Experimental Use of Weathered Basalt Gravels on Roads in Ethiopia

PETER BEAVEN, RICHARD ROBINSON, AND KASSAYE AKLILU

Specifications for aggregate surfacings in Ethiopia are based on plasticity and grading with a maximum aggregate size of 38 mm. Roads built to these specifications have performed well, but the cost of construction has usually been relatively high because it is often necessary to process the material through crushers and screening plants. The natural gravels, including weathered basalts, do not normally comply with aggregate surfacing specifications, but their abundance makes them a relatively cheap construction material. Two experimental roads were constructed in Ethiopia in a joint study by the Ethiopian Transport Construction Authority and the Transport and Road Research Laboratory of the United Kingdom to examine the possibility of using weathered basalt gravels as a surfacing material for unpaved roads. These experiments involved the study of gravels from several different sources under traffic levels that ranged from 30 to 175 vehicles per day. Test sections were placed on roads with different geometric characteristics so that their performance could be studied under a range of conditions. The performance of the materials was assessed in terms of resistance to deformation, rate of gravel loss, and deterioration of riding quality. These factors were related to the physical characteristics of the gravel, including any possible change with time, and to the traffic loads. The measurements of the road surface were based on optical levelling, which was used to monitor rutting, corrugations, and gravel loss. These standard measurements were supplemented by visual inspection to identify features such as surface texture or the development of potholes. Riding quality was measured with a vehicle-mounted bump integrator. Materials were tested by means of density measurements and grading checks. The results of the experiments have led to proposals for the use of weathered basalt gravels and have shown that crushing or screening is cost-effective to reduce oversized material when used on roads with traffic levels greater than about 50 vehicles per day.

The Ethiopian Transport Construction Authority (ETCA) is responsible for the construction of a considerable length of gravel road each year and is concerned about the problem of finding suitable gravel materials to provide adequate running surfaces.

The first set of materials specifications introduced by the ETCA were based on those published by the U.S. Bureau of Public Roads. The specifications for aggregate surfacing are based on plasticity and grading with a maximum allowable aggregate size of 38 mm. Roads built to these specifications have performed well, but the cost of construction has usually been relatively high, because the material must normally be processed through crushers and screening plants. The natural gravels, such as volcanic cinders, weathered basalt, and river gravels, which are available in some areas in large quantities, do not normally comply with the aggregate surfacing specifications because of their coarse nature and plasticity characteristics. In order to make full use of these local materials, it is necessary either to modify them so that they comply with existing specifications, or to broaden the specifications to include a wider range of materials. The first alternative would increase the cost of using the natural gravels, whereas the second alternative implies an increase in vehicle operating costs or road maintenance. One effective way to justify changes in specifications is to study the behavior of the materials in the field.

Various low-grade materials have been studied in the Joint Road Research Project of the ETCA and the Transport and Road Research Laboratory (TRRL) to determine if effective specifications can be devised for their use on lightly trafficked roads. One experiment has been constructed to study the performance of volcanic cinders and tuff and two other experiments are described that have been used to study weathered basalts (*1*). Experimental roads were constructed using basalt gravels. The first was on the Gelemso-Mechara project and the second was on the Ghion-Jimma project. Each experiment contained several stretches of construction on different parts of the road line so that different conditions could be studied.

GELEMSO-MECHARA EXPERIMENT

The first of these experiments, which was conducted near Gelemso, was designed to investigate aspects of variation in gravel quality and the effect of geometry on road performance. The project was constructed to gravel standards and the estimated traffic flow was 30 vehicles per day (vpd).

Several sources of gravel had been tested for use on the project and some had been rejected because they were outside specifications. Sections were laid using gravel that met project specifications and were compared with sections that contained gravel with excess plasticity or unsuitable gravel that had been improved. In one case, this involved running gravel through a crusher to reduce the maximum size of aggregate. A second case involved the addition of sand to reduce the plasticity of the fines. Studies were also made of the effect of different compaction equipment on the breakdown of the gravel.

In order to assess performance on steep gradients, two gravel sections were constructed on gradients of 7 to 8 percent and were compared with sections with gradients of 1.5 percent. Most of the sections were straight but two had a moderate degree of horizontal curvature.

P. Beaven and R. Robinson, United Kingdom Transport and Road Research Laboratory. K. Aklilu, Ethiopian Transport Construction Authority.

GHION-JIMMA EXPERIMENT

The second experiment was incorporated into a bitumen surfacing project that enabled an accelerated study to be made using a higher level of traffic on gravel-surfaced experimental lengths of road. The main objective was to compare gravels within specification to those with higher plasticity under a range of horizontal and vertical curvatures. The proposal to modify a gravel by crushing had to be abandoned because there was no spare crushing capacity near the gravel pits.

PROPERTIES OF BASALT GRAVELS

A visual inspection of a typical weathered basalt indicates that it consists of coarse gravel aggregate with plastic fines. The aggregate can vary from apparently fresh rock to hard weathered material to a highly weathered skin that is easily broken down by handling. A sharp boundary often exists between different stages of weathering. The presence of highly weathered material and a large proportion of coarse gravel complicates the testing of these soils and makes interpretation of the resulting data more difficult.

Typical weathered basalts in Ethiopia are predominantly gravel with a low proportion of sand. In practice, it is difficult to find materials that, when excavated, meet ETCA specifications for a "special subbase," which require that between 30 and 70 percent of the material should be retained on the U.S. No. 4 (5-mm) sieve. Only coarse gravel that has been run through a crusher typically meets this specification.

In addition to grading, the plasticity characteristics are usually included in specifications because these two properties can be related to density and strength. Weathered basalt gravels tend to have high plasticities, which can restrict the use of these materials. Preparation of the sample for testing can also affect the result. The change in grading of a material on compaction can be accompanied by a change in plasticity.

Strength testing of weathered basalts can be difficult to interpret because the usual test procedure, the California Bearing Ratio (CBR), uses material less than 20 mm in size. However, exclusion of material that is greater than 20 mm in size can drastically alter the grading of the material. The recommended procedure for laboratory compaction tests is that the coarse gravel be replaced by an equivalent amount of material between 5 and 20 mm in size. However, if a significant proportion of the sample is replaced in this way, a highly distorted grading curve results. This is bound to alter the density, which will affect the strength. Tests that use coarse gravel in a 45-cm-diameter mold have shown that the density is reduced by 3 percent when material larger than 20 mm in size is replaced in this way. Standard correction procedures have been proposed to correlate laboratory densities on material less than 20 mm in size with field densities of the natural gravel.

It must be acknowledged that when measuring the CBR of weathered basalt, the laboratory value will only be a guide to the strength of the material in the field because of the differences in the grading between the two. A typical soaked CBR of weathered basalt is in the range of 15 to 30, which means that, when an allowance is made for the presence of large aggregate (which is presumed to increase the stability), much weathered basalt is adequate as a subbase, but none is suitable for use as a base beneath a bitumen surface.

PERFORMANCE MODELS

Models for predicting the performance of gravel roads under traffic have been developed by TRRL in Kenya (*2*). Performance is related to traffic loading in terms of the progression of gravel loss, roughness, and rutting. The present generation of performance relationships defines gravel type in a simple, generic way, such as volcanic, lateritic, and quartzitic, although the relationship for gravel loss also has components for rainfall and gradient. The results of these experiments are compared with those of Kenyan volcanic gravels.

EXPERIMENTAL ROADS

Gelemso-Mechara Experimental Sections

The layout and characteristics of the experimental sections constructed on the Gelemso-Mechara project are given in Table 1. Each of the test sections was 400 m long, but only the 100-m central section was used for detailed measurement. The running surface was 6 m wide and the gravel wearing course was laid 200 mm thick, with the exception of Section 2. The gravel surfacing material came from three quarries that were sited at km 62, 66, and 74. A summary of their properties is given in Table 2.

TABLE 1 GELEMSO-MECHARA TEST SECTIONS

Section	Horizontal Curvature Over Section	Gradient (%)	Subgrade	Gravel
1	Straight	1.5	Black cotton	Km 66 (200 mm)
2	Straight	2.2	Black cotton	Km 66 (400 mm)
3	38 degrees	7.6	Sand	Km 74
4	Straight	8.6	Sand	Km 62
5	Straight	1.7	Red clay	Km 74
6	13 degrees	1.6	Red clay	Km 62[a]
7	Straight	1.2	Red clay	Km 62
8	Straight	1.5	Black cotton	Km 62 + 10% sand
9	Straight	0.6	Black cotton	Km 62 crushed
10	Straight	1.1	Black cotton	Km 74

[a]Both grid and vibrating rollers were used on Section 6. All other sections were compacted with a vibrating roller only.

The gravel from km 62 contained a fair proportion of oversized material (greater than 75 mm) and was deficient in sand and fine material. However, the fines that were present had a high plasticity. An attempt was made to improve this gravel by crushing it but, crushed or uncrushed, the material did not meet the material specification requirements for the main construction project.

The gravels from km 66 and km 74 were similar to those from km 62, but the gradings were better and the natural fines were less plastic. These two materials were used to construct the main project.

Ghion-Jimma Experimental Sections

The layout and characteristics of the experimental sections constructed on the Ghion-Jimma project are given in Table 3. The test sections were constructed at four sites to obtain the variety of traffic flow and geometric conditions that was required. Sections 1 to 11 were built on the main Ghion-Jimma road. The first seven sections were located just outside the town of Welkite and the remainder were located in the Gibe gorge. The other sections were constructed on side roads to Hosaina and Dadale to obtain lower traffic flows.

Each test section was 100 m long with a 100-m transition in between the sections. Because of the local road geometry, it was necessary to split Section 9 into two 50-m subsections. The sections were 7 or 8 m wide with the exception of those on the road to Dadale, one of which was 4 m and the other 6 m. Gravel was laid to a compacted thickness of 150 mm with the exception of the sections on the road to Dadale, which had been recently constructed by ETCA and on which no new construction was applied. All of the sections at all of the sites were built on a similar subgrade of expansive black clay.

The gravel surfacing material came from three quarries sited at km 167 on the main project, and from quarries on the roads to Hosaina and Dadale. A summary of the properties of the km 167 and Dadale materials is given in Table 4. The material from the quarry on the Hosaina road was virtually identical to that from km 167, and the properties are not reported separately.

The Dadale material contained a higher proportion of fines than that from km 167 and was slightly more plastic. Both materials contained oversized material, the proportion of which was higher in the Dadale material than in the km 167 material.

TABLE 2 PROPERTIES OF SURFACING MATERIALS USED AT GELEMSO-MECHARA

Gravel Type	Liquid Limit	Plasticity Index	Fines Content (% Passing 75mm That Pass 75μm)	Maximum Dry Density (Mg/m^3) (BS1377)	Optimum Moisture Content (%)	Soaked CBR at 0.1 in. pen (%)
Km 62 (pit run)	49	24	6	1.69	19	16
Km 62 (crushed)	50	21	9	1.92	15	18
Km 66	33	6	11	2.03	12	30
Km 74	35	7	7	2.03	12	25

TABLE 3 GHION-JIMMA TEST SECTIONS

Section	Traffic ADT	Horizontal Curvature Over Section	Gradient (%)	Gravel	Location
1		Straight	-3.7	Km 167	
2		Straight	-2.8	Dadale	
3		59°L	-1.4	Dadale	
4	175	Straight	-0.9	Dadale	Welkite
5		Straight	+0.4	Km 167	
6[a]		Straight	+0.5	Km 167	
7[b]		Straight	+0.5	Stabilized	
8		63°L	-4.3	Km 167	
9A		27°L	-6.3	Dadale	
9B	175	66°R	-6.2	Dadale	Gibe
10		Straight	-5.0	Dadale	
11		Straight	-4.7	Km 167	
12	75	Straight	+6.2	Hosaina	Hosaina
13		Straight	+2.2	Hosaina	
14	25	Straight	+6.5	Dadale	Dadale
15		Straight	+1.8	Dadale	

[a]Section 6 was designed to have a 6 percent camber, whereas all other sections were designed with a 4 percent camber.
[b]Section 7 was stabilized with lime and sealed with a single surface dressing.

TABLE 4 PROPERTIES OF MATERIALS FROM QUARRIES USED ON GHION-JIMMA EXPERIMENT

Gravel Type	Liquid Limit	Plasticity Index	Fines Content (% Passing 75mm That Pass 75 μm)	Maximum Dry Density (Mg/m^3) (BS1377)	Optimum Moisture Content (%)	Soaked CBR (%)
Km 167	41	23	7	2.07	13	44
Dadale	50	29	11	1.97	14	24

It was originally planned to lay experimental sections using crushed materials but the cost of hauling from the quarries to the nearest available crusher proved to be prohibitive and this part of the experiment was abandoned. The material from the km 167 quarry was marginal. It was at the limit of the ETCA grading specification, whereas the Dadale material fell outside the specification.

Climate

The Gelemso-Mechara district has an annual, moderate rainfall of about 1000 mm. Most of the rain falls in the months from April to September. The mean annual temperature is about 19°C and is fairly constant throughout the year.

The mean annual temperature at Welkite, one of the sites of the Ghion-Jimma project, is approximately 16°C and monthly means vary from this by only a few degrees. The mean annual rainfall is about 1400 mm, and varies from about 25 mm during January to over 250 mm during July. No information is available on climatic differences between the Welkite and Gibe sites, although a subjective assessment indicates that Gibe is both hotter and wetter.

Traffic

A manual traffic count was performed on the Gelemso-Mechara road and indicated that the average daily traffic was about 30 vpd. Because of the low traffic volume and the observation that the traffic was composed largely of a few vehicles that passed over the road several times, it was decided not to perform an axle load survey.

A traffic survey was performed near the Welkite site shortly after construction. A classified traffic count was made for 6 days and an axle load survey was performed for 7 days. In both cases, vehicles were surveyed from 7:00 am to 7:00 pm each day. Little traffic was on the road outside this period. Automatic traffic counters were also placed on the Hosaina and Dadale sites, each for one complete week. The traffic loads for the four sites were estimated from the results of these surveys and are shown in Table 5.

TABLE 5 TRAFFIC LOADS IN GHION-JIMMA EXPERIMENT

	Site		
	Welkite/Gibe	Hosaina	Dadale
ADT light vehicles	59	70	25
ADT heavy vehicles	116	5	-
ADT all vehicles	175	75	25
Daily one-direction standard axles	542	74	-
Total one-direction standard axles	140,000	10,000	-

Note: Dash indicates that the value is negligible.

MEASUREMENT TECHNIQUES

General Measurement of the Road Surface

The adopted system involved the survey of a 100-m length of road with an optical level using 8-m cross-sections. Elevations were measured at 0.25-m intervals across the road and spaced at 10-m intervals along the road. Survey levels were related to pipes in the verge and the center line was marked with a 100- or 150-mm nail placed in the road surface at 30-m intervals, so that cross-sections could be reestablished on exactly the same line using a measuring tape of this length. Nails were placed at 20-m intervals on bends. Experience showed that these nails could be found relatively easily at subsequent surveys and were not pulled out of the road.

The levels that were recorded in this manner were related to monument heights and a computer program was developed to compare surveys and determine average gravel loss over the section. Cross-sections were also plotted and a 2-m straight-edge scale was then used to measure rut depth. Some sections contained two ruts and some contained four. In each case, the maximum depth was measured for each rut, and the mean was recorded. The data from the Ghion-Jimma experiment were also analyzed by computer to identify and measure all of the ruts.

Corrugations

Corrugations on the Gelemso-Mechara sections only occurred on one section during the period of measurement. These were recorded using a technique that was applied to 30 m of the center line and at a distance of 1 m on either side. The spacing of corrugations was determined using a measuring tape. This tape was also stretched between adjacent crests to provide a datum from which the deepest part of each trough could be measured using an optical level to give absolute heights that could reveal long wavelengths. The broad contact from the base of the staff avoided penetration of the loose material.

Roughness

Comparative measurements of riding quality were made only on the Ghion-Jimma sites using a vehicle-mounted bump integratoı that was fixed on a Range Rover vehicle. This measured the sum of the upward movements of the rear axle in relation to the chassis of the measuring vehicle over the length of the test run. Calibration runs over a length of bitumen-surfaced road were used to compensate for any changes in the vehicle's suspension over time and to standardize values at 2.5 m/km. However, at the relatively high roughness levels recorded in this study, quoted readings are unlikely to be comparable with standard international roughness units (*4*). Nevertheless, the readings still provide a useful index of riding quality for the purpose of comparing the performance of one test section with another.

Materials Testing

Testing after construction was only possible on the Ghion-Jimma site and was confined to checking density and particle size distribution to see if there was any change in these properties as a result of trafficking. The difficulties that resulted from the large size of the aggregate have already been discussed. However, one other difficulty was encountered when comparing densities that were measured on a freshly constructed road with those on a trafficked section that had a rough surface. In the latter case, the sand bottle that was used to determine the volume of soil being tested was held away from the surface by protruding stones. This allowed excess sand to escape, which led to an underestimate of density. To compensate for this, the pouring cylinder was calibrated for each density site to determine the volume of sand that escaped from the standard equipment.

PERFORMANCE OF THE EXPERIMENTAL SECTIONS

The Ghion-Jimma experiment was monitored for a 9-month period following construction. The Gelemso-Mechara experiment was monitored for 11 months. It was originally planned to monitor the Gelemso-Mechara site for a longer period, but this proved to be impossible because of the security situation in the vicinity of the experiment.

Density and Grading

Grading curves for the gravels that were used in the Gelemso-Mechara experiment are shown in Figure 1. No further sieve analyses were performed for these materials.

The results of the sieve analysis of the Ghion-Jimma experiment are shown in Figure 2 to illustrate both the similarities between the materials and the variability of the gravels actually laid. The sample size was deliberately restricted to avoid damaging the surface of the road, which meant that it would not be possible to measure the oversized aggregate. When the results of the sieve analysis are plotted for 20-mm down material, as shown in Figure 3, the differences in the materials becomes more apparent and it is possible to study the change in grading after construction. Only one of the gradings had changed by more than 10 percent, and two sections that

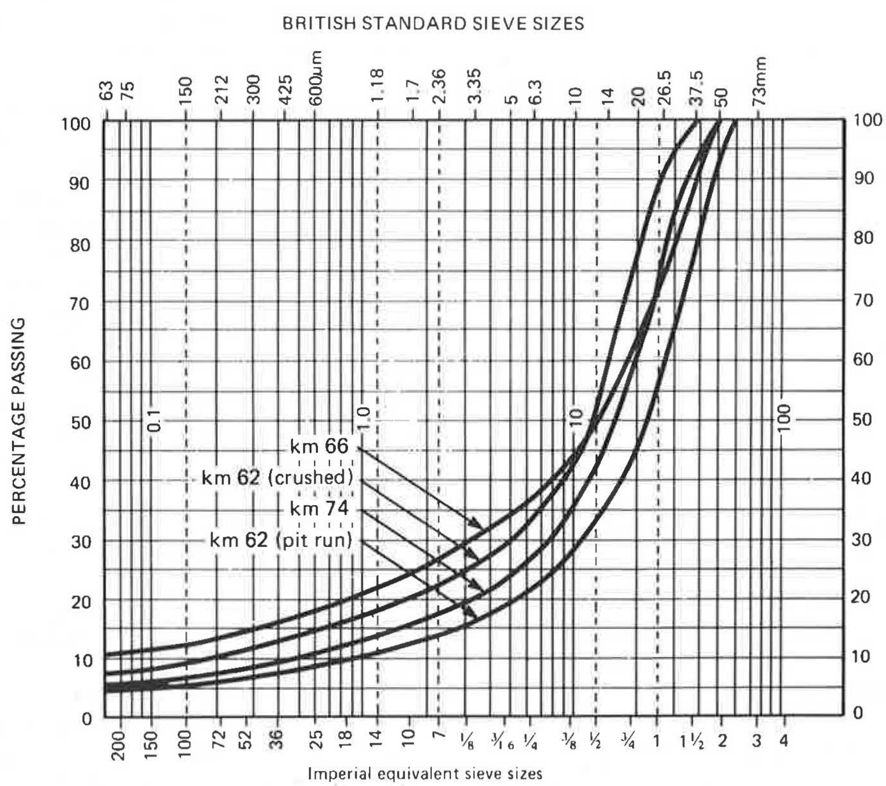

FIGURE 1 Grading of Gelemso-Mechara gravels.

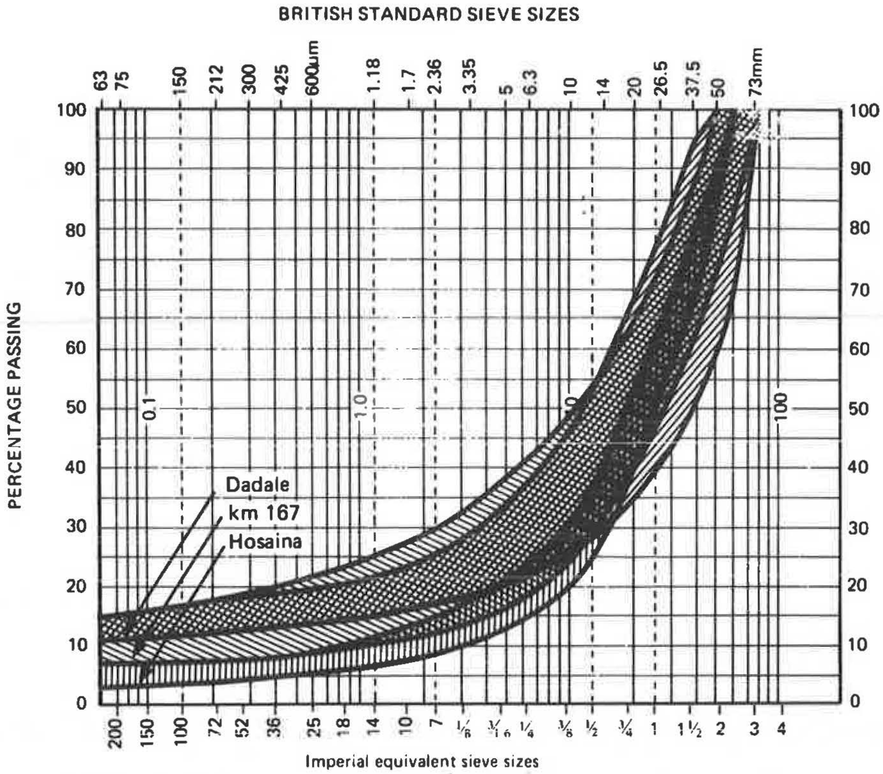

FIGURE 2 Grading envelopes for Ghion-Jimma materials at construction.

corrugated had not changed at all. There was no consistent pattern to the small changes that were detected and it was concluded that the difference in the gradings that were obtained at two different times was a reflection of the inherent variability of the materials. Therefore, no further grading measurements were performed.

Measurements were made of density and moisture content 4 months after construction. However, because the values changed little during this period, the measurements were not repeated.

Rutting on the Gelemso-Mechara Project

The development of rutting on the Gelemso-Mechara experimental sections is depicted in Figure 4. It is shown in the figure that the development of ruts is very irregular at this early stage in the life of the road. However, certain features can be seen. The majority of sections, which were constructed with gravel that met normal specifications, behaved similarly. The use of the more plastic gravel from km 62 had increased rutting by 50 percent. Sections 3 and 4 were on steep gradients. Rut depth increased significantly in these sections in comparison to the flat sections that were constructed from the same material. It was not possible to detect any changes that resulted from horizontal curvature. However, on Sections 4, 7, 9, and 10, the uphill lane had significantly deeper ruts than the downhill lane, even though both lanes had the same traffic loads.

Rutting on the Ghion-Jimma Project

Mean rut depths are plotted against traffic in the Ghion-Jimma project in Figures 5 and 6. Five sets of readings were taken over a 9-month period in this experiment.

The following general observations can be made from these figures. The sections in the Gibe gorge, in which the speed of vehicles was considerably reduced, have lower rut depths than the sections at Welkite. At both sites, the Dadale material had deeper ruts than the km 167 material, and the rut depth tended to increase with time after the initial period. The km 167 material did not change much after the initial period. The performance of Section 6 was much different from all other sections. Sections 5 and 6 developed corrugations, but those of Section 6 were more severe. Large potholes also developed. It was intended that this section be constructed with a 6 percent camber instead of the normal 4 percent. During construction, a large part of the test section was given a final pass by the grader, which resulted in an almost flat crown. A comparison has been made between the deformation of normal sections (Figure 7) and of those with a crown that had been flattened to a transverse gradient of less than 2 percent (Figure 8). A typical rutting pattern developed on normal sections, but all flattened sections developed a single, large depression in the center of the road.

It was expected from comparisons of rut depth and gradient in the Gelemso-Mechara experiment that the sections in the Gibe gorge would have deeper ruts than equivalent sections at Welkite. However, rutting at Welkite was generally deeper, which implied that differences in such factors as vehicle speed were having an effect. Research in Australia has defined a "speed environment" for a road that is related not only to road geometry, but also to the topography and other features surrounding the road (*5*). The speed environment of the Welkite site was significantly higher than that of the Gibe site in the Ghion-Jimma experiment. The deeper ruts could therefore be partly a result of higher speeds. A change of gradient from 0.9 percent to 2.8 percent on Sections 2 and 4 at Welkite increased the rut depth between 10 and 15 percent.

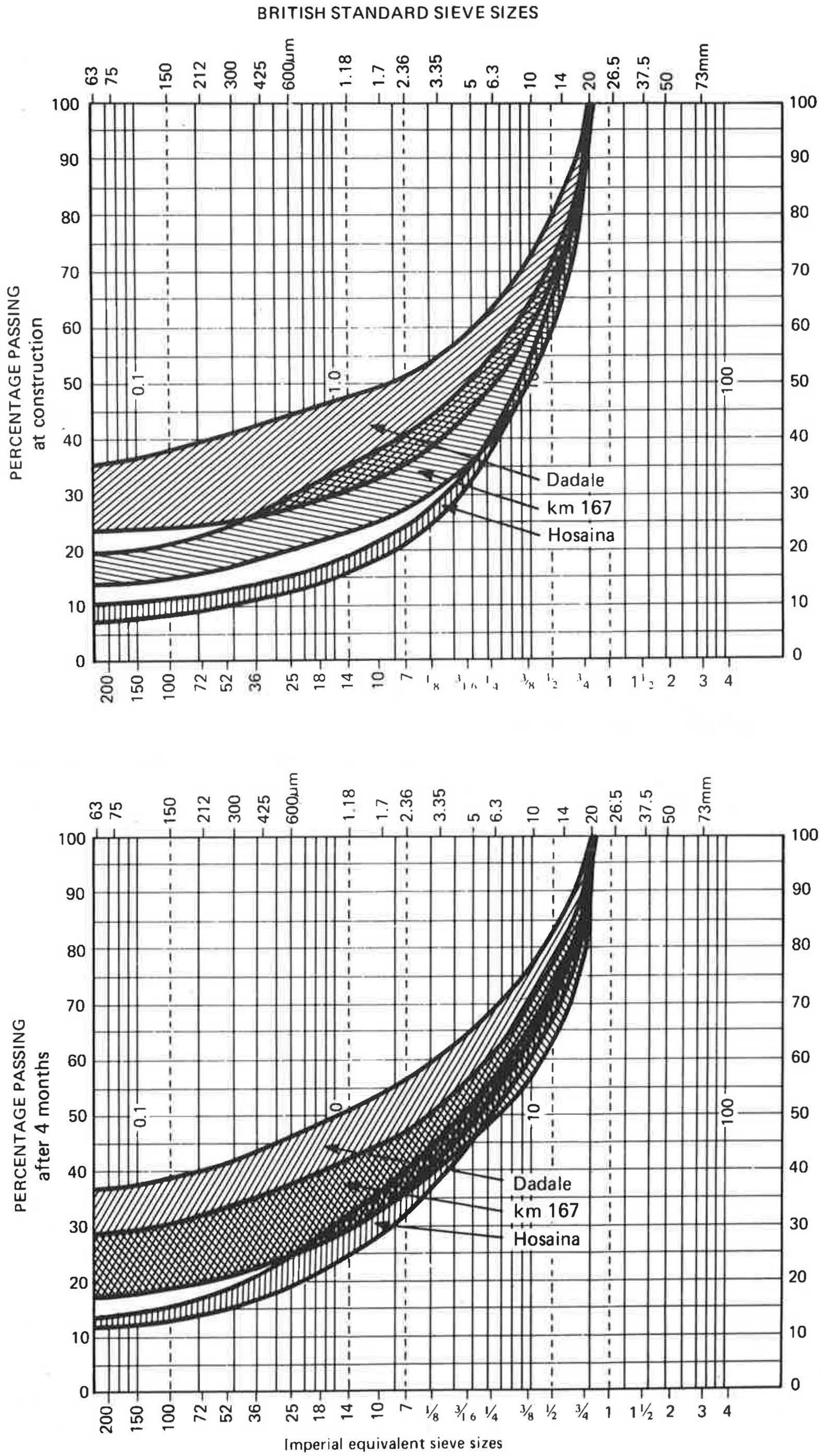

FIGURE 3 Grading envelopes for Ghion-Jimma materials less than 20 mm in size at construction and 4 months later.

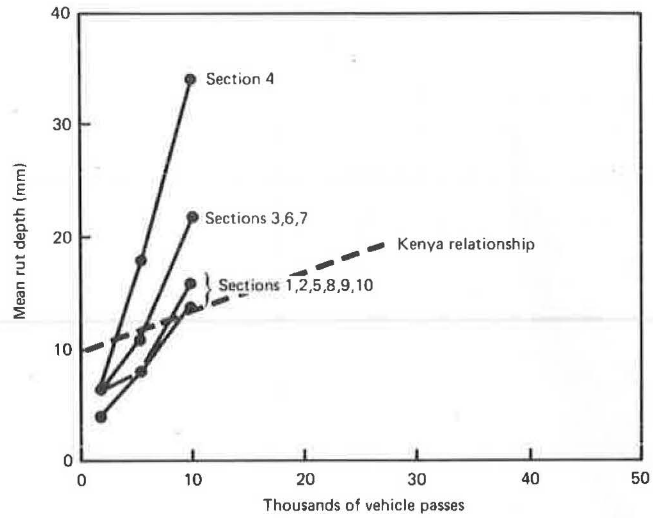

FIGURE 4 Mean rut depths for the Gelemso-Mechara experiment.

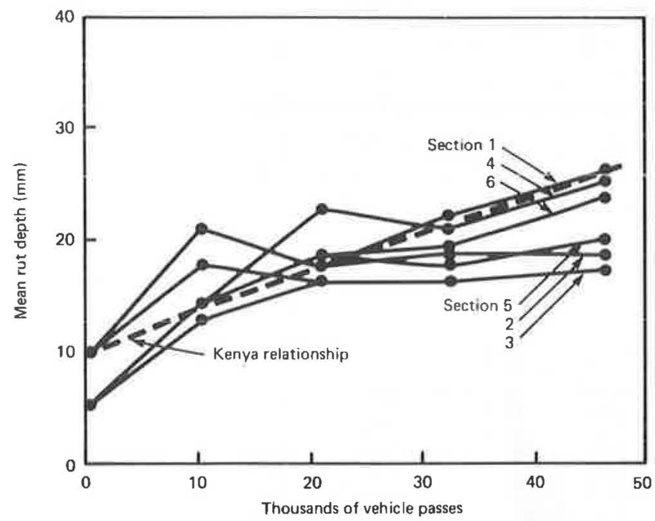

FIGURE 5 Mean rut depth for Ghion-Jimma test sections at Welkite.

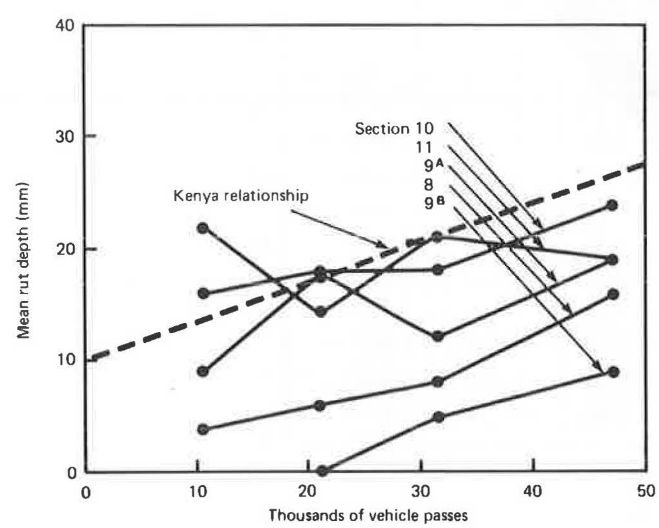

FIGURE 6 Mean rut depth for Ghion-Jimma test sections at Gibe Gorge.

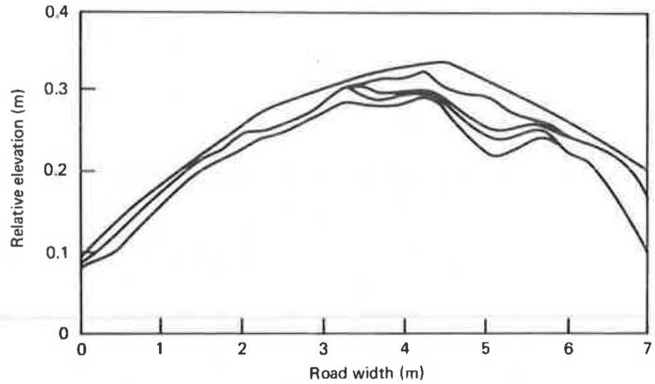

FIGURE 7 Deformation of normal cambered cross-section from Section 6 of Ghion-Jimma experiment.

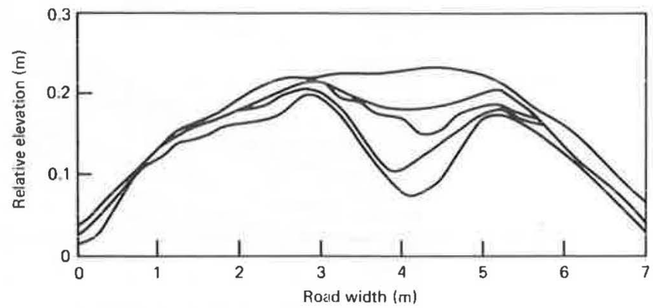

FIGURE 8 Deformation of flattened cross-section from Section 6 of Ghion-Jimma experiment.

Comparison of Rutting With Results From Kenya

A study of the performance of volcanic gravels has also been performed by the TRRL in Kenya (*2*). This study monitored the increase in mean rut depth and resulted in the development of the following predictive equation:

$$RD = 10.11 + 0.314T + 0.00031T^2 + 0.00002T^3$$

where

RD = mean of all ruts in mm measured under a 2-m straight edge, and
T = cumulative traffic in both directions since grading, measured in thousands of vehicle passes in both directions.

This relationship has been plotted on the mean rut depth results from Ethiopia, and are directly comparable in Figures 4 to 6. The experiments in Kenya measured the performance of gravels up to about 90,000 vehicle passes. The traffic levels studied in Ethiopia were much lower than this level and, over this range, the plotted relationship is essentially linear.

The agreement shown by the test sections at Welkite in Figure 5 is very good. However, the rut depths of the sections in the Gibe Gorge, shown in Figure 6, tend to be lower than the predictive equation from Kenya. As was noted earlier, the lower speed environment of Gibe Gorge led to lower rut depths. The Kenya relationship was made only in terms of traffic; the effects of speed or geometry were not modelled. The Kenya relationship does not provide good predictions for the lightly trafficked sections shown in Figure 4. In these cases, the effect of climate is likely to play a relatively more significant role than traffic. It is

not surprising that the Kenya equation, which is made only in terms of traffic, does not give good predictions of performance in terms of rut depth in these cases.

Corrugations

Eleven months after the Gelemso-Mechara experiment was constructed, only Section 9 showed signs of corrugations. Subsequent examination of stereoscopic photographs that were taken 4 months after construction showed no trace of corrugations (*3*). This suggests that the formation of the corrugations took place during the dry season. It was not possible to take measurements at 1 m on either side of the center line because the corrugations were not sufficiently well developed. The mean crest spacing was 0.89 m and the mean depth was 19 mm. Crushed gravel from km 62 was used to construct Section 9. This suggests that a more effective way to improve the stability of this material is to blend it with sand instead of crushing it.

The development of corrugations on Sections 5 and 6 of the Ghion-Jimma experiment is shown in Figure 9. The sections were monitored at the end of October, 9 months after construction (47,000 vehicle passes). Measurements were only made of corrugations along the center lines even though the corrugations extended to at least 1 m on either side. By this time, the corrugation troughs had mostly become potholes. The wet season at Welkite extends from the beginning of May to the end of September.

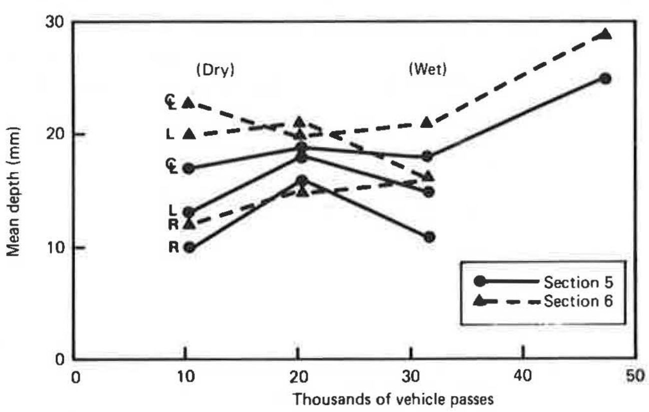

FIGURE 9 Ghion-Jimma corrugation depth.

The graphs indicate that the severity tended to reduce during the rainy season and then to increase again as the road surface dried out after the rains. This phenomenon was observed in another experiment performed in Ethiopia by the Joint Road Research Project and confirms other observations that the severity of corrugations is related, among other things, to the moisture content of the road-building material (*6*). This is because the moisture helps bind the material together and therefore inhibits its ability to move under the action of traffic.

The most significant thing about these results is that (a) of all the test sections, only Sections 5 and 6 showed any signs of corrugating, (b) the corrugations formed were severe, and (c) they formed very soon after construction. It is unclear why these and no other sections corrugated. From a materials point of view, nothing from the grading or in situ density results would account for the marked difference in the deterioration shown by these sections when compared with that of the remainder of the experiment. In addition, because both sections were straight and level, it is unlikely that road geometry accounted for the deformation. The only possible explanation appears to be that Section 6 was adjacent to Section 7, which was paved, whereas all other test sections were adjacent to unpaved sections of road. It is probable that vehicle speeds were higher on the paved section and, therefore, vehicles travelling towards Welkite entered Section 6 at a higher speed than on other sections. This higher speed, coupled with probable braking, could be critical factors that triggered the corrugations. This is supported by the fact that corrugations were less severe on Section 5, in which speeds were probably lower, and braking was possibly gentler. By the time vehicles reached Section 4, they were no longer braking and their speeds were reduced to values similar to those experienced by the other gravel sections.

Roughness

No measurements of roughness were made in the Gelemso-Mechara experiment. In Figures 10 and 11 roughness has been plotted against traffic volume in the Ghion-Jimma experiment. Because most of the traffic tended to drive down the middle of the road, the average of the roughness measurements in each direction was determined and plotted against total traffic in both directions. Because it was not possible to perform a detailed calibration of the measuring unit, the absolute, recorded values of roughness are probably unreliable, particularly the higher readings. Nevertheless, the relative values obtained give a good indication of the relative riding quality on each of the sections.

The corrugations on Sections 5 and 6 have a clear effect on the riding quality and Section 6 is noticeably bumpier than Section 5 (*cf.* corrugation results). The remaining section at the Welkite site (Section 1) became approximately twice as uneven as any of the sections that were built with this material at either the Gibe or Hosaina sites (Sections 8 and 11 to 13). By the close of the experiment, some of the sections that were surfaced with Dadale material (Sections 2 and 4) had become almost as

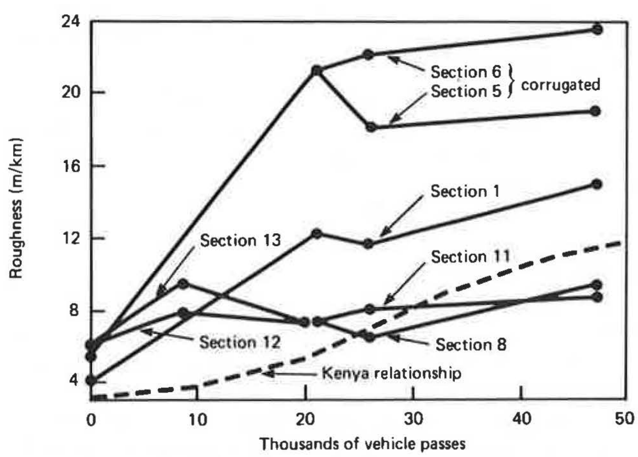

FIGURE 10 Ghion-Jimma roughness progression for km 167 material.

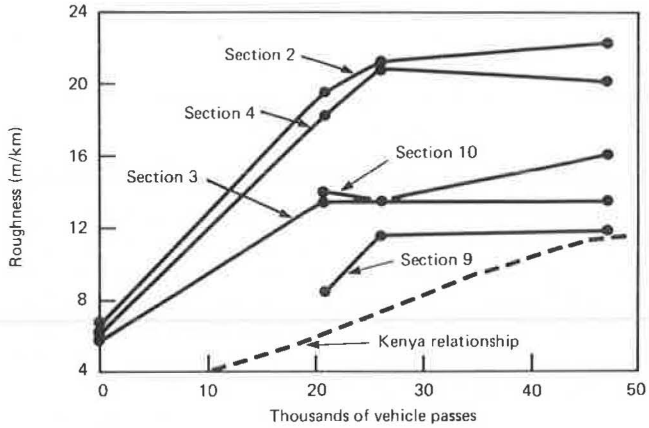

FIGURE 11 Ghion-Jimma roughness progression for Dadale material.

bumpy as the corrugated sections. In general, the range of surface irregularity attained by the Dadale sections was very large when one considers that none of these sections corrugated.

The roughness equation for volcanic gravels in Kenya is plotted in Figures 10 and 11 (*2*). This predictive equation is of the following form:

$$R = 0.0032\,(3442 - 2.519T + 8.111T^2 - 0.09347T^3)^{0.89}$$

where

R = mean roughness in the wheel tracks measured in m/km IRI, and
T = cumulative traffic in both directions since grading, measured in thousands of vehicle passes in both directions (*4*).

Despite the lack of a detailed calibration in this study, the sections built with km 167 material that did not corrugate fit the Kenya relationship tolerably well (Figure 10). None of the test sections monitored in the Kenya study corrugated and it is interesting to compare the form of the lines through the corrugated points with the cubic equation that was used to model the Kenya data. It is likely that the true shape of the relationship for gravels that corrugate will rise to high roughness values very quickly, possibly after the passage of only 5,000 to 10,000 vehicles.

The Dadale gravels gave very high roughness readings (Figure 11). It is clear that as the original surface was abraded by traffic, oversized material was exposed and roughness levels increased rapidly.

Gravel Loss

All the test sections on both experiments were leveled on a regular basis to attempt to establish the loss of surface material over time. This is a well-established procedure that was used successfully in other parts of Ethiopia by the Joint Road Research Project. Unfortunately, it was found that the specially constructed benchmarks on the Ghion-Jimma experiment were moving in relation to one another. Even massive rocks and culvert headwalls, to which the benchmarks were related, were observed to move during the period in which the experiments were conducted. This was thought to be because the subgrade in the area consisted of a deep profile of expansive black clay. It was impossible to use the benchmarks at Gelemso-Mechara to make an estimate of gravel loss because they had been vandalized. At Ghion-Jimma, it was thought that the galvanized pipes that were used to delineate the sections and were driven into the edge of the carriageway may have moved in the same way as the road. An attempt was therefore made to determine the change in road level based on the galvanized pipe levels. The results that were obtained in this way are comparable with gravel loss measurements made in other experiments. It is reasonable to assume that, as the embankment heaved in the rainy season, the relative levels of the galvanized pipes and the surface did not change, although the relative differences between these and other benchmarks may have changed. The actual measurement of gravel loss was determined from the level results using a specially written computer program that determined the drop in level between successive surveys using an end-area method.

Problems with the survey method that was performed after 4 months led to a loss of results for those sections on a curve for this round of measurements. The galvanized pipes on the Hosaina sections were bent by a grader 2 months after the survey, so it was impossible to measure the loss of material on these sections. In addition, results that were collected on certain other sections suggested a significant relative movement of benchmarks that could not be reconciled.

The progression of gravel loss with traffic for those sections in which continuous measurements were possible and for which a reasonable degree of confidence can be placed in the results is shown in Figure 12. These values are also compared with the gravel loss predictive equation that was developed in Kenya (*2*).

$$G_L = 0.96\left[\frac{T^2}{T^2 + 50}\right](4.2 + 0.092T + 3.50R_L^2 + 1.88V_c)$$

where

G_L = annual gravel loss in millimeters,
T = annual traffic volume in both directions measured in thousands of vehicle passes,
R_L = annual rainfall in meters, and
V_c = percentage gradient.

The plotted curve is based on the following values for Ghion-Jimma:

R_L = 1.40 meters, and
V_c = 2.64 percent (mean of sections plotted).

It is clear that the rates of loss on this experiment were generally considerably higher than those experienced in Kenya. The reasons for this included a lack of good mechanical interlock as a result of the material grading and the problem of traffic pushing loose material beyond the edge of the road.

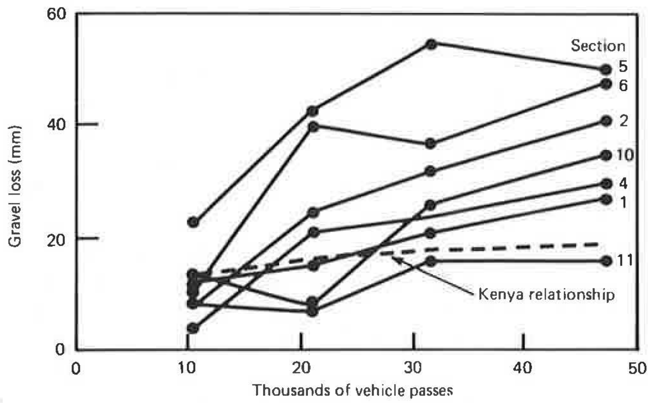

FIGURE 12 Gravel loss for Ghion-Jimma experiment.

The results of the Welkite site (Sections 1 to 6) indicate a high rate of loss on Sections 5 and 6, both of which corrugated badly. A high loss was also indicated on Section 2, which was noticeably rougher than adjacent sections at Welkite. The results at Gibe are particularly difficult to interpret because of problems with measurements on curves and with benchmarks. However, the results suggest that the Dadale material on Sections 9A and 10 exhibited approximately twice the rate of loss as the km 167 material on Section 11. The mean loss of material for all sections after 9 months from reliable sections that were surfaced with Dadale gravel (Sections 2, 4, 9A, 10, 14, and 15) was 37 mm. This figure can be compared with the 27 mm lost from Section 1 and the 16 mm lost from Section 11, both of which were surfaced with km 167 material.

DISCUSSION OF MATERIAL PERFORMANCE

Effect of Aggregate Size on Vehicle Operating Cost

One of the main difficulties in using weathered volcanic gravels is to find material that does not contain large amounts of oversized aggregate. The experiments on the Ghion-Jimma road show that such gravels can be used to make a strong base, but the presence of oversized material creates a very rough surface. An assessment was made, using the data presented in Figures 10 and 11, of the likely increase in vehicle operating costs as a result of the larger aggregate in relation to the cost of improving the grading.

Studies performed in Kenya and elsewhere have produced data that relate vehicle operating costs to road standards (*7-10*). A relationship has been extracted between vehicle operating costs and roughness for typical vehicles on these experiments (Figure 13). It should be remembered when a comparison is made that the values shown for roughness above about 10.0 m/km are not well-established. The measurements of roughness in Ethiopia used a vehicle that had not been calibrated over the whole range of roughness values. However, the results show that the roughness of the test sections using oversized material in Ethiopia were higher than that predicted by the relationship that was based on finer-grained gravels found in other countries. A conservative estimate of the increase appears to be about 4.0 m/km. It can be seen from

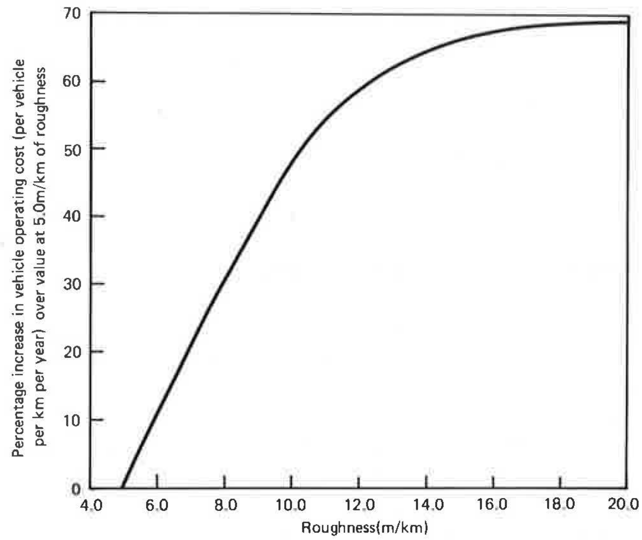

FIGURE 13 Relationship between vehicle operating cost and roughness.

Figure 13 that this causes an increase of about 40 percent in the vehicle operating costs, which, for a road that carries 30 vpd, represents an extra annual cost of about $1,200.

Cost-Effectiveness of Material Processing

Such nonstandard materials can be processed to meet specifications in two main ways: screening or crushing. A variation of the second method is the travelling rock breaker. It is a form of hammer crusher that has been recently tested in many countries. In a recent example from Australia a cost of $2.00/m^3 is quoted to process gravel on a road, which is equivalent to a cost of $2,000/km (*11*). Similar costs have been quoted in Botswana, and they were equivalent to the alternative of using a stationary plant.

Even if the increased costs of operating such equipment in Ethiopia are allowed, a strong case exists for processing material to decrease surface roughness on roads in which traffic levels are greater than about 50 vpd. These costs are based on the vehicle cost savings quoted in this paper.

Recommendations for Gelemso-Mechara Gravels

Of the three sources of weathered basalt material that were used to construct the 10 experimental sites on the Gelemso-Mechara road, two were obtained from borrow pits in dolerite dykes. They provided gravel that met ETCA specifications and performed well on the road. The third type of material was from a basaltic lava flow. This material did not meet ETCA specifications and the rut depths were 50 percent greater than normal. This gravel could be improved either by the addition of 10 percent sand or by crushing. Because the crushed material corrugated, it is recommended that the addition of fines is the most effective way to improve performance. The depth of ruts appears to increase linearly with traffic, but the rate of increase depends on the material type and the gradient of the road. The different subgrades and the difference in layer thickness did not

appear to affect the performance of the gravel. The grid roller did not significantly improve the properties of the gravel. The petrographical studies showed that the basalt rock from km 62 was typical of the basalt that covers about half of Ethiopia. Therefore, the results of the experiment can be applied to other regions with similar climatic characteristics.

Recommendations for Ghion-Jimma Gravels

The worst deformation occurred on Sections 5 and 6, which corrugated badly. The reason for these corrugations is not clear because none of the materials tests indicated what was responsible for them. The corrugations can most likely be related to the fact that the vehicle speeds of these two sections were higher than those of adjacent sections. All gravel surfacings rutted to a certain extent, but the amount and rate of increase was highly variable and could not be related to either the road geometry or the different materials used. When it is considered that the Welkite and Gibe sites were subjected to high traffic loads for a gravel road during the experimentation period, and that they did not receive any maintenance, the materials performed satisfactorily from the point of view of resistance to deformation, with the exception of those that corrugated.

The main problem with the materials was the high values of roughness that were obtained. Using this scale of indices, riding qualities for gravel roads in good condition would normally be expected to have values of between 5.0 and 10.0 m/km. Roads with indices greater than 15.0 would usually be considered too rough. The two sections of km 167 material that corrugated had very high indices and three out of the five sections of Dadale material had indices in excess of 15.0 m/km. The oversized material from the Dadale quarry probably accounted for the high readings on these sections. The road curvature and gradient appeared to have little effect on the performance of the materials. It would be cost-effective to crush or screen materials from both sites to reduce the amount of oversized material for roads that carry more than about 50 vpd.

Performance Modelling

In cases of rutting, roughness, and gravel loss, the results of deterioration with time and traffic were compared with predictive relationships that were developed for volcanic gravels in Kenya (*2*). These relationships were developed to be incorporated into such road investment models as RTIM2 and HDM-III (*12, 13*).

Sections at the Welkite site of the Ghion-Jimma experiment showed good agreement on the development of rutting with traffic when compared with similar studies performed in Kenya. However, there was poor agreement between the Kenyan relationships and results from other sites in which traffic levels and the speed environment were lower.

The scatter on the results obtained in this study makes them unsuitable for the development of performance relationships, specifically weathered basalt gravels. However, work is in progress at TRRL to combine these results with other studies performed in Ethiopia, Kenya, Ghana, and Brazil to provide generalized road deterioration relationships for a range of gravel types and climatic conditions (*1, 2, 14-16*).

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The Gelemso-Mechara experiment was designed by Mr. C. I. Ellis and the materials analysis was performed by Ato Hamza Mohammed Shiek. Petrographic and physical analyses were performed by Mr. M. R. Owen and Miss P. M. Dingwall, who were working as vacation students at TRRL. All members of the Joint Road Research Project were involved in the monitoring of the experiments.

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Theory of the Use of Low-Strength Granulated Materials in the Construction of Low-Volume Roads in the USSR

VALERY A. SEMENOV

An original theoretical model for packing particles that are not uniform in either size or shape is presented in this paper. A solution was obtained for the packing density and contact strength in multi-component mediums, and nomograms were constructed from the theoretical solutions. A method was developed for theoretically determining the density of soils and granulated materials. A practical method for determining the type of roller to be used for packing is also proposed. The use of the theoretical solutions that were obtained has allowed local low-strength materials to be widely used in the construction of local roads in the USSR, which substantially reduces the cost of road construction.

Local low-strength materials and industrial byproducts are used for highway construction in many countries. The strength of these materials averages 30 to 40 MPa. Consequently, they fragment during the packing process, which creates a large number of fine particles (up to 22 percent). The process of particle fragmentation continues over the lifetime of the road, which lowers the usable lifetime of the pavement to 5 to 7 years. Stronger materials, with a strength of 80 to 140 MPa, undergo a similar, but slower, fragmentation process. The particles fragment because of the high contact stresses that arise in the material. The reduction of these stresses during the packing process and under exposure to traffic will allow low-strength materials to be used and their usable lifespan in road coverings to be increased. However, no methods for calculating the contact stresses in complex stochastic media (any real granulated material, such as crushed stone, gravel, sand, and soil) currently exist. The purpose of this paper is to develop a theoretical model and engineering methods for calculating stresses in granulated materials. A stochastic model and theoretical nomograms for calculating the contact stresses have been developed. The proposed model includes the packing of particles of various sizes and shapes. The results presented here are based on 5 years of research performed at the Vladimir Polytechnical Institute in the USSR.

School of Highway and Agricultural Construction, Highway Department of The Polytechnical Institute of Vladimir, Gorky, 87, Vladimir, 600 005, USSR.

THEORETICAL MODEL FOR DETERMINING THE PACKING DENSITY OF A STOCHASTIC MEDIUM

The packing density of a stochastic medium can be determined from geometric considerations by averaging the results of a large number of iterations in regard to random packings that are composed of individual particles. The number of iterations is determined by the required calculation accuracy and ranges from 100 to 300.

The particle sizes in each iteration are selected randomly (using the Monte Carlo method, the Korobov algorithm, or a