lund[6] on cinder gravels in the United States of America who found that dark coloured cinders (purple, grey and black) were harder than the lighter coloured red and brown cinders.

4.2 Variation of cinder gravel within a cone

At three of the cones where material had previously been excavated, samples were collected to examine the variation of cinder within a cone.

Particle-size distribution and modified

Table 1. Modified aggregate impact values of cinder gravels from different cones.

Location (area)	Colour of cinder gravel	Modified aggregate impact value	Modified aggregate impact value-soaked
Batajira	Red	46	
Lake Zwai	Red	50	53
Butajira	Red	54	
Butajira	Red	58	
Debre Zeit	Red	59	
Lake Zwai	Light Brown	60	56
Butajira	Black	67	
Butajira	Black	68	
Akaki	Red-brown	83	
Debre Zeit	Black	83	81
Bekojo	Black	93	
Bekojo	Red	98	95
Lake Zwai	Grey	100	81
Butajira	Black	106	
Butajira	Red-black	107	
Nazaret	Black	113	110
Loggia	Red	113	
Nazaret	Brown	126	
Nazaret	Red	128	
Lake Zwai	Light grey	131	162
Lake Zwai	Red-brown	132	126
Modjo	Black	145	130
Bekojo	Black	177	

Notes: 1. The modified aggregate impact values were determined on the 14 mm - 10 mm sized fraction.

2. Aggregate impact values of less than 35 are normally recommended for road surfacing aggregates.

aggregate impact tests were carried out and the results are shown in Tables 2 and 3. The grading envelope for six samples from one of the cones, at Modjo, was similar to that obtained for all of the samples collected during the survey (cf Fig 3) illustrating that at depths below the weathered zone the amount of coarse material could vary but that the amount of fine material in the fraction less than 75 microns was consistently low.

The modified impact values measured on a number of samples from each of three cones (at Modjo, at Bekojo and at Guse near to Butajira) showed that the strengths of cinder particles could also vary within the same cone. As the particle size increased then generally the strength increased.

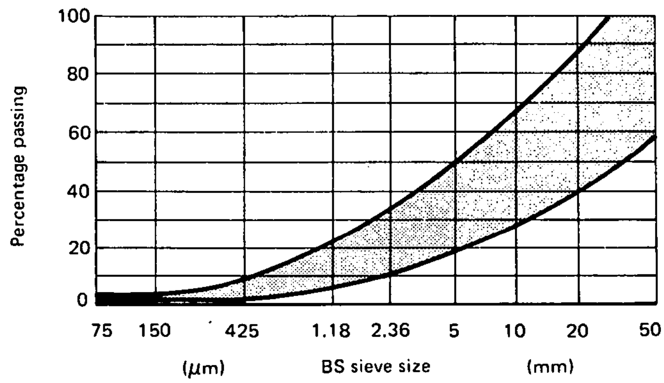

Fig. 3 Grading envelope of samples from Modjo quarry

Table 2. Modified aggregate impact values of same-sized samples obtained from different points in the same cinder core.

Location		Colour of cinder gravel	Modified aggregate impact value
	Sample 1	Black	142
	" 2	Black	144
	" 3	Grey/black	129
Modjo	" 4	Grey/black	121
	" 5	Brown/red	134
	" 6	Red/brown	131
	Sample 1	Red	54
Guse quarry	" 2	Black	68
near to	" 3	Brown	96
Butajira	" 4	Black	66
	" 5	Red	82

Note: Size of samples tested 14 mm - 10 mm.

Table 3. Modified aggregate impact values of different sized samples from the same cinder cone.

Location		Size of sample	Modified aggregate impact value
	Sample 1	50 mm	70
Modjo	" 2	50 - 25 mm	83
	" 3	25 - 14 mm	110
	" 4	14 - 10 mm	145
	Sample 1	50 - 38 mm	89
Bekojo	" 2	38 - 25 mm	95
	" 3	25 - 14 mm	102
	" 4	14 - 10 mm	102

Note: The samples were crushed to 14 - 10 mm for the test.

4.3 Compaction and California Bearing Ratio (CBR) tests

The compaction and CBR tests were important in obtaining further information on the engineering properties of the cinder gravels and the following factors were investigated.

i) the effect of three different levels of compaction on the density/CBR/moisture content relation.

ii) the effect of the different levels of compaction on the grading and the resultant changes in density and strength (CBR) that occurred.

iii) the effect on the density and strength of soaking in water.

iv) the effect on the strength of the addition of fines to make up for the deficiency of material in the less than 75 μm fraction.

The cinder gravels used for the laboratory compaction and CBR tests were from cones at Modjo and close to km 6, Debre Zeit - Bekojo road. Material from the cones had previously been used in nearby low-cost road projects and it was the DebreZeit - Bekojo road that was used to measure the road performance of cinder gravel which is described later in the paper. Materials from these two cones were also subsequently used in the full-scale experiment.

The three levels of compaction[2] used in the tests were:

i) British Standard 2.5 kg (5.5 lb) hammer method.

ii) British Standard 4.5 kg (10 lb) hammer method.

iii) British Standard Vibrating hammer method.

Because compaction was expected to cause breakdown of the weak aggregate particles two series of tests were carried out initially which both involved measuring the changes in grading. In the first series separate samples were used for each point in the density/CBR/moisture content relation with particle-size analyses determined after each point, and in the second series the same material was used for all of the points of the dry density/CBR/moisture content relation. In the second series, therefore, the materials was subjected to repeated cycles of compaction and particle size analyses were determined after the first, third and fifth cycle.

In both series of tests the results obtained for the two cinder gravels followed a similar pattern. For illustrative pruposes, therefore, only one of the samples, that from Modjo is referred to in detail. These results, given in Figs 4 to 9, showed that:

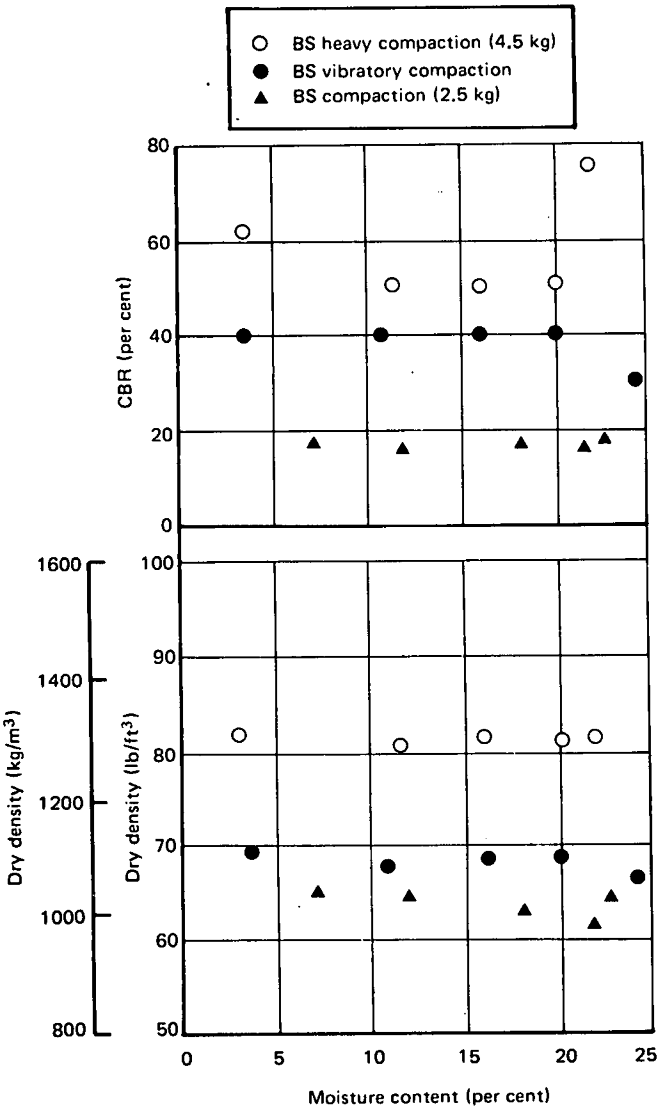

Fig. 4 Dry density/CBR/ Moisture content at different levels of compaction. Separate samples used for each point on the compaction curve

i) Higher densities and CBR values were obtained as the compactive effort increased but, unusually, in the first series of tests using separate samples there was virtually no change in dry density or CBR values as the moisture content increased (Fig 4).

ii) In the second series of tests the dry density and CBR values did increase with moisture content (Fig 6).

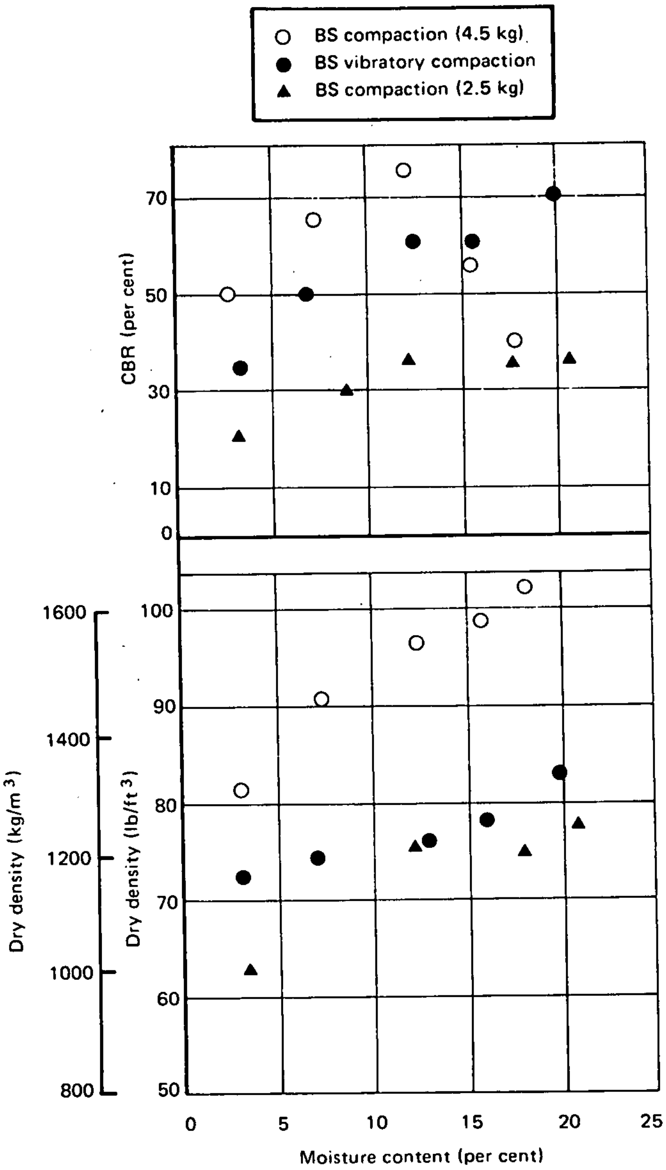

Fig. 6 Dry density/CBR/Moisture content relationship at three levels of compaction. The same sample used at each level of compaction

iii) The difference in the results of the two series of tests can be explained by the effect of compaction of the grading of the materials. The first series showed that different levels of compaction produced different amounts of breakdown (Fig 5).

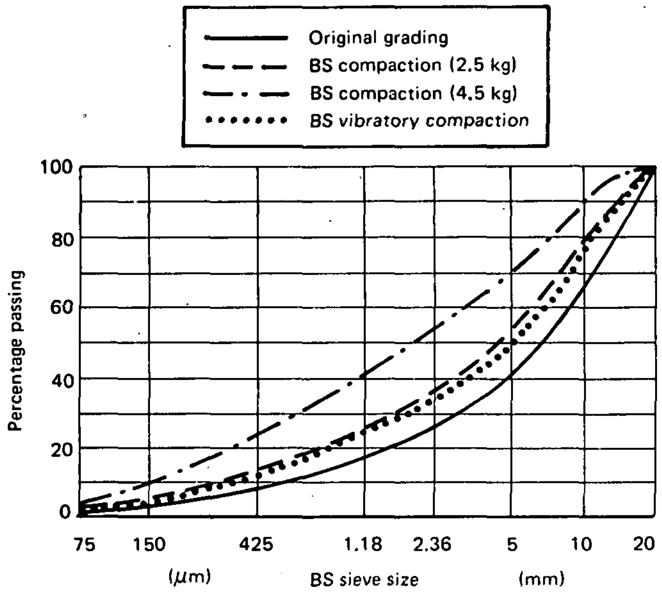

Fig. 5 Effect of compaction on grading—Separate samples used for each point. Each curve is an average of five points

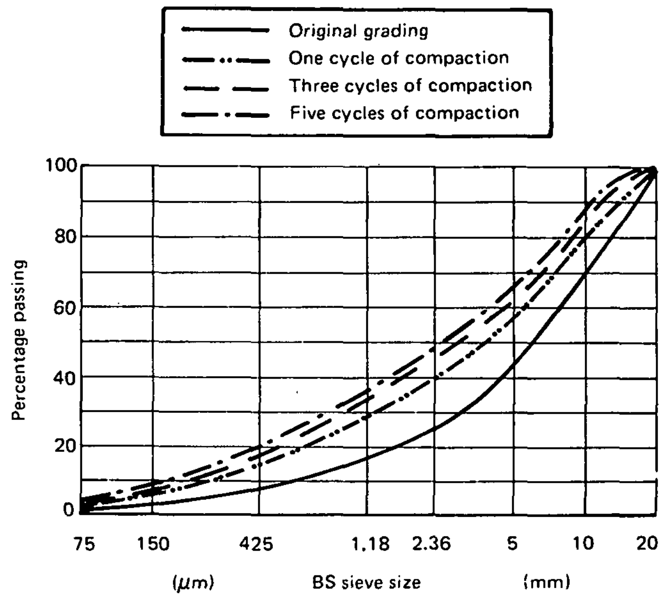

Fig. 8 Effect of repeated compaction on grading, BS vibrating compaction

In the second series, however, because the same sample was used, there was an additional, cumulative effect of compaction which is shown by the increased amount of breakdown between the first, third and fifth cycles (Figs 7, 8 and 9). The difference between the third and fifth cycle though was only marginal and showed that the changes do become less as maximum packing of the particles by compaction is achieved.

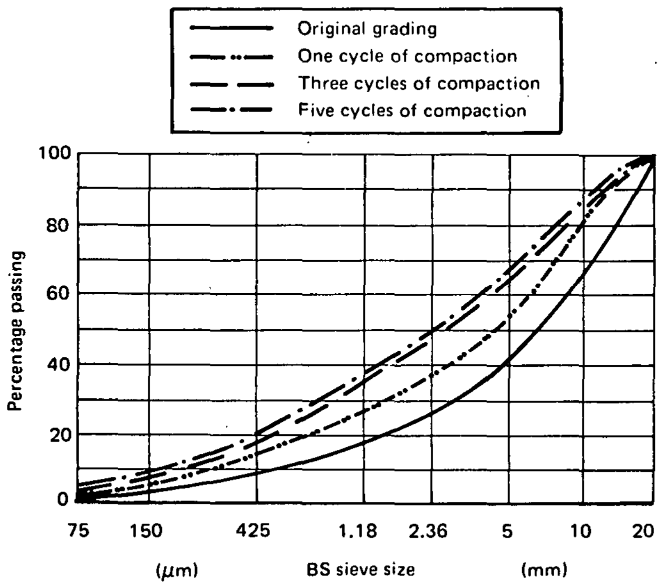

Fig. 7 Effect of repeated compaction on grading, BS compaction (2.5 kg)

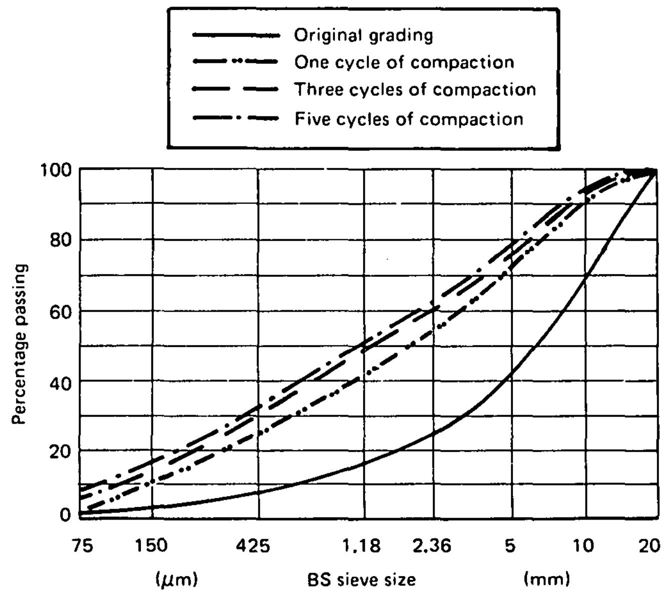

Fig. 9 Effect of repeated compaction on grading, BS compaction (4.5 kg)

iv) The effect of compaction resulted in improved gradings for the cinder gravels which, apart from a deficiency of fine material in the fraction less than 75 microns, now conformed to the recommended limits for materials used in road bases.

v) The increase in density and CBR values, because of the change of grading, was appreciable with maximum CBR values of 75 per cent and 105 per cent being obtained for the two cinder gravels. These results indicated that if the same levels of density were reached in practice in road construction the cinder gravels were likely to prove suitable for use in road bases.

vi) CBR tests on the cinder gravels after being immersed in water for four days following compaction showed that there was no loss of strength.

4.4 Mechanical stabilization: the addition of fines to cinder gravel.

It has been shown that the effect of compaction improved the grading of cinder gravels but that there was still a deficiency in the fine fraction of material less than 75 microns. A further series of tests was, therefore, carried out with additional fine material added. In practice this would appear to be a feasible proposition as suitable material, volcanic ash, is invariably found adjacent to cinder cones and so is available locally.

In the laboratory investigation, the Modjo cinder gravel was used and 10 per cent by weight of clayey ash soil from near the cone was added. The soil had a liquid limit of 64 per cent and a plasticity index of 24.

The tests carried out were the determination of dry density/CBR/moisture content relations at two levels of compaction (2.5 kg and 4.5 kg hammers) with separate samples used for each point of the test as in the first series of compaction tests.

The effect of immersion in water for four days was also examined.

The results are given in Table 4 and in Fig 10 which compares the density/CBR/moisture content relations for the cinder gravel with and without the fines added.

The addition of fines increased the dry density for both levels of compaction by about 8 per cent and the CBR values were also increased with an improvement from 60 per cent to 80 per cent for the heavier level of compaction and from 18 per cent to about 26 per cent for the lighter compaction. Soaking in water for 4 days reduced these values to those for the cinders without fines added.

A further effect of the addition of fines was that the moisture content at compaction could influence the density and CBR obtained, although not in a very marked way.

5. INVESTIGATION OF A CINDER GRAVEL ROAD

It has been stated that in order to provide recommendations for the use of cinder gravels, an understanding of their engineering properties and performance in the road was required. A gravel road about 20 kilometres long between the town of Debre-Zeit and the small village of Bekojo, which had been in service for about two years and was constructed with cinder gravel taken from a cinder cone close to kilometre 6 from DebreZeit, provided the opportunity to carry out an investigation to obtain data on the performance of the material used, and to make a comparison with the results of the laboratory investigation.

The road, which was first visited at the end of the rainy season and was in good condition with only slight rutting in the wheel-tracks and few signs of corrugations had been built by labour-intensive methods. Construction plant had been confined to the use of a blade-grader to spread the material across the formation width of 6 metres, with compaction being left to the

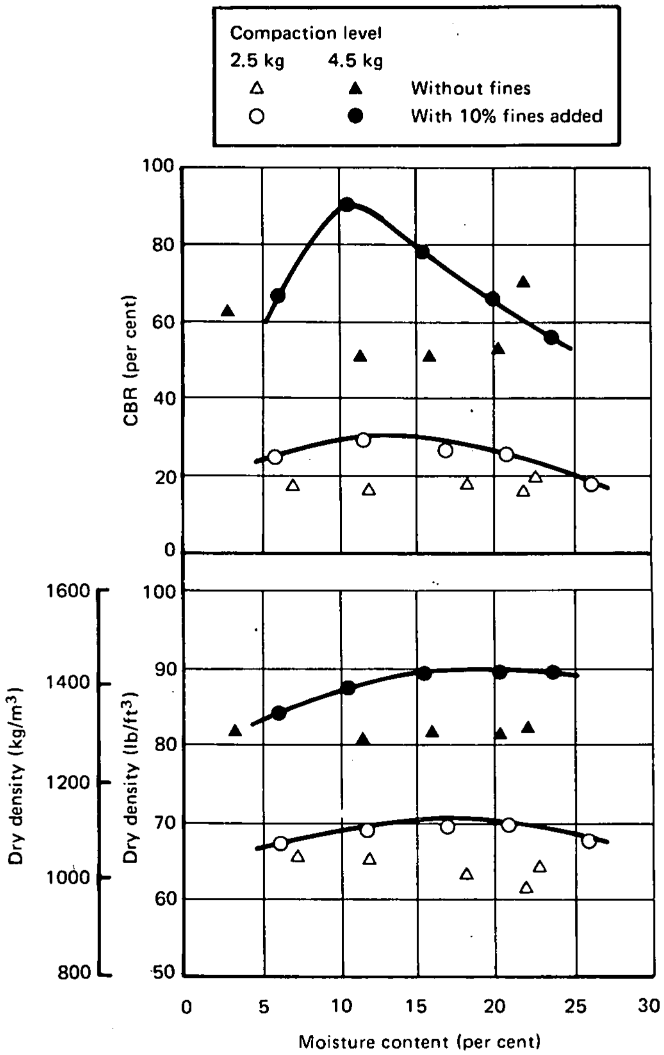

Fig. 10 Comparison of density/CBR/Moisture content relation for Modjo cinder gravel with and without fines added

Table 4. Dry density and CBR values for Modjo cinder gravel with 10 per cent of fines added.

Level of compaction	Dry density km/m³	Dry density lb/ft³	Moisture content - per cent		CBR - per cent
British Standard 2.5 kg hammer	1074	67.1	6.3		25
	1102	68.8	11.7		29
	1105	69.0	17.2		26
	1116	69.7	21.8		25
	1084	67.7	26.3		18
4 days soaking	1073	67.0	5.0	Before soaking	19
" " "	1119	69.9	18.0		20
British Standard 4.5 kg hammer	1345	84.0	6.4		66
	1400	87.4	10.6		85
	1427	89.1	15.6		79
	1435	89.6	20.3		66
	1440	89.9	23.6		56
4 days soaking	1341	83.7	5.0	Before soaking	60
" " "	1428	89.2	18.0		55

action of local traffic which was of the order of 20 vehicles per day.

5.1 In-situ density tests and particle-size analyses.

Three sites were chosen at intervals along the road to measure the in-situ density and grading of the cinder gravel. At each site measurements were made at five points across the road with one on the centre-line, two in the outside wheel-tracks and two in the inside wheel-tracks where the influence of traffic on the compacted density and on the grading was expected to be greatest. The densities were determined by the sand replacement method[2] and samples for grading analysis were taken from positions adjacent to the density holes.

Results of the road investigation and comparisons with some of the results of the laboratory investigation are given in Table 5 and Figs 11 and 12. Additional measurements were made at each site of surface deformation, the thickness of the gravel layer as well as the moisture content and plasticity of the subgrade soil but these results are not reported here.

The results of the in-situ density and grading tests at each of the three sites on the road showed that:

i) The highest densities and greatest degree of breakdown occurred in the position of the wheel-tracks (Table 5 and Fig 12).

ii) The mean value for the in-situ densities in the wheel-tracks was 1538 kg/m³ (96 lb/ft³). This was higher than those obtained for both compaction levels (2.5 kg hammer and 4.5 kg hammer) using separate samples and the same as that for

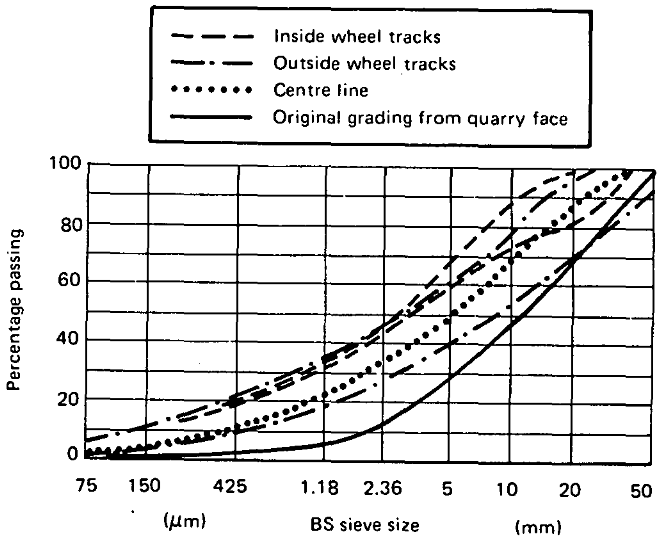

Fig. 11 Grading of samples taken at km 2 Debre Zeit-Bekojo Rd

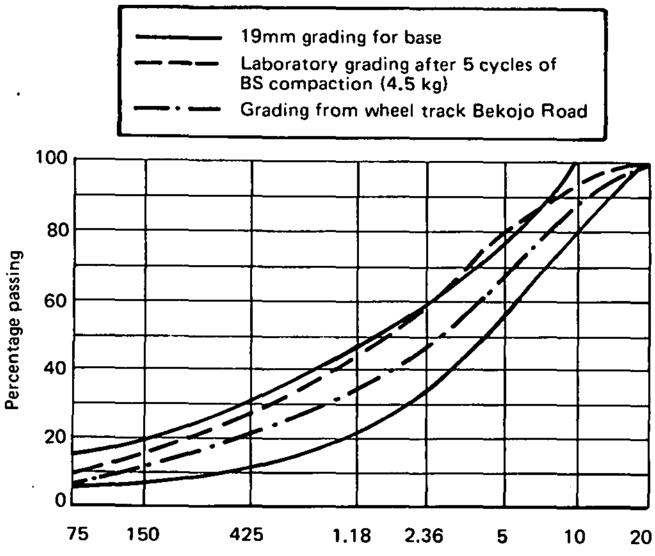

Fig. 12 Comparison of laboratory and in-situ grading with the recommended 19mm (¾in) grading envelope for bases

Table 5. Comparison of in-situ densities with densities obtained in the laboratory investigation

	Road Investigation				Laboratory Investigation				
Site No	Position	Dry Density kg/m^3	Dry Density lb/ft^3	Moisture content - per cent	Level of Compaction	Dry Density kg/m^3	Dry Density lb/ft^3	Moisture content - per cent	CBR - per cent
	Outer wheel-track	1394	87	4.8		1218	76	4.7	25
	Inner wheel-track	1394	87	6.3	British Standard	1202	75	10.5	20
1	Centre-line	1426	89	4.8	2.5 kg hammer	1202	75	14.4	25
	Inner wheel-track	1570	98	9.5	(Separate samples)	1202	75	17.9	25
	Outer wheel-track	1266	79	-		1218	76	18.4	25
	Outer wheel-track	1490	93	3.4		1394	87	4.8	60
	Inner wheel-track	1666	104	4.3	British Standard	1394	87	10.2	60
2	Centre-line	1538	96	2.4	4.5 kg hammer	1426	89	12.7	55
	Inner wheel-track	1538	96	3.5	(Separate samples)	1392	87	17.3	55
	Outer wheel-track	1394	87	6.5		1378	86	19.3	50
	Outer wheel-track	1330	83	3.9		1362	85	5.2	60
	Inner wheel-track	1538	96	4.5	British Standard	1538	96	9.0	80
3	Centre-line	1378	86	3.5	4.5 kg hammer	1587	99	13.3	75
	Inner wheel-track	1490	93	4.9	(Same sample-	1715	107	16.7	105
	Outer wheel-track	1298	81	6.9	repeated compaction)	1731	108	18.3	60

the heavy compaction when repeated compaction of the same sample was used. At that density the laboratory CBR value was 80 per cent (see Table 5).

iii) Trafficking produced changes in the grading of the cinder gravel similar to those obtained in the laboratory compaction tests. The improvement was sufficient in the position of the wheel-tracks, to meet the normally recommended limits for road base materials.

6. CONCLUSIONS

The main conclusions from this first stage of the investigation of cinder gravels which comprised a field survey, a laboratory study and an examination of a cinder gravel road are:

i) Cinder gravels are more widespread in Ethiopia than was originally believed. This showed the value of using aerial photographs in survey work and enabled a preliminary map to be prepared giving the distribution of cinder cones.

ii) In order to obtain representative material from a cinder cone it is important that samples are taken from below the weathered zone which can extend to a depth of two metres.

iii) Although "as-dug" cinder gravels do not meet the recommended grading requirements for road base materials the laboratory investigation revealed that, because of the weak nature of the aggregate particles, breakdown under compaction occurred with an improvement in both grading and strength properties.

iv) In the laboratory investigation the cinder gravels were not affected by changes in moisture and even complete immersion in water only reduced their strength slightly.

v) The addition of locally available clayey soil to make up for the deficiency of fine material in the grading improved the stability of cinder gravels and indicated that this could be a useful construction practice.

vi) The gravel road study confirmed that an improvement in the grading and the strength of cinder gravels occurred under normal road conditions, even when the means of compaction was simply the effect of traffic.

The indications from the study carried out so far are that cinder gravels should make useful road construction materials especially for gravel roads. Further work, however, is necessary to examine a range of cinder gravels under known conditions of traffic and climate in bituminous surfaced roads as well as in gravel roads before limits can be recommended for their various uses. This was the purpose of the full-scale road experiment which is in progress.

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