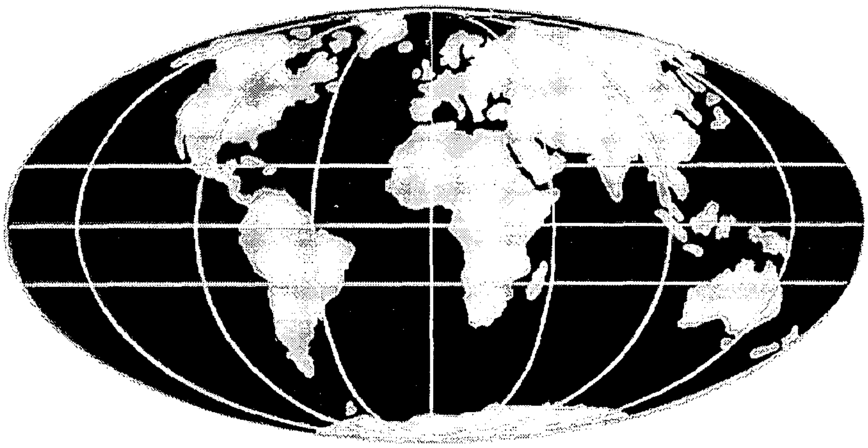
TRANSPORT RESEARCH LABORATORY

DFID Department For International Development

TITLE: Use of 'substandard lateritic' gravels as roadbase materials in southern Africa

by: C S Gourley and P A K Greening



Overseas Centre
Transport Research Laboratory
Crowthorne
Berkshire RG45 6AU
United Kingdom

PA3281/97

PA3281/97 GOURLEY,C S and PA K GREENING (1997). **Use of sub-standard laterite gravels as road base materials in southern Africa.** *International Symposium on Thin Pavements, Surface Treatments and Unbound Roads, University of New Brunswick, Canada, 24 - 25 June 1997.*

FINAL

Use of "sub-standard" lateritic gravels as road base materials in southern Africa

By

C S Gourley and P A K Greening
Transport Research Laboratory
Zimbabwe Office
P O Box CY38 CAUSEWAY
Harare
Zimbabwe

Tel: 263-4-726723
Fax: 263-4-726631
E-Mail: Tony@uz.zw

ABSTRACT

Lateritic gravels are widespread throughout the tropical and sub-tropical regions of the world. True laterites self-harden irreversibly on exposure to air but the vast majority of the lateritic gravels occurring in southern Africa do not possess this capability. They do however seem to perform extremely well as road base materials even though the majority of the deposits fail to meet at least one of the design criteria called for in the specifications. This paper describes two road projects in the region where "sub-standard" lateritic gravels have been successfully used as base materials under thin surfacings. The gravels are generally finely graded and are outside the normally accepted specifications on strength and plasticity. The pavement structures are generally thin and comprise 100mm to 150mm base and sub-base layers. The roads, both of which are over 10 years old, have taken over 0.5 million equivalent standard axles to date and show little, if any, major signs of deformation or deterioration. A pavement thickness design chart is presented for low volume sealed roads where lateritic gravels are used as the base material. Where proper account is taken of the influence of local conditions of climate and traffic, substantial relaxation of the materials design standards can be made with large cost savings being achieved.

1. INTRODUCTION

It is estimated that approximately 70 to 80 per cent of the total length of the road network in sub-Saharan Africa is of gravel or earth standard. Much of the current investment in new road projects is involved with upgrading these secondary and feeder roads to a bituminous standard. One method of improving the return on the investment in these roads is to reduce construction costs by utilising locally available natural gravels in the upper pavement layers rather than the more commonly adopted and expensive option of using crushed rock. The Transport Research Laboratory (TRL) is currently conducting a regional research project in Southern Africa on behalf of the UK Department for International Development (DFID) to investigate the possibility of achieving increased savings by relaxing the design criteria for some natural gravels and to extend their use in the upper pavement layers.

A group of materials where this approach could be adopted are the lateritic gravels which occur extensively throughout the northern reaches of the SADC (Southern Africa Development Community) region of southern Africa. The southern African region does not now provide the ideal conditions for laterisation and thus most of the profiles occur as "fossil" laterites.

Most road building documents, guidelines and specifications used in the region have evolved from experience in the developed world where the characteristics of climate, traffic and the road construction materials have been very different from those experienced in the tropics and sub-tropics. The use of lateritic gravels as base course materials for sealed roads has generally been sporadic in the region mainly because of the variability in their engineering characteristics and their failure to meet these criteria. The lateritic gravels found in the region commonly exhibit gaps in the grading curve (eg. in the sand fraction); high plasticity indices (Ip's greater than 20) and soaked CBR values lower than the minimum of 80 normally specified. Most lateritic gravels are therefore considered sub-standard and are generally precluded from use as base course materials even for low volume roads. Therefore, other more expensive options such as hauling other natural gravels (which meet the specifications) over long distances; stabilising the lateritic gravels with cement and lime (the preferred option in Zambia and Zimbabwe) or using crushed stone for the base (the preferred option in Malawi). All of these options can be prohibitively expensive, particularly in the provision of low volume roads. However, increasing evidence is emerging within the region that some of these "sub-standard" lateritic gravels can be successfully used as road base materials for low to medium traffic levels. By way of example two roads in Malawi are considered which have been monitored over a number of years and have given a better than expected performance.

2. LATERITIC GRAVEL BASES IN MALAWI

Of the 35 trunk routes in Malawi with an estimated total length of 1859km, 26 (with a total length of 1384km) have been constructed using crushed stone in the base. Therefore, nearly 75 per cent of the base construction in Malawi utilises crushed stone and on many of these routes the design traffic was below 1 million equivalent standard axles (ESA's). One notable exception is the Lilongwe-Mchinji road where locally available lateritic gravels were used for the base. Research sections were established on this road and also on a one kilometre trial section with a lateritic base on the Kasungu-Mzimba road. The characteristics of each of the sections was measured, including pavement structure, geometry and engineering properties of the materials used. Permanent access points were established across the road to enable periodic measurement of moisture using a nuclear gauge. Monitoring was carried out at the end of the wet and dry seasons over a 3-year period to determine seasonal moisture and strength (using Dynamic Cone Penetrometer and Falling Weight Deflectometer) variations. Rut depth and roughness measurements were carried out in addition to visual examinations.

2.1 Lilongwe-Mchinji Road

This road comprises a 6.7m surface dressed carriageway and was constructed in 1976 with one metre wide gravel shoulders. The carriageway cross-fall is around 3 per cent with shallow gradients maintained longitudinally through the relatively flat terrain. The road is well drained and the subgrade materials are generally strong (soaked CBR>9) with only localised patches of weaker subgrade materials (soaked CBR <5). The pavement structure comprises 120-180mm of lateritic gravel sub-base and 100-200mm of generally "sub-standard" lateritic gravel in the base course throughout its 129km length. The area receives an annual rainfall of over 900mm and the water table is generally deep. The road received a maintenance reseal in 1991. Two test sections (LI1 and LI2) were established on the road in 1994 and have been monitored until the end of the 1997 rainy season. The road base materials gave 4-day soaked CBR values between 40 and 50, with plasticity indices between 15 and 17. The grading envelopes for the three sections are shown in Figure 1.

2.2 Kasungu-Mzimba road

A 1-km trial section was constructed in 1984-85 on the Kasungu-Mzimba (M12) road. Lateritic gravels were locally abundant and the trial section utilised 150mm of "as-dug" lateritic gravels in the base in place of the crushed stone base which was used on the remainder of the project. The road is well drained and the subgrade is a residual sandy-clay of soaked CBR >15. The sub-base was 100mm of lateritic gravel. The road is 6.5m wide and crosses steep terrain in the humid Viphya highlands in Northern Malawi. The area receives an annual rainfall of over 1300mm and the water table is generally deep.

The original concept of the trial was to construct three sections, each 300m in length, using the following road base materials:-

(i) Unscreened lateritic gravel of soaked CBR 40, KA1
(ii) Screened lateritic gravel of soaked CBR 40, KA2
(iii) Screened lateritic gravel of soaked CBR 30, KA3.

Sections KA1 and KA3 were surfaced with a double surface dressing soon after construction in January 1985, whilst section KA2 was surfaced some eight months after construction (during the dry season) after trafficking and drying back of the materials. The road base materials gave 4-day soaked CBR values between 40 and 50 and plasticity indices between 18 and 20. A control section (KA4) comprising 150mm of crushed stone base for the normal construction was established adjacent to the trial sections.

3. PAVEMENT PERFORMANCE

3.1 Lilongwe-Mchinji Road

Section LI1 is located close to Lilongwe and has carried an estimated 0.84 million equivalent standard axles since construction and at present carries around 900 vehicles per day, of which about 20 per cent are heavy vehicles. Section LI2 is located closer to the Zambian border and has taken about 0.65 million equivalent standard axles. The volume of traffic is lighter at this end of the road which at present carries about 270 vehicles per day, although about 30 per cent are heavy vehicles. A 1991 axle load survey carried out on the road showed that over 35 per cent of these heavy vehicles were over loaded, with one vehicle registering an axle load of nearly 15 tonnes. The performance characteristics of the road are summarised in Table 1. The road has performed extremely well with very little rutting or cracking developed after 21 years in service.

TABLE 1: Performance characteristics and traffic for research sections

SITE	CRACKS (%)	OUTER WHEEL TRACK (OWT)				ESA's since construction	Vehicles per day	% Heavy vehicles
		Ruts 90th %ile	Roughness (IRI m/km)	Do* Dry '95	Do* Wet '96			
LI1	0	8	2.12	570	605	0.84	923	22
LI2	7	6	2.33	530	570	0.65	270	32
KA1	0	10	3.25	815	740	0.50	282	57
KA2	0	12	3.15	610	630	0.50	282	57
KA3	0	10	3.13	715	700	0.50	282	57
KA4	0	6	3.25	330	300	0.50	282	57

* Do is the Falling Weight Deflectometer central deflection in microns

Some stretches of the road showed distress in the base in May 1989. An investigation carried out at that time showed that some significant rutting had occurred (>20mm in OWT). The properties of the base materials were: Soaked CBR at 98 per cent Mod.AASHTO compaction <45, liquid limit >32, plasticity index >17, plasticity modulus >550. Where these localised failures had occurred the sections were rehabilitated. However, it is worth noting that the road at this time had carried over 0.3 million equivalent standard axles. The remainder of the road has remained strong and has performed exceptionally well to date.

The strength of the base materials in the outside wheel track decreased slightly from the dry to the wet season. However, the bulk of pavement width remained relatively insensitive to the seasonal changes in moisture as shown in Figure 2. Where high levels of relative compaction were achieved (>100 per cent Mod.AASHTO) the field/optimum moisture content ratio for the base was generally less than 1. The influence of the moisture ingress can be observed from the plot of the structural number across the pavement shown in Figure 2. The central deflection, measured using a Falling Weight Deflectometer, showed very little variation in the outside wheel track between seasons.

3.2 Kasungu-Mzimba trial sections

Although the trial section on this road is younger than the Lilongwe-Mchinji road and the traffic volumes generally lower, it carries more than double the proportion of heavy traffic and it has taken about 0.5 million equivalent standard axles to date. The road has performed well as shown in Table 1. The 90th percentile rut depths have only recently reached double figures and as yet no cracking has been observed on any of the sections, although the deflections are about double those measured on the control section, KA4. The surfacing is in good condition even though the section has not received a maintenance reseal. The low *in situ* base CBR's (35 to 55) recorded on the outside wheel tracks, and given in Table 2, have not resulted in excessive rutting or shear failure in the base.

No evidence of self cementing was found for the laterite used on the trial sections (Toll 1988), and also there was no measurable increase in density having been achieved on section KA2 as a result of trafficking before sealing when compared to the other sections, all of which showed relatively low levels of compaction in the base. The high *in-situ* CBR values (>150) measured just before and after sealing reduced to levels comparable with those observed on the other sections two years after sealing. Successive monitoring since construction has shown a drop in the *in-situ* CBR's in the outer wheel track from KA1=70, KA2=85, and KA3=105 to around 55, 50 and 60 for the sections respectively.

TABLE 2: Variation in *in-situ* strength and moisture condition between wet and dry seasons (1995-1996)

	OWT Dry season (1995)			OWT Wet season (1996)			Per cent relative compaction	Subgrade CBR	
SITE	Base CBR	SN	Field/ Optimum (base)	Base CBR	SN	Field/ Optimum (base)		Soaked	*In-situ*
LI1	100-105	1.54-1.55	0.57-0.62	75-85	1.51-1.62	0.57-0.60	88-97	14	18-21
LI2	65-90	1.57-1.71	0.76-0.91	60-70	1.53-1.67	0.76-0.98	90-101	24	41-54
KA1	55	1.26-1.29	1.05-1.17	50-55	1.29-1.32	0.86-1.00	88-93	13	25-28
KA2	40-45	1.19	0.98-1.00	45-55	1.24-1.30	0.99-1.00	92-96	13	16-28
KA3	35-50	1.19-1.36	1.01	40-55	1.20-1.42	1.02-1.12	92-96	35	24-33
KA4	150	1.86-1.90	0.93-0.99	150	1.87-1.93	1.01-1.05	92-102	6	44-68

SN is structural number

The *in-situ* moisture condition of the base in the outside wheel track shows very little seasonal variation although there is evidence of a slight decrease in strength of the base at the end of the wet season. However, the bulk of the pavement remains fairly insensitive to the seasonal changes in moisture as shown in Figure 2 and the relatively stable deflections recorded in the outer wheel tracks. The structural number and modified structural number remained high throughout the year. The field/optimum moisture content ratio for the base was approximately unity with only a very slight increase recorded as a result of the wet season. These are slightly higher than those recorded for the Lilongwe-Mchinji road where the climate is drier and the compacted densities better, indicating the importance of attaining adequate levels of field compaction during construction. The field/optimum moisture for the sub-base and subgrade layers were also close to unity. The influence of the moisture ingress can be observed from the plot of the structural number across the pavement as shown in Figure 2.

4. DEVELOPMENT OF STRUCTURAL DESIGN CHARTS UTILISING LATERITIC GRAVEL ROAD BASES

A structural design chart given in Table 3 has been developed to enable better use to be made of the lateritic gravels available in the region. The chart is based primarily on the performance of low to medium volume rural roads constructed with marginal quality materials throughout the southern African region including the lateritic gravel sections in Malawi. The chart presented is specific for lateritic gravel base designs and is applicable to the moderate to wet climatic regime that predominates in Malawi.

In developing the design chart, the performance of each structure was associated with the actual field conditions that were experienced by that structure. Thus the performance of individual roads were associated with the most adverse conditions experienced by that road. In practice, this means the weakest conditions experienced by the subgrade and, by implication, all the other pavement layers.

TABLE 3: Proposed guideline for pavement thickness/design for low volume roads with lateritic gravel bases and unsealed shoulders

	DESIGN TRAFFIC (ESA's)				
Subgrade CBR	<0.01	0.05	0.1	0.3	0.5
3^1-4	B 150 (45) SF 150 (15)	B 120 (65) SB 120 (30) SF 120 (15)	B 150 (65) SB 120 (30) SF 120 (15)	B 150 (80) SB 120 (30) SF 150 (15)	B 175 (80) SB 150 (30) SF 150 (15)
5-7	B 120 (45) SF 150 (15)	B 150 (55) SB 120 (30)	B 150 (65) SB 150 (30)	B 175 (65) SB 175 (30)	B 200 (65) SB 200 (30)
8-14	B 150^2	B 120 (45) SB 120 (30)	B 150 (55) SB 120 (30)	B 175 (65) SB 120 (30)	B 200 (65) SB 120 (30)
15-29	B 150^2	B 200 (45)	B 120 (45) SB 120 (30)	B 120 (55) SB 120 (30)	B 150 (55) SB 120 (30)
30+	B 150^2	B 150 (45)	B 150 (45)	B 150 (55)	B 175 (55)

NOTES: B = base. SB = sub-base. SF = selected fill. 1. Non-expansive subgrade. 2. Gravel wearing course quality. Base CBR's in brackets are soaked and at 100% Mod.AASHTO compaction. Base CBR swell requirements are for CBR 45, 55 and 65-80, not greater than 0.5, 0.3 and 0.2 per cent respectively. Selected fill and sub-base CBR's are soaked and at 95% Mod.AASHTO compaction.

Examination of the data for road sites in wet climates which were poorly drained showed that the most adverse *in-situ* conditions gave *in-situ* CBR values generally no worse than the laboratory soaked values. This was the case for the sections with lateritic base materials in Malawi where the *in-situ* subgrade CBR values were close to the laboratory soaked values. Sufficient other examples were found in the region to confirm the performance of low volume roads at various points in the inference space.

Traditional design principles for the traffic factor rely on two assumptions:

a) the thickness design is sufficient to protect the subgrade from traffic 'fatigue' type failure such that greater traffic means thicker structures.

b) the strength of the base is sufficient to prevent failures of any sort, ie. the base is a zero risk design.

The evidence from the current study indicates that marginal quality (in the traditional sense) base course materials, including the lateritic gravels, have performed satisfactorily for low volume rural roads carrying typical rural road traffic. In general, this will not include vehicles of excessive axle loads, although these were prevalent on the sections studied in Malawi. If for any reason, the functional use of roads at lower traffic levels differs from the basic assumption, eg. roads serving a specific "heavy" but small industry, then either the road base specifications can be tightened or, more simply, the next higher traffic category can be used for design to reduce risks. However, where lateritic gravels are used in the base, such as those available in Malawi, the field evidence has shown that these materials can sustain very heavy axle loads. At lower traffic levels, traffic induced failure is most unlikely, deterioration being controlled mainly by the environment. The thickness designs and material specifications have been devised to mitigate this factor, therefore the increases in thickness as traffic increases have been kept to a minimum commensurate with gradual transitions to the thickness required at the higher traffic levels where road function essentially changes.

There is very little design data available for very weak subgrades and problem soils. As a consequence, it is not advisable to reduce the specifications or design recommendations in the local Ministry guidelines or in Road Note 31 (Transport Research Laboratory 1993).

5. ACCEPTANCE CRITERIA FOR LATERITIC BASE MATERIALS

In tropical and sub-tropical areas the characteristics of the pavement materials, the environment and the type and level of traffic play an important role in determining the performance of road materials. Materials specifications should take these factors into consideration if successful and economically viable roads are to be constructed.

Standard particle size distribution curves are developed to ensure that materials are capable of being compacted to high density and maximum stability. Many lateritic materials in the tropics have high percentages of fines and/or gaps in the grading which without modification would preclude their use as road base materials. Base materials are also required to meet limits on plasticity as a means of controlling the swelling or shrinkage in response to changes in moisture condition. Again, lateritic gravels can show a wide range of plasticity characteristics and are commonly well over the normal limiting value of six for the plasticity index. Previous work (Lawrance and Toole 1984) has shown that there is reasonably good correlation between soaked CBR and the product of the fines (passing the 0.425mm sieve) content and plasticity characteristics of the material, rather than using either the grading or plasticity characteristics on their own. This has also been borne out in the analysis carried out for the natural gravel sections on the current research project. The guidelines for selection and use of lateritic gravels for bases presented in Table 4 uses this product as a controlling factor in base material selection, which can be increased if the road shoulders are to be sealed.

The materials design given in Table 4 is applicable for design traffic levels up to 0.5 million ESA's and follows the format of the pavement design chart in Table 3. The upper limits on material properties have been assigned based on traffic level and the supporting subgrade design class. Within the subgrade and traffic ranges suitable for the low volume pavement designs (ie. excluding problem soils and higher traffic levels), the road base properties have been set at values that are more conservative than the examples quoted earlier in the paper.

TABLE 4: Proposed guideline for selection of lateritic gravel base materials for low volume roads with unsealed shoulders

		DESIGN TRAFFIC (ESA's)				
Subgrade CBR		≯0.01	0.05	0.1	0.3	0.5
3[1], 4[1]	Ip PM GE	≯15 ≯400 B	≯15 ≯250 B	≯12 ≯150 B	≯9 ≯150 A	≯9 ≯120 A
5-7	Ip PM GE	≯18 ≯550 B	≯15 ≯320 B	≯15 ≯250 B	≯12 ≯180 B	≤9 ≯120 A
8-14	Ip PM GE	≯20[2] ≯800 GM 1.6-2.6	≯18 ≯450 B	≯15 ≯320 B	≯15 ≯300 B	≤9 ≯200 B
15-29	Ip PM GE	≯20[2] NS GM 1.6-2.6	≯18 ≯550 B	≯18 ≯400 B	≯15 ≯350 B	≯12 ≯250 B
30+	Ip PM GE	≯20[2] NS GM 1.6-2.6	≯18 ≯650 B	≯18 ≯550 B	≯18 ≯400 B	≯15 ≯300 B

NOTES: 1. Non-expansive subgrade. 2. Ip maximum = 8 x GM Ip = plasticity index PM = plasticity modulus
GE = grading envelope GM = grading modulus NS = not specified

This is because there are insufficient samples for each combination of subgrade and traffic for percentile values to be defined, hence no risks have been taken and all the road base materials from the road networks studied are weaker than those specified in Table 4. This may be further relaxed when additional performance data becomes available. The principles of the materials design table are:-

(i) The strength, plasticity and grading requirement varies depending on the traffic level and climate.

(ii) The soaked CBR test has been used to specify the minimum base material strength. The compaction requirement for the test is 100 per cent Mod.AASHTO (or B.S. 4.5kg rammer heavy compaction). This is a relaxation of the normal soaked CBR requirement for natural gravel base materials where the CBR requirement is at 98 per cent Mod.AASHTO compaction. The soaking time is minimum 4 days or until zero swell is recorded.

(iii) Two grading envelopes (A and B) are used which depend on the traffic and subgrade design class. Envelope A (Table 5) varies depending on the nominal maximum particle size (37.5, 20 and 10mm). Envelope B has a nominal maximum particle size of 37.5mm. To prevent excessive loss in stability a requirement of 5 per cent retained on successive sieves is recommended. For very low traffic levels (<0.01 million ESA's) the only grading requirement is that the grading modulus of the material must lie between 1.5 and 2.5.

(iv) The maximum plasticity index of the base also depends on the traffic and subgrade design class. A maximum Ip of 9 has been specified for higher traffic levels and weak subgrades. For design traffic levels ≥0.3 million ESA's a requirement of ≯30 is set for the liquid limit. This requirement is relaxed to ≯35 for the remaining traffic design classes. Where sealed shoulders over 1m wide are specified in the design the requirement on the maximum plasticity modulus may be increased by 40 per cent, although there is no change to the upper limit on the plasticity index given in Table 4.

TABLE 5: Recommended particle size distributions for lateritic gravel road bases

Test sieve size (mm)	Per cent by mass of total aggregate passing test sieve			
	Nominal maximum particle size			
	37.5mm	20mm	10mm	37.5mm
	GRADING ENVELOPE 'A'			GRADING ENVELOPE 'B'
50	100	--	--	100
37.5	80-100	100	--	80-100
20	55-95	80-100	100	55-100
10	40-80	55-85	60-100	40-100
5	30-65	40-70	45-80	30-80
2.36	20-50	30-55	35-75	20-70
0.425	8-30	12-30	12-45	8-45
0.075	5-20	5-20	5-20	5-20

The requirement for sub-base and selected fill materials should follow those currently recommended in the design manuals or guidance documents such as Road Note 31 (Transport Research Laboratory 1993).

6. CONSTRUCTION REQUIREMENTS

The investigation of the natural gravel bases in the region has shown the importance of good cross-section design in achieving better than expected performance from the pavement and in particular the base layer. Where base materials were used which would normally be considered "sub-standard", including the lateritic materials discussed in this paper, and a good cross section design and deep side drains were used, a satisfactory performance was achieved. A minimum crown height of 0.75 metres was found to be adequate to stabilise the moisture conditions in the upper pavement layers. The base materials should be uniformly compacted to at least the 98 per cent Mod.AASHTO compaction specification in the field to minimise the seasonal moisture movements in the layer. Timely re-sealing is also important to ensure a waterproof seal is maintained over the base and underlying layers. Further guidance on the construction techniques applicable to the construction of lateritic bases can be found in the CIRIA report on laterite in road pavements (CIRIA 1988).

7. CONCLUSIONS

Deposits of lateritic gravels are abundant in the northernmost countries of southern Africa. Although they are widely used as gravel wearing courses on unpaved roads their use as road base materials on paved roads has been limited because they generally fail to meet the strength, plasticity and grading required for materials used at this level in the pavement structure. However, examples of two roads in Malawi have been described where "sub-standard" lateritic gravels have been successfully used as road base in bituminous pavements. Although the climate in these areas is wetter than that generally experienced in the rest of the southern African region and the levels of traffic in terms of axle loading have been high these road base materials used have given a much better performance than would normally have been expected.

A structural design table has been developed for low volume roads utilising lateritic gravel base materials. The design chart is applicable to the more humid areas of southern Africa (mean annual rainfall of 750-1500mm) where deposits of lateritic gravels occur. Encompassed with the structural design chart are guidelines for the selection of lateritic road base materials. These allow a significant relaxation in the properties required of the road base materials if lateritic materials are used.

Over the 52km length of the Kasungu-Mzimba road section the cost of the crushed stone base was about 15 per cent of the total project cost. The differential between the cost of 1km of crushed stone base and the 1km lateritic gravel base trial section on this road (where both materials were locally available) was about 4:1. Substantial savings on the cost of construction of low volume roads can be achieved if these locally abundant lateritic gravels can be utilised for the base construction. Had crushed stone base been used on the Lilongwe-Mchinji road the differential cost between this and the lateritic gravel base would have been higher than the 4:1 quoted above because there are not readily available sources for crushed rock.

8. REFERENCES

CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION (1988). Laterite in road pavements. CIRIA special publication 47.

LAWRANCE, C.J AND TOOLE, T (1984). The location, selection and use of calcrete for bituminous road construction in Botswana. Report No. LR1112. Transport Research Laboratory. Crowthorne. Berkshire. U.K.

TOLL, D.G (1988). The behaviour of unsaturated naturally occurring gravel. Ph.D. Thesis. Imperial College of Science and Technology, London, U.K.

TRANSPORT RESEARCH LABORATORY (1993). Overseas Road Note 31. A guide to the structural design of bitumen-surfaced roads in tropical and sub-tropical countries. Transport Research Laboratory. Crowthorne. Berkshire. U.K.

9. ACKNOWLEDGEMENTS

The work discussed in this paper has been carried out as part of a collaborative research programme with the Ministry of Works in Malawi. The support of the Director of Roads and the staff of the Roads Department, without whom this work would not have been possible, is gratefully acknowledged.

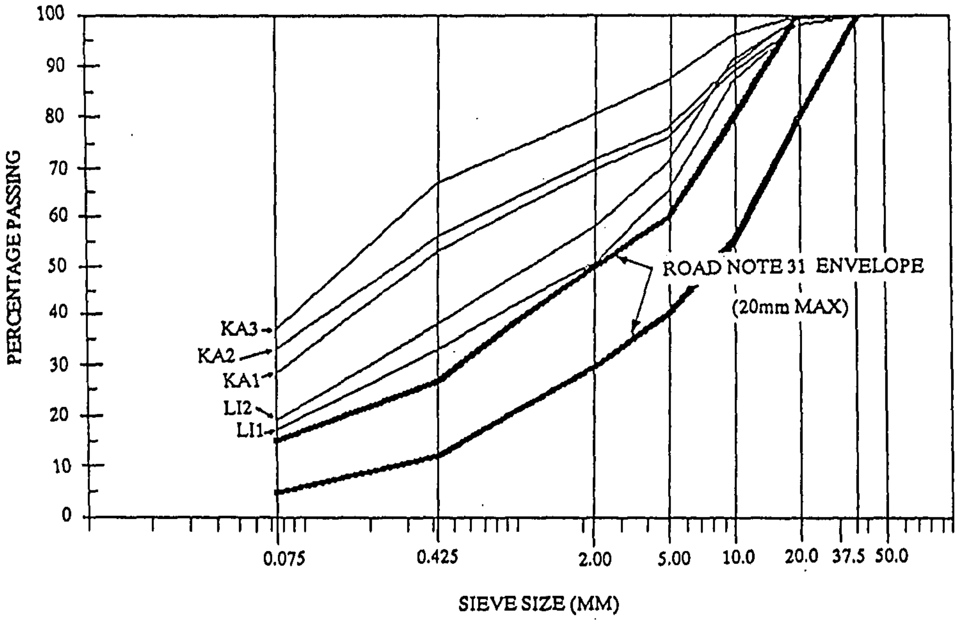


Fig 1. Particle size distributions of Malawi lateritic gravel road bases

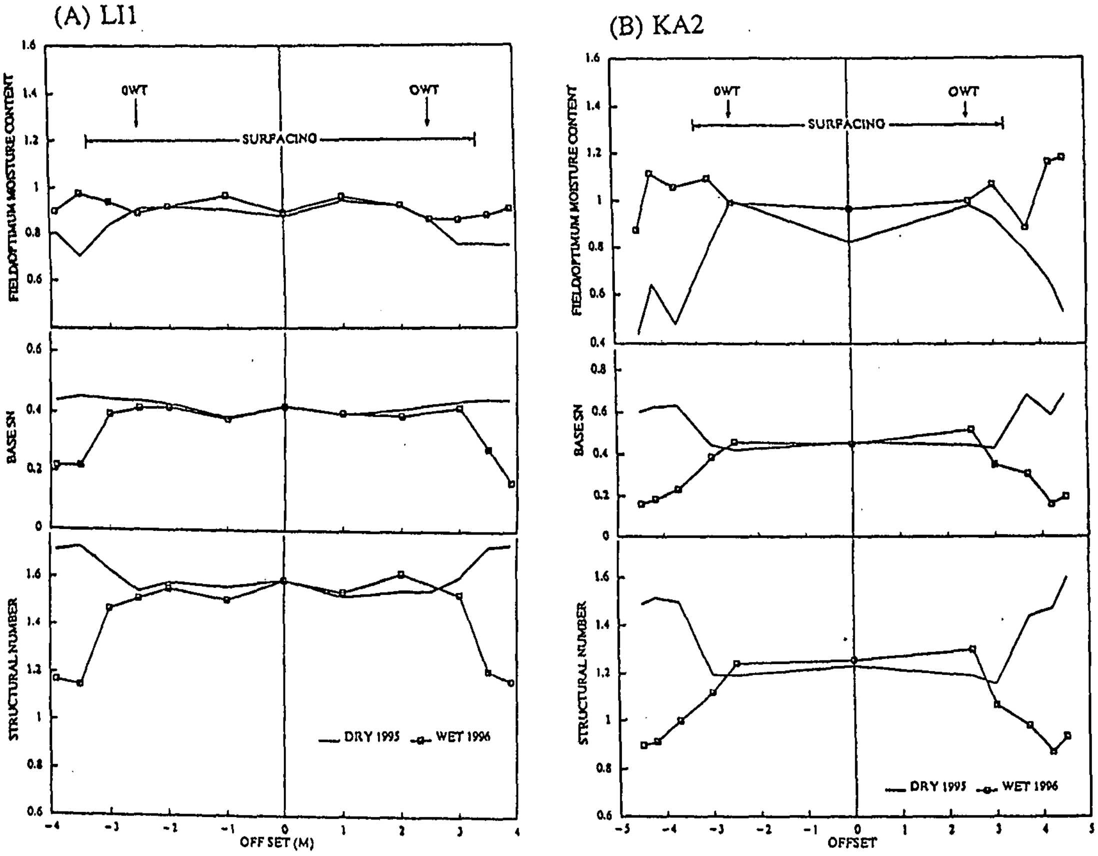


Fig 2. Field/optimum moisture, base structural number and pavement structural numbers for sections LI1(A) and KA2(B) measured at the end of the dry season (1995) and wet season (1996)

(OWT is outside wheel track and base SN is the base only component of the structural number).