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DEPARTMENT OF TRANSPORT

Recommendations on the use of marginal base course materials in low volume roads in South Africa

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SINOPSIS:

'n Ondersoek is uitgevoer na die werkverrigting van 57 gedeeltes pad in Suid Afrika wat deur die Provinsiale Padowerhede geïdentifiseer is as gebou met marginale kwaliteit kroonlaag materiale. Die ondersoek het getoon dat waardevolle padbou materiale bespaar is asook 'n vermindering in die onderhoudskoste van voorheen ongeplaveide paaie. Verder is ook 'n betekenisvolle beter vlak van diens behaal met die gepaardgaande vermindering in padgebruikerskoste. Alhoewel die paaie onderbroke onderhoud nodig gehad het gedurende hul lewensduur, is daar duidelik getoon dat die huidige materiaal standaarde te konserwatief is vir bekostigbare lae volume paaie. Die studie het getoon dat dreinering en die kwaliteit van konstruksie die primêre voorvereistes is vir suksesvolle lae volume paaie. 'n Verslapping in die sterkte vereistes vir hierdie tipe paaie word voorgestel.

SYNOPSIS:

An investigation into the performance of 57 sections of road in South Africa identified by the Provincial Road Authorities as being constructed using marginal quality base course materials has been carried out. The investigation has shown that, apart from conserving precious construction materials and reducing the maintenance requirements of the previously unpaved roads, a significantly better level of service was achieved with a concomitant reduction in road user costs. Although the roads have required intermittent maintenance during their lives, they have clearly shown that current material standards may be too conservative for affordable low volume roads. The study has shown that good drainage and construction quality are the primary requisites for successful low volume roads. A relaxation of the strength requirements for these roads is proposed.

KEYWORDS Low volume roads, materials, marginal materials, specifications
TREFWOORDE Lae volume paaie, materiale, marginale materiale, spesifikasies

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DISCLAIMER

The views and opinions expressed in this report are those of the author and do not represent -Department of Transport Policy.

The Department of Transport does not accept liability for the consequences of application of the findings expressed in this report.

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LIST OF CONTENTS

Page

1. Introduction 1.1

2. Background 2-1
2.1 Existing Information 2-1
2.2 Experimental Design 2-2
2.3 Material Types 2-3
2.4 Climate 2-4
2.5 Traffic 2-8
2.6 Sampling Matrix 2-10

3. Investigation 3.1
3.1 Field Evaluation 3.1
3.2 Laboratory Investigation 3.2
3.3 Performance Classification 3.3

4. Discussion of Findings 4-1
4.1 Base 4-1
4.2 Surfacing 4-6
4.3 Lower Layers 4-7
4.4 Drainage 4-10
4.5 Construction 4-11
4.6 Performance 4-12
4.7 Structural Characteristics 4-13
4.8 Relevance of Traditional Concepts 4-14
4.9 Risk 4-15
4.10 Variability 4-15
4.11 Maintenance 4-16
4.12 Time Effects 4-16

5. Recommended Material Requirements for Bases 5-1

6. Recommendations 6-1

7. Conclusions 7-1

8. References 8-1

Appendix A: Summary of Locations of Sites Investigated A-1

Appendix B: Selected Summary Statistics of Base Course Data Collected B-1

Appendix C: Correlation of Various Base Properties with Performance (All Sites) C-1

Appendix D: Correlation of Various Base Properties with Performance (Only Wheel Tracks) D-1

Appendix E: Correlation of Various Base Properties with Performance (Outer Wheel Track Only) E-1

LIST OF TABLES

Page
Table 4.1: Average densities of base by province 4-2
Table 4.2: Increase in moisture content during soaking for CBR test 4-5
Table 4.3: Summary of condition of some roads at beginning and end of project 4-17
Table 5.1: Poor correlation between grading parameters and performance 5-3

LIST OF FIGURES

Page

Figure 2.1: Map of Weinert'S N-values 2-5
Figure 2.2: Climatic Regions according to Köppens classification 2-6
Figure 2.3: Thornthwaite's climatic classification 2.7
Figure 2.4: Experimental design matrix 2-11
Figure 4.1: Subgrade moisture content versus optimum moisture content 4-9
Figure 4.2: Predicted versus actual field moisture content (Model 15 in Ref 30) 4-9
Figure 5.1 Performance versus percentage passing 37.5 mm sieve 5-4
Figure 5.2. Performance versus percentage passing 0.425 mm sieve 5-4
Figure 5.3 Performance versus percentage passing 0.075 mm sieve 5-5
Figure 5.4 Performance versus grading modulus 5-5
Figure 5.5 Performance versus grading coefficient 5-6
Figure 5.6 Performance versus plasticity index 5-7
Figure 5.7 Performance versus bar linear shrinkage 5-7
Figure 5.8 Performance versus Mod AASHTO soaked CBR 5-9
Figure 5.9 Performance versus Proctor soaked CBR 5-9
Figure 5.10 Performance versus CBR at OMC 5-10
Figure 5.11 Performance versus in-situ CBR (from DCP) 5-10
Figure 5.12 Performance versus Fineness Product 5-11
Figure 5.13 Performance versus Durability Mill Index 5-11
Figure 5.14 Performance versus CBR for roads with good to average drainage 5-13
Figure 5.15 Performance versus in situ CBR for roads with good to average drainage 5-13
Figure 5.16 Material group versus performance for roads with good to average drainage 5-14
Figure 5.17 Performance versus in situ CBR for acid crystalline materials 5-14
Figure 5.18 Performance versus Mod AASHTO CBR for acid crystalline materials . . 5-15
Figure 5.19 Performance versus in situ CBR for pedocretes 5-15
Figure 5.20 Performance versus Mod AASHTO CBR for pedocretes 5-16

EXECUTIVE SUMMARY

1. INTRODUCTION

South Africa has an enormous unpaved road network, many of these roads which could justify upgrading to a paved standard on both economic or social grounds but be classified as lightly trafficked or low volume roads.

The provision of suitable base course materials complying with recognised standards for paved roads is becoming increasingly expensive. It has been shown that, depending on the region, topography and road structure it is often cost-effective to upgrade unpaved roads to a bituminous surfaced standard at a traffic count as low as 50 vehicles per day. It is clear, however, that the minimum design criteria in the current standards for roads carrying less than 200 000 E80's per lane over their design life is far too high for a road designed to carry 20 000 or 50 000 E80's in both directions over 20 years.

The current project was initiated in order to investigate as many of these roads as possible and make use of their performance records to:

i) determine under which conditions marginal quality materials can perform adequately;
ii) derive specifications for the use of marginal materials; and
iii) identify any construction or maintenance procedures necessary to ensure satisfactory performance of these materials.

This report discusses the findings of the investigation of 57 sections of road identified by the relevant road agencies as being constructed with non-traditional natural gravel or marginal quality bases.

2. BACKGROUND

2.1 EXISTING INFORMATION

Despite numerous roads having been built in southern Africa since the mid 1960's using relaxed material specifications or structures, very little work has been done to actually relate the properties of the layers in the roads to the performance of the pavements. A number of references are reviewed but it is concluded that unless the specifications are performance-related, there seems to be some reticence concerning their use.

2.2 EXPERIMENTAL DESIGN

A factorial experimental design including Weinert's material classification group and N-values as the factors was used. The age of the roads was taken into account directly by combining the years of service with the annual equivalent standard axle count. A greater number of roads constructed with basic igneous rocks and pedocretes were investigated. The levels used for the various factors are discussed in the following sections.

2.3 MATERIAL TYPES

The roads investigated during this project include materials from six of Weinert's nine material classification groups. The objective of the project was to include as many of these groups as possible with a range of climatic and traffic conditions within each group.

During the early stages of the project it was envisaged that only untreated natural gravels would be investigated. However, with the progress of the project this was reconsidered and lightly stabilised materials were also included. Many of the roads incorporate stabilisation (often only modification) in order to avoid hauling other material over considerable distances. A number of the base materials in Natal had been treated with ionic soil stabilisers (sulphonated petroleum products) but these roads were analysed as if they had been untreated. The SPP does not cause any cementation and so does not affect the test results.

2.4 CLIMATE

Three levels for the climate were used in the design, Weinert-N values less than 2 (wet areas with a water surplus), N between 2 and 4 and N greater than 4 (drier areas). An N-value greater than 5 is usually taken as the boundary between dry and moderate areas but only a few roads could be located in areas with N greater than 5. The bulk of the roads investigated fell into the areas where N is less than 2 as these are the wetter areas where moisture problems are common. The range of Weinert's N-values in which the roads investigated are located is between 1,0 and 8.

The average annual rainfall in the areas studied varied between 265 and 1224 mm and thus a wide climatic range was included in the study.

2.5 TRAFFIC

Traffic counts were obtained from records of the respective Road Authorities or Regional Services Councils. Concern was expressed about the accuracy of some of these and revised estimates were obtained after consultation with officers within the specific regions. Most of the counts are based on manual methods although automatic counts carried out over longer periods were available for certain roads. The majority of the counts were in terms of average daily traffic (ADT) and percentage heavies, although some were obtained as equivalent vehicle units (evu) and percentage heavies. It was interesting to note how little is known about the traffic characteristics of these lightly trafficked roads.

The estimated cumulative equivalent E80 axles per lane for each road was calculated from the traffic counts, percentage heavy, average number of axles per vehicle, axle load factors, age of the roads and estimated traffic growth rates where applicable. Modifications to the equivalency factor based on recent research were made.

2.6 SAMPLING MATRIX

A factorial experimental design matrix was developed. The discussion, recommendations and conclusions in the report are based on the evaluation of the structure, materials and performance of fifty seven "lightly trafficked roads" ostensibly containing marginal base course materials" from across South Africa.

3. INVESTIGATION

The investigation procedure involved the location of sites on each identified road, at which both distressed areas (usually in the outer wheel track) and sound areas occurred in close proximity. Usually the failed area occurred in the outer wheel track (OWT) and the sound area could be located in the adjacent inner wheel track (IWT) which facilitated direct comparison of the performance of good and bad structures with minimal material variation between the sites.

The lane showing the most distress was sampled in all cases as this was considered to be representative of the heavier traffic.

3.1 FIELD EVALUATION

In the field the condition of each road in the vicinity of the site was described and the riding quality of each section of road was also measured with a Linear Displacement Integrator (LDI). The performance of the road was rated in the field on a five-point scale. The drainage was rated on a three-point scale.

In situ testing at each site consisted of DCP tests and the determination of the in situ density and moisture content of each layer of the pavement. Gravimetric moisture contents were used to calculate the dry density from the nuclear wet density.

Representative bulk samples of the base, subbase, selected layers and subgrade were collected from each site.

The pavement profile, layer thicknesses and materials in each test hole were fully described.

3.2 LABORATORY INVESTIGATION

All of the samples collected were returned to the laboratory, individual bags thoroughly mixed and the material quartered and prepared for both routine and non-routine, specialised testing.

It was clear from the results that very wide ranges were measured in all of the tests. This indicates that the findings of this research are applicable over a wide range of materials.

3.3 PERFORMANCE CLASSIFICATION

Although the performance of each section of road investigated was rated in the field, problems were encountered when using this rating in the analyses. It was eventually concluded that traditional classification of distress results in a totally inappropriate rating for low volume roads. It is suggested that the performance of low volume roads is best classified on the basis of the cost of maintenance which is necessary to ensure that the structural integrity of the road is retained.

4. DISCUSSION OF FINDINGS

The findings of the investigation are discussed in this section. These are based on the examination of 57 roads with a wide range of material types, traffic conditions and climatic characteristics.

4.1 BASE

The bases investigated during the project consisted mostly of natural gravels, although some crushed stone was used in the Cape Province and a number of treated gravels were used in the Transvaal (10 sections) and some sections were treated with ionic soil stabilisers in Natal. The treated sections in the Transvaal all had between 2 and 3 per cent of added stabiliser (lime, cement, lime-slag and "wallcrete" were used) and can thus be classified as being mostly "modified" as opposed to "cemented" in most cases.

The investigation has shown that the achievement of high densities during construction is critical to ensure satisfactory performance. Low densities lead to rutting, and theoretically have a higher capacity for water ingress and retention, more interparticle abrasion and degradation and generally a greater propensity for the pavement to deteriorate. The highest density economically and practically achievable should be strived for and perhaps some form of compaction aid should be employed to assist the compaction process. It is shown that the maximum densities achievable in all the provinces are up to between 104 and 106 per cent of Mod AASHTO density.

The average moisture regimes of all the roads investigated irrespective of the climatic region in which they occurred, were considerably wetter than predicted by the existing models. The investigation showed that the average rating for drainage of all the roads is between fair and poor and this could indicate why the in situ moisture contents are higher than predicted.

Materials with a wide range of properties were investigated during the project. The majority of the test results are outside the traditionally accepted limits.

The conclusion from the results obtained is that materials not complying with the traditional requirements in terms of these parameters should not be rejected for use in lightly trafficked roads without careful consideration.

Testing of the durability of the materials indicated that very few of the materials investigated complied with the currently recommended requirements of the Durability Mill test and Fineness Product. However, equally few of the problems noted in the field could be directly attributed to degradation of the material in service indicating that durability problems are, in general, unlikely to affect lightly trafficked roads.

4.2 SURFACING

Although the project objectives do not include an investigation of the life and effectiveness of the different types of seals, they are obviously closely associated with the overall performance of pavements constructed with marginal materials. Roads consisting of almost every type of surfacing commonly used in South Africa were investigated. A number of important interrelationships between the surfacing and base (and pavement structure as a whole) arise from the use of marginal materials in the base and are discussed.

4.3 LOWER LAYERS

The pavement layers beneath the base both affect and are affected by the base. It is these layers which provide a platform on which the base is compacted (ie a reaction to the compaction effort). After construction the base protects the lower layers from being overstressed.

Forty seven per cent of the roads investigated during the project had no subbase or selected layers whilst 14 per cent had both subbase and at least one selected layer (often remnants of previous gravel wearing course layers). It is notable that the average performance of the roads constructed directly on the subgrade was no worse than those with a subbase. Sixty two per cent of both types of road had performance rated as two or better. Four per cent of the roads without a subbase and six per cent of those with a subbase were classified as poor. It would thus appear that for lightly trafficked roads, the South African subgrade conditions often make the importation of layers other than the base redundant. Seven hundred millimetres of imported gravel was measured on one road which had an average in situ subgrade CBR in excess of 20.

An analysis of the subgrade conditions of the roads investigated showed that the average soaked CBR strength at Modified AASHTO compaction was 50 per cent. At Proctor compaction, the average was 21. The average unsoaked CBR at Mod AASHTO density was 79. It is clear that ripping and compaction of the in situ materials (preferably in more than one layer) will, in many cases, obviate the need for the importation of other material.

One imported layer on the compacted subgrade would thus appear to suffice for most pavements for lightly trafficked roads. The practice of importing layers of various strengths onto strong subgrades often results in poor pavement balance.

In order to evaluate the requirements of layers beneath the base course, a number of detailed mechanistic analyses of the pavement structures were carried out. It was concluded that the mechanistic analyses, in their current forms, are generally inappropriate for low volume roads. The E moduli and c and ϕ values recommended for low quality materials all appear to be significantly under-estimated. The linear analysis also fails to approximate the actual behaviour of the pavement in many cases, with the biggest problem being thick base courses and strong subgrade layers.

4.4 DRAINAGE

A critical aspect of the use of marginal materials in lightly trafficked roads is the influence of moisture on the materials. The importance of investigating the moisture/strength relationships has already been emphasised in this report. However, even the highest quality materials, when saturated, will produce high pore water pressures under load and thus often have unacceptable shear strengths at critical times.

The rating of the effectiveness of the drainage at each site indicated that the majority of the areas investigated were averagely to poorly drained. The very important aspect of regular and adequate maintenance of the drainage structures which were installed was often overlooked which exacerbated the condition.

It is recommended that roads using marginal materials are raised above the natural ground level where possible or have side drains cut so that the bottom of the base course is at least 0,75 m above the potential standing water level in order to facilitate the retention of low moisture contents in the critical pavement layers.

4.5 CONSTRUCTION

As discussed under the base materials, the achievement of high densities is critical to ensure good performance. The highest density economically and practically achievable should be strived for in the upper subgrade and all other pavement layers. At the appropriate moisture content, this density should generally be achievable without excessive compaction effort.

4.6 PERFORMANCE

The investigation has clearly shown that significantly thinner pavement structures using materials which would not normally be considered as base course quality can perform successfully under lightly trafficked conditions in South Africa. The problems of rating the performance of lightly trafficked pavements have been discussed previously. Despite these, the adjusted five point field rating was used and resulted in most of the roads being classified as having a satisfactory to good performance.

4.7 STRUCTURAL CHARACTERISTICS

Nearly all of the roads investigated so far are structurally sound. The superposition of adequacy curves (for a future 10 000 E80's, significantly more than the design traffic of most of the roads) on the redefined layer strength diagrams indicates that in every case the shear strengths of the pavement layers are adequate and no structural problems with the pavement should be expected provided that the roads do not wet up significantly. All but about 9 of the roads were structurally capable of carrying over 50 000 E80's and many could even carry over 500 000 E80's in their present moisture conditions.

4.8 RELEVANCE OF TRADITIONAL CONCEPTS

The traditional concepts of failure criteria and residual life require some modification or a different form of interpretation for lightly trafficked roads. The standard criteria for identifying trigger conditions are probably over-conservative for very lightly trafficked paved roads where the alternative to be considered would generally be an unsealed road.

The concept of remaining life is also considered to be inappropriate for lightly trafficked roads consisting of natural gravels. Unless water is allowed to accumulate in the pavement structure, most natural gravels increase in strength (stiffen) with time as they densify and remould with rutting being produced at the surface. This can usually be rectified during maintenance activities.

4.9 RISK

There is no doubt that the risk of premature distress or failure through unexpected environmental conditions will be increased if marginal materials are used. This risk can, however, be managed by Road Authorities by ensuring that the construction quality is well controlled and drainage measures are implemented and maintained.

An important aspect of increased risk is the public awareness. The public need to be informed of the economic benefits which can be achieved through the use of thin pavement structures but at the same time, the increased risk needs to be explained. As well as the public acceptance of this increased risk, political acceptance needs to be obtained.

4.10 MAINTENANCE

The importance of adequate, appropriate and timeous maintenance is emphasised throughout the document. The maintenance must also be carried out to a high standard.

Preventative maintenance in terms of timely resealing is also very necessary to ensure that the pavement does not reach a stage where routine maintenance becomes excessive.

4.11 TIME EFFECTS

The sites which were investigated early in the project were revisited during the final stages of the project and the condition compared with the original one to see whether deterioration had occurred. It is clear that some of the roads have hardly deteriorated whilst others have developed significant ruts and the cracking has become more serious.

5. RECOMMENDED MATERIAL REQUIREMENTS FOR BASES

One of the primary objectives of this project was to develop material specifications which would allow the use of lower quality materials than typically specified in bases for lightly trafficked roads with an appropriate degree of confidence. It is considered that this class of road will become increasingly important in future. In order to conserve good quality construction materials which are becoming scarcer and more costly, to minimise road user costs and provide a standard of road which meets the aspirations of the future commuter and township resident, lightly trafficked paved roads will be necessary and appropriate specifications for their materials and structural design are urgently required.

The test results obtained were evaluated with the purpose of fulfilling these needs. A number of multiple correlation analyses were carried out in order to establish which of the individual factors in the data base affected the performance of the pavements in a statistically significant way.

The only parameters with any correlation with performance are the field to optimum moisture content ratio, drainage, traffic, in situ wet density, Weinert N-value, relative compaction and gravimetric moisture. It is notable that five of the parameters which correlated well were related directly to the moisture content. None of the standard indicator tests has any correlation with performance. The grading coefficient was significant at a level of 10 per cent and the bar linear shrinkage at 15 per cent. All other parameters were worse than this. Correlations using combinations of selected parameters with drainage and moisture also produced no significant results.

The fact that the performance of the roads depends primarily on the moisture-related parameters is indicative of the influence of drainage on roads in the longer term. This also indicates that the moisture parameters determined during a one-off investigation of road problems are probably not always indicative of the worst possible conditions.

Following various analyses, it was clear that the performance of marginal quality materials in lightly trafficked roads depends to a far greater extent on the drainage and seasonal moisture variations than on the quality of the material.

6. RECOMMENDATIONS

A number of recommendations are made. The most important of these are that the design of lightly trafficked roads using marginal materials in the base course needs to follow a holistic approach with attention being paid to compatibility between the pavement structure, the materials used, the type of surfacing, construction processes and control and the associated drainage.

Many of the traditional specifications and philosophies applicable to roads appear to be invalid when marginal materials are used in thin pavement structures.

Problems with the evaluation of traffic and performance for low volume roads have been found and recommendations regarding their solution are made.

Moisture contents measured in the field were mostly considerably higher than those predicted by the currently available models which were developed on traditional provincial roads. Methods of correcting these models for light pavement structures with marginal materials need to be developed.

The use of flexible, durable surfacings is recommended in order to accommodate high deflections, provide a good adhesion to potentially soft bases and large stones and to retard the ageing process.

Despite a large data base it has not been possible to isolate any particular test or material parameter which will predict the performance of paved roads. It is thus recommended that provided the drainage is carefully designed and controlled, the pavement is raised above the potential standing water level (at least 0,75 m below the bottom of the base course), all the pavement layers are compacted to as high a density as possible (between 98 and 106 per cent Mod AASHTO) and the pavement is adequately maintained, an in situ CBR of 60 will be adequate for most low volume road pavements. This would be for traffic up to 100 000 E80's.

7 CONCLUSIONS

Many roads specifically designed for light traffic volumes have been constructed in South Africa using marginal materials and reduced pavement structures. Most of these have provided an adequate level of service for the specific situation with a number of additional advantages. These include conserving gravel wearing course materials, reducing maintenance costs compared with the unpaved alternative, reducing vehicle operating costs and providing a sound structure for future upgrading of the road.

In order to optimise the use of marginal materials a holistic approach to pavement design, material selection, construction and maintenance is necessary. This will allow thin pavement structures to be constructed using materials with properties outside the traditional specifications.

An analysis of data collected from 57 different sections of lightly trafficked roads constructed with marginal base course materials in South Africa has shown that the properties of the materials used in the roads have little influence on the performance of the pavement structures in comparison with the effects of inadequate drainage. The prevalence of excessive moisture within the pavement structures results in problems almost irrespective of the quality of the materials within the pavements.

In terms of the specification of material properties for lightly trafficked roads, extensive analysis of the large data base compiled has shown that no material property will predict the performance of the road, without taking into account the drainage. In situ CBR values of less than 30 have performed well whilst other roads with in situ CBR values in excess of 400 have performed poorly. Provided the pavement is well drained, well constructed (particularly with regard to compaction) and properly maintained, an in situ CBR value of 60 will prove adequate for roads carrying up to at least 100 000 E80's.

The primary requirements of satisfactory low volume roads are that the pavement is well drained, the construction quality is very tightly controlled, high compaction standards are achieved in all layers and the road is timeously and effectively maintained.

A conclusion which can be drawn from this project is that significantly more material degradation can occur in lightly trafficked roads than is permissible in standard designs without undue deterioration of the road occurring. No durability requirements are necessary for lightly trafficked roads. However, should the traffic increase or the life of the road be extended without upgrading, overstressing of the structure can be expected.

1. INTRODUCTION

Recent research[1] has shown that there are approximately 160 000 km of proclaimed unpaved roads in South Africa and almost 260 000 km of unproclaimed road, most of which are gravel or earth. This research[1] also identified a significant backlog, of about 9 000 km, of road in the provision of adequate service to the poorer urban and rural sectors of the community. Many of these roads could be considered as low volume but some should probably be constructed to traditional standards. However, it is considered that, in general, many kilometres of unpaved roads in South Africa could justify upgrading to a paved standard on both economic or social grounds but be classified as lightly trafficked or low volume roads.

The provision of suitable base course materials complying with recognised standards for paved roads (eg TRH4[2], TRH14[3] and CSRA[4]) is becoming increasingly expensive, especially for roads carrying relatively light traffic. As shown above, however, it is important that many of these roads are paved, as all-weather passability is required, the cost of maintenance of the existing gravel road is becoming prohibitive, vehicle operating costs are excessive and the aspirations of the travelling public are increasing. An additional problem is that many of these roads carry vehicles transporting agricultural produce whose quality and marketability may be affected by excessive road roughness or impassability. It has been shown that, depending on the region, topography and road structure it is often cost-effective to upgrade unpaved roads to a bituminous surfaced standard at a traffic count as low as 50 vehicles per day[5]. The necessity to conserve increasingly scarce wearing course gravels and minimise environmental degradation is also becoming a high priority.

It is clear that the minimum design criteria in the current standards (eg TRH4[2], CSRA[4]) for roads carrying less than 200 000 E80's per lane over their design life (E0 traffic class and category C road) is far too high for a road designed to carry 20 000 or 50 000 E80's in both directions over 20 years. The TRH4 design will provide a structure which is almost guaranteed to carry 200 000 E80's/lane (400 000 E80's in both directions over the design life) even under extreme environmental conditions.

Many kilometres of road have been constructed in southern Africa using materials of a quality which would not normally be considered as suitable for base course according to TRH4[2] and TRH14[3] and often using very light pavement structures. Some of these have been constructed as experimental sections, others through necessity whilst some substandard or marginal materials have been used "inadvertently".

The current project was initiated in order to investigate as many of these roads as possible and make use of their performance records to:

i) determine under which conditions marginal quality materials can perform adequately;
ii) derive specifications for the use of marginal materials; and
iii) identify any construction or maintenance procedures necessary to ensure satisfactory performance of these materials.

This report discusses the findings of the investigation of 57 sections of road identified by the relevant road agencies (Transvaal, Orange Free State, Cape and Natal Provincial Authorities and National Parks Board) as being constructed with non-traditional natural gravel or marginal quality bases (ie not complying with their traditional standards[6-9]). The Project has run since 1988 and has involved the field investigation and laboratory testing of about 12 appropriate sections of road per year. A full summary of the locations of the sites investigated is provided in Appendix A. The sites in the Transvaal and Orange Free State which were investigated during the early stages of the project were revisited towards the end of the project to determine whether they had deteriorated since the initial investigation.

2. BACKGROUND

2.1 EXISTING INFORMATION

Despite numerous roads having been built in southern Africa since the mid 1960's using relaxed material specifications or structures, very little work has been done to actually relate the properties of the layers in the roads to the performance of the pavements. Paterson and Marais[10] evaluated the performance of a number of roads constructed with low standard pavements (reduced thicknesses and cement stabilised bases) in the south-western Transvaal. No mention was, however, made of the material properties in this study. Netterberg and Paige-Green[11] carried out an extensive review of the literature concerning materials for low volume roads and concluded that materials greatly inferior to those required by traditional specifications can be used under favourable circumstances. What was significant from this study was that very few proper investigations of in-service low volume roads had been carried out relating the properties of the layers to the performance of the road with time.

Another significant aspect was that after a colloquium of experienced engineers held in 1977[12] a number of recommendations were proposed for relaxed standards for lightly trafficked roads. A minimum soaked CBR of 50 was recommended for the base. More than 15 years later none of these has been included in any recognised local specification. It would thus appear that because these specifications were not fully performance-related, there was some trepidation regarding their use.

Kleyn and Van Zyl[13] used the Dynamic Cone Penetrometer (DCP) on existing light pavement structures to develop a catalogue of designs for lightly trafficked roads in the Transvaal. The procedure optimises the use of the in situ strength (in an existing gravel road or subgrade) and allows significant relaxation of traditional specifications for low volume roads.

Wolff et al[14] used some of the preliminary findings of this project to develop a structural design catalogue for low volume roads. For this catalogue, the material specifications were not relaxed but lower quality materials in terms of the TRH14[3] G classification were used in layers where higher quality materials were traditionally used. The same catalogue of designs has been incorporated into the document on Appropriate Standards commissioned by the Department of Transport[15]

In southern Africa, only Botswana has developed standards specifically for low volume roads (< 0,2 million E80's) which require a minimum in situ CBR of 45[16].

Netterberg[17] developed specifications for calcrete bases significantly lower than the traditional requirements. These specifications cover a wide range of properties and allow significant relaxation of plasticity and grading parameters. The PI should not exceed 15 for roads carrying less than 500 vpd and 8 for roads carrying between 2 000 and 4 000 vpd. A minimum grading modulus of 1,5 is specified for bases irrespective of the traffic. The soaked CBR at 98 per cent Mod AASHTO compaction (2,54 mm penetration) should not be less than 60 for roads carrying less than 500 vpd and 80 for all other roads.

A number of specific case studies are described in the literature in which the traditional material properties are given and the performance of the road shortly after construction is described[18-20]. None of these covers the performance after any extended period of time and only the basic material properties are reported. The value of these reports, however, should not be underestimated, particularly when working in similar areas or with similar materials.

A small study was carried out in the Orange Free State (partly in conjunction with this project) in which six special secondary roads were investigated[21]. It was concluded from this project that a minimum soaked CBR at 98 per cent Mod AASHTO compaction of 70 is recommended although values as low as 50 can be considered borderline. Limits of 8 and 2,2 for the PI and grading modulus respectively are recommended whilst border-line values of 12 and 1,5 are given. These recommendations[21] were actually somewhat stricter than a composite specification developed by Maree based on a number of recommendations given in the literature[12,22,23].

2.2 EXPERIMENTAL DESIGN

The experimental design was similar to that used for the unpaved roads project carried out at the Division of Roads and Transport Technology (Transportek) during the middle 1980's[24] where a factorial design with material type and climate as the main factors, was used. The age of the roads was taken into account directly by combining the years of service with the annual equivalent standard axle count. The major difference between the two experiments is that the cells were filled during the experiment in this study (as the roads were investigated) as opposed to filling them prior to monitoring as was the case in the unpaved roads project. This was necessary as detailed records of the roads were required before final selection and these were often only obtainable with considerable effort. This also avoided unnecessary replication of roads within any cell, although certain known problem materials were investigated in greater detail. A greater number of roads constructed with basic igneous rocks[25] and pedocretes were thus investigated. The levels used for the various factors are discussed in the following sections.

It should be recorded that the aim of this investigation was to determine the pavement structure at a given time on the assumption that this was representative of the pavement over time. the limitations of this were recognised but a very useful data base has been compiled for this analysis. It is also recommended that the investigation should be extended in order to evaluate the temporal and seasonal variation of the properties.

2.3 MATERIAL TYPES

The roads investigated during this project include materials from six of Weinert's nine material classification groups[25]. The objective of the project was to include as many of these groups as possible with a range of climatic and traffic conditions within each group. Groups such as the Metalliferous rocks were not investigated because of their limited occurrence and other factors which mitigate against their general use eg their very high relative densities make haulage uneconomical. The carbonate group was also not investigated as dolomites, the major component of the group, seldom weather to a suitable natural base course material. They typically form a chert-rich wad which is classified as a high silica rock for engineering geological and road-building purposes[25]. Tillites were not included as no suitable roads could be located, despite requesting these specifically. Tillites were investigated early in the 1980's[26] but recent developments in pavement engineering have resulted in a different approach to the analysis.

During the early stages of the project it was envisaged that only untreated natural gravels would be investigated. However, with the progress of the project this was reconsidered and lightly stabilised materials were also included. Many of the roads incorporate stabilisation (often only modification) in order to avoid hauling other material over considerable distances. None of the base materials tested in the Cape or Natal was stabilised although a subbase in one road in the Cape was heavily stabilised and reacted strongly with phenolphthalein. Many of the base materials effervesced strongly with hydrochloric acid but this was attributed to naturally occurring calcium carbonate (calcite) in the weathered materials. A number of the base materials in Natal had been treated with ionic soil stabilisers (sulphonated petroleum products) but these roads were analysed as if they had been untreated. The SPP does not cause any cementation and so does not affect the test results[27].

Although the geological classifications of each material are fully described in the individual pavement investigation reports, the main emphasis is on the material groups as defined by Weinert[25]. This was considered the most appropriate level for the material factor as, although various genetically different geological materials are classified within one Weinert Group, their engineering geological behaviour is similar. All materials classifying as acid crystalline rocks, for instance, will weather to the same residual components under similar environmental conditions.

2.4 CLIMATE

Three levels for the climate were used in the design, Weinert-N values[25] less than 2 (wet areas with a water surplus), N between 2 and 4 and N greater than 4 (drier areas) (Figure 2.1). An N-value greater than 5 is usually taken as the boundary between dry and moderate areas but only a few roads could be located in areas with N greater than 5. In view of the small difference in the effects of one Weinert-N value unit at a value of 5 and the aims of the project this was considered not to be a serious obstacle. The bulk of the roads investigated fell into the areas where N is less than 2 as these are the wetter areas where moisture problems are common. The range of Weinert's N-values in which the roads investigated are located is between 1,0 and 8.

The roads investigated during this project cover a wide area and have climates varying from arid steppe (BS) to temperate (C) according to Köppen's classification[28]. These are illustrated in Figure 2.2. The roads in the temperate zones cover all categories (dry winter (Cw), dry summer (Cs) and humid (Cf)). According to Thornthwaite's classification[29] the roads fall into areas classified as humid (B), subhumid (C) and semi-arid (D) in terms of their moisture and mesothermal (B) in terms of their temperatures (Figure 2.3). Thornthwaite's Moisture Index (I_m) varied between -35 and 40[30]. Almost half of the roads investigated (23 sites) have a moisture surplus in summer and two sites have a moisture surplus in winter according to Thornthwaite's classification. The remaining 32 sites have an annual moisture deficiency[29].

The average annual rainfall in the areas studied[31] varied between 265 and 1224 mm. The period of maximum rainfall is during winter in the western Cape, during summer in the northern areas and reasonably well spaced throughout the year in the southern and south-eastern areas.

The roads investigated fall into all the macroclimatic regions defined in TRH 4[2].

During the statistical analysis, the Weinert N-value, Thornthwaite's moisture index (I_m) and annual average rainfall at each site investigated were included as possible independent variables.

More detailed information on the climatic conditions pertaining to each road investigated is provided in the background reports[32-44]. It is, however, clear that a wide range of climates was included in the sampling programme.

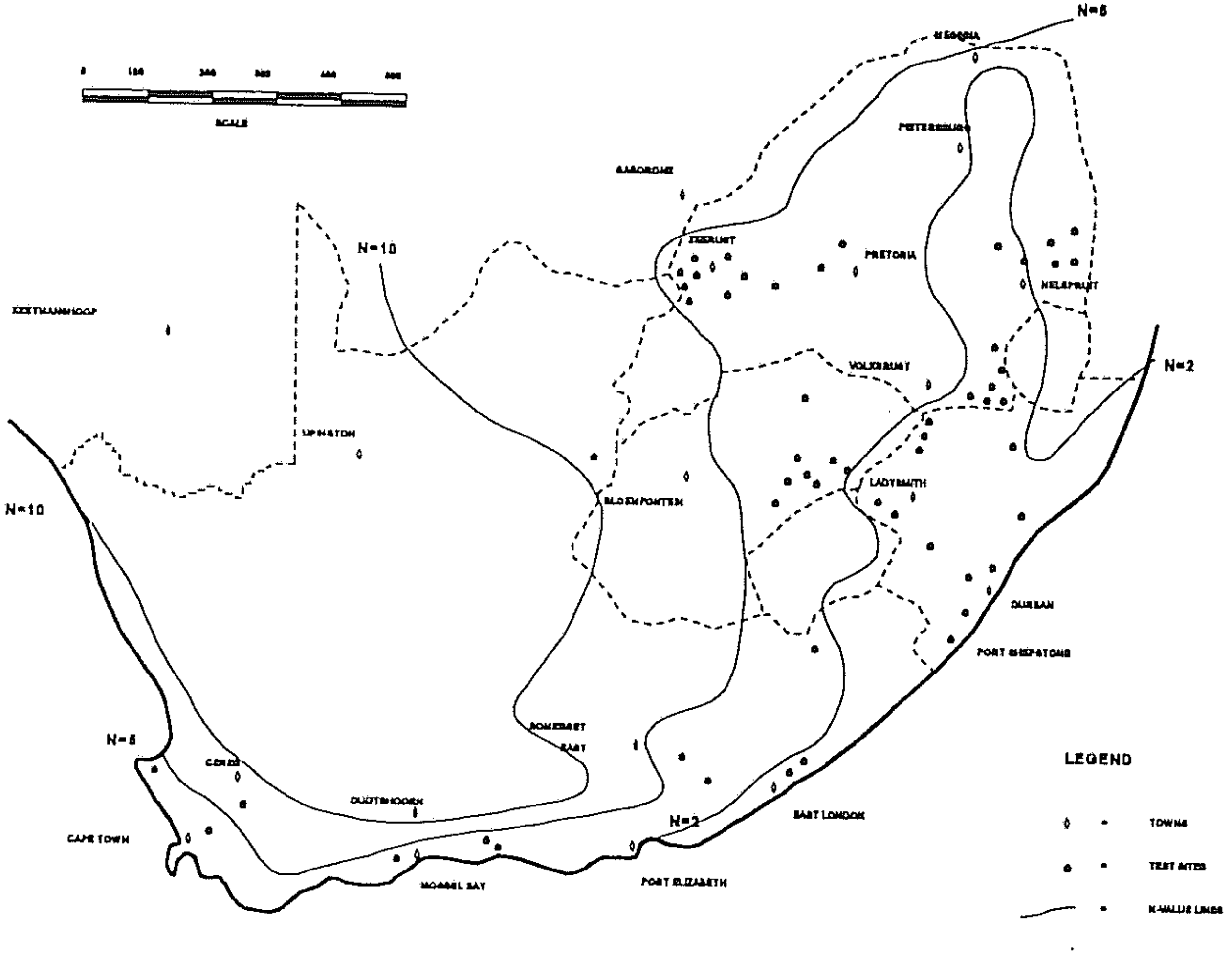

FIGURE 2.1 - MAP OF WEINERT'S N-VALUES

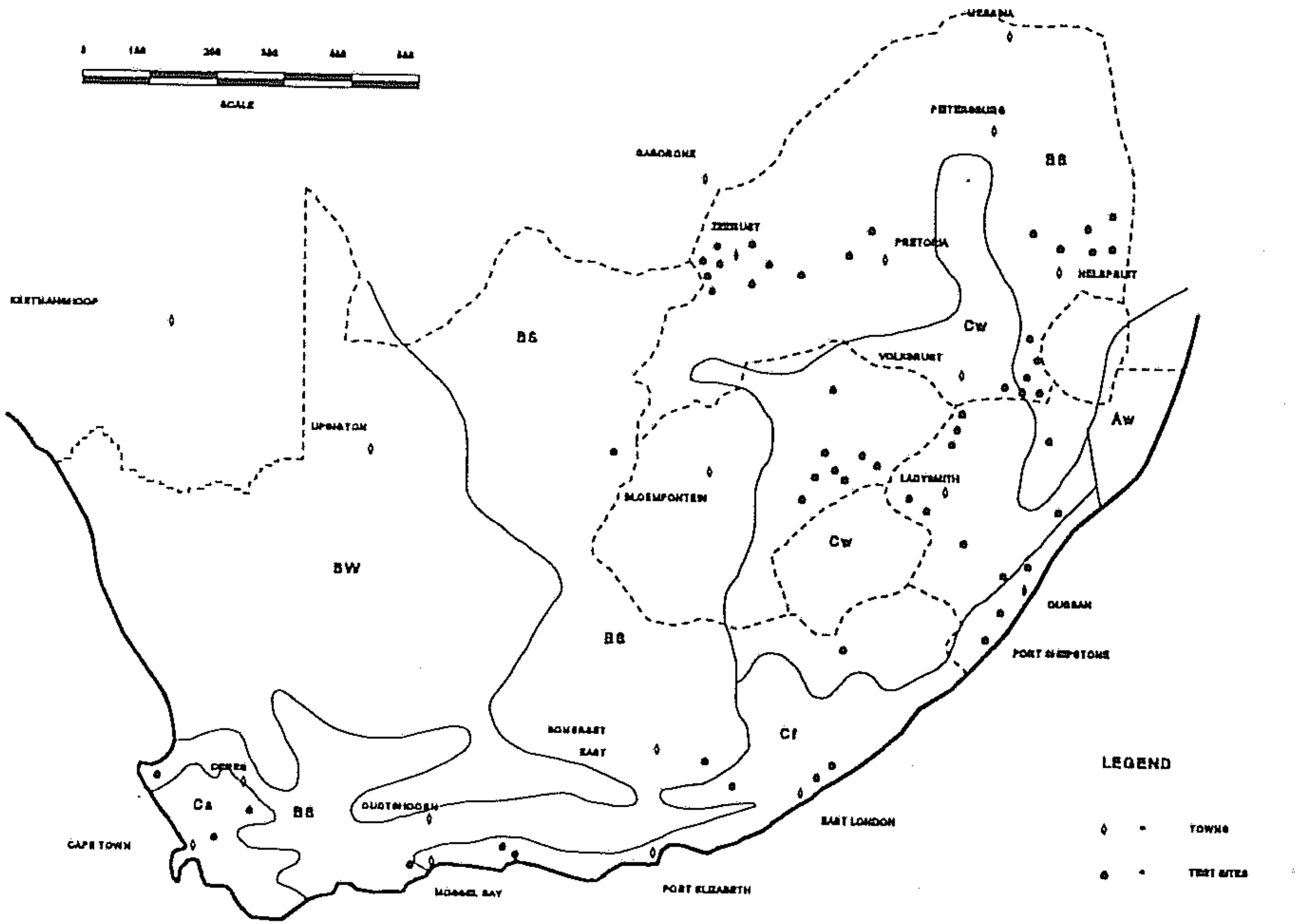

FIGURE 2.2 - CLIMATIC REGIONS ACCORDING TO KÖPPEN'S CLASSIFICATION

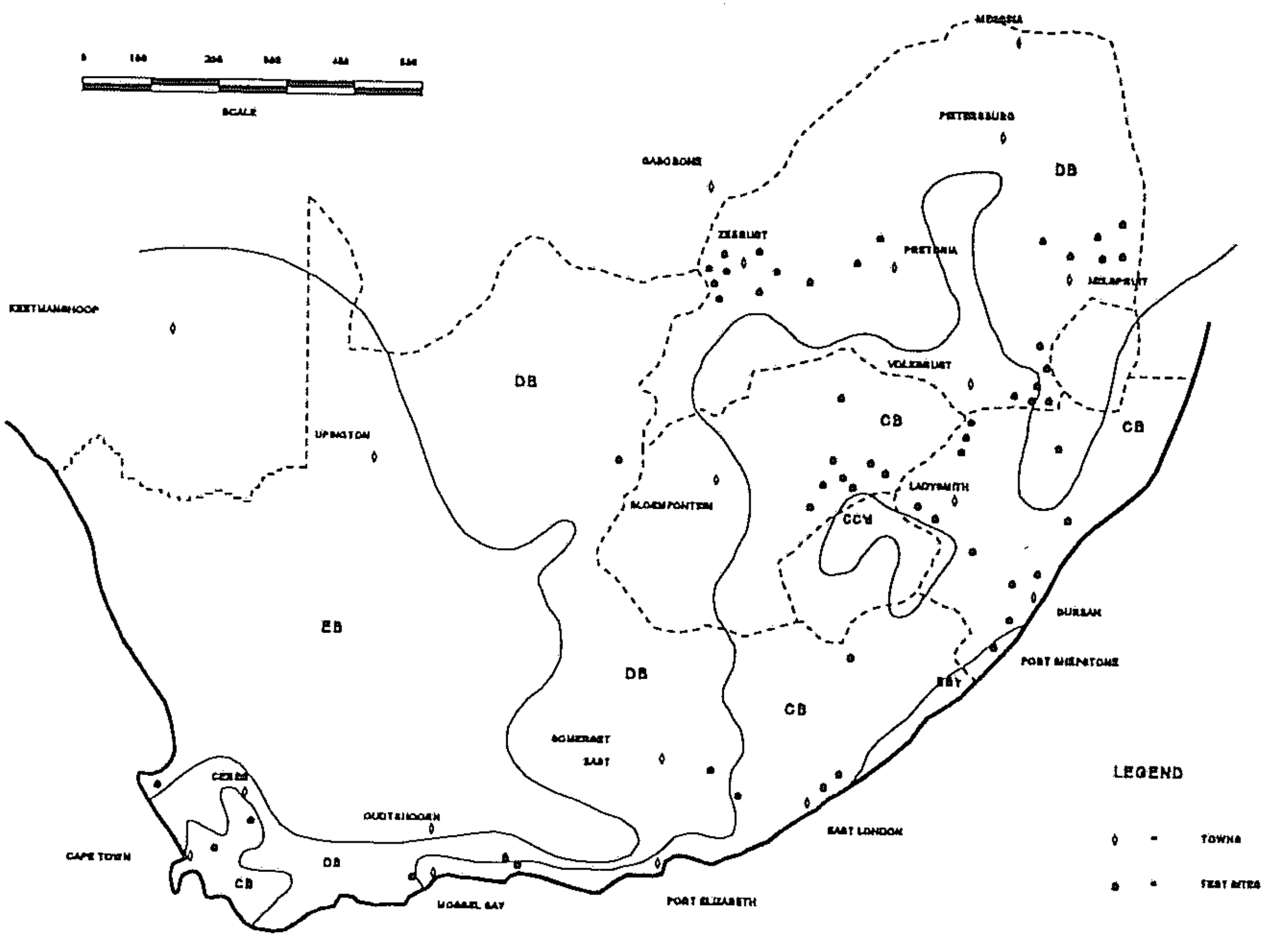

FIGURE 2.3 - THORNTHWAITE'S CLIMATIC CLASSIFICATION

2.5 TRAFFIC

Traffic counts were obtained from records of the respective Road Authorities or Regional Services Councils. Concern was expressed about the accuracy of some of these and revised estimates were obtained after consultation with officers within the specific regions. Most of the counts are based on manual methods although automatic counts carried out over longer periods were available for certain roads. The majority of the counts were in terms of average daily traffic (ADT) and percentage heavies although some were obtained as equivalent vehicle units (evu) and percentage heavies. It was interesting to note how little is known about the traffic characteristics of these lightly trafficked roads.

The estimated cumulative equivalent E80 axles per lane for each road was calculated from the traffic counts, percentage heavy, average number of axles per vehicle, axle load factors, age of the roads and estimated traffic growth rates where applicable. No account was taken of any potential or possible overloading as this could not be quantified. It was assumed that most vehicles complied with the normal legal loading requirements. The traffic was not a parameter included in the factorial design but was accepted as being one of the major parameters affecting the performance of the roads. It was anticipated that a wide range of traffic counts would be obtained by sampling both newly-constructed and old roads.

The most recent counts at the kilometre points nearest the sites investigated were generally used in the analysis. An equivalent E80 per heavy vehicle of 0,575 (0,25 E80/axle x 2,3 axles per heavy) was initially used for all the Transvaal and Orange Free State roads based on the standard method of determination of equivalent axle loads for low volume roads used in the TPA Pavement Management System (PMS) during the early stages of the project. A value of 1,02 was used for all calculations in the Cape and Natal after the work of Bosman[45] as this was determined for the whole of South Africa on a wider basis.

Recent work in the Transvaal, however, has resulted in new values which are considerably higher than those used in the TPA PMS[46].

The value recommended for L1 traffic (more than 70 per cent of the heavy vehicles have only 2 axles) which is the most appropriate classification for low volume roads is 0,97 equivalent E80's per vehicle. This value was based on only 11 roads within this traffic category which had full Traffic Data Logger (TDL) information but is considered to be the best data available. There was, however, a large range of results varying between 0,7 and 1,28 with 95 per cent confidence[47]. This analysis used the traditional damage factor exponent (n) of 4 in the model for the equivalency factor. Following the work of Kleyn[48] and more recent unpublished work at DRTT[49] it is clear that a damage factor of 4 is probably not applicable to low volume roads consisting of marginal quality granular materials. A value of 2 to 3 is likely to be more appropriate depending on the pavement strength balance.

These elements, together with the inherent variation in the traffic on low volume roads with season, local community activity and location (eg in tourist areas) make the estimation of traffic very difficult. A small absolute change in traffic (eg 3 or 4 extra heavies per day) would result in a large change in the percentage of heavies on a low volume road and consequently a significant increase in the cumulative actual traffic over a number of years.

For the purpose of this project and in order to obviate major problems with the interpretation of the traffic volume, which is crucial in the analyses carried out, a range of values is used. The standard E80 per axle found for the Transvaal using an "n" exponent of 4 was 0,36 (95 per cent confidence interval for the equivalency E80s per heavy was 0,7 to 1,28). By decreasing the exponent to 3 and 2 the standard E80 per axle value becomes 0,465 and 0,601 respectively. The 95 per cent confidence intervals for the E80s per vehicle of these two values are 0,91 to 1,68 and 1,18 to 2,18 respectively. It is clear that the standard E80s per vehicle could range from 0,7 to 2,18 depending on the pavement structure and the actual traffic selected. In order to obtain meaningful results with an acceptable range of traffic, the value for an exponent of 3 was used in the analyses with the mean (F = 1,26) and the upper (1,68) and lower (0,91) 95 per cent confidence intervals being the discrete values used. The mean value is similar to the recommended average value (1,2 E80's/heavy) given in the appropriate standards manual[15] for 50 per cent of the heavies being laden. It is also close to the average of the E80's/vehicle for 2 and 3 axle trucks (0,7 and 1,7 respectively)[15].

Maree[50] has discussed the effect of traffic wander and provided a guide for the reduction of the E80's to take this into account. As most of the defined wheel tracks were less than 500 mm in width and for reasons of conservatism, this aspect was excluded from the modelling. In all cases the factor for the traffic distribution per lane was taken as 0,5 ie a 50:50 split.

On this basis the roads had carried between 2 191 and 1 046 300 equivalent standard axles per lane at the time of sampling using the factor of 1,26. The traffic counts using 0,91 and 1,68 as the factors had ranges of 1 582 to 755 656 and 2 921 to 1 395 059 respectively. The remaining discussion refers to the 1,26 factor unless otherwise stated.

The old roads had very high cumulative traffic counts but only 23 per cent of the roads investigated had carried in excess of 100 000 E80's. The traffic on the remaining 77 per cent of the roads is clearly classified as a low E0 according to TRH4[2]. These roads should by definition[2] carry very few heavy vehicles. This was the case on the roads investigated, most of which carried low percentages of heavy vehicles although some conveyed produce to markets and silos, sugar-cane to mills and timber to saw-mills. As nearly all of the roads serve a limited and fairly consistent community or industry the growth rate has been taken as zero. Many of the traffic counts were taken close to the middle of the lives of the roads and assuming a consistent growth rate, the average traffic would in most cases take the growth into account.

In summary, it is clear that the estimation of the traffic depends on a number of variables which are difficult to quantify without very detailed axle weight classification and analysis. It, is, however considered that the cumulative axles used in this report are representative of the conditions prevailing on the roads investigated, but in order to improve the findings of this project, detailed traffic analyses on selected roads are recommended.

2.6 SAMPLING MATRIX

The final experimental design matrix is shown in Figure 2.4.

The discussion, recommendations and conclusions in this report are based on the evaluation of the structure, materials and performance of fifty seven "lightly trafficked roads" ostensibly containing marginal base course materials" from across South Africa. (Some of the roads identified by the agencies involved were found to contain materials which should perhaps not have been classified as marginal in the true sense of the word although all roads had some degree of marginality). Individual inspection details are summarised in interim reports[32-44], copies of which have been submitted to the Department of Transport and the Provinces previously.

	Basic Crystalline	Acid Crystalline	High Silica	Arenaceous	Argillaceous	Pedocrete
N ≤ 2	Dol - S43 Dol - S796 Dol - P220 Dol - P169 Dol - P197/3 Dol - P500	Gr - 514 Gr - 390 Gr - 646 Gr - 518	Qrtzite - P390 Chrt - 421	Sst - P1532 Sst - P390 Sst - P326 Sst - D594 Sst/Cong - P102	Sh - P2738 Sh - P2753 Sh - 736 Sh - P10/1 Sh - P10/2 Mudst - P39	Ferr - 466 Ferr - 466 Ferr - 466 Ferr - P39 Ferr - P39
N = 2 - 4	Dol - S63 Dol - S65 Dol - S65 Dol - S191 Dol - P13/2 Dol - S18 Dol - H6 Nor - 467	Gr - H1-1 Gr - S3 Gr - 514	Qrtzite - P1351 Qrtzite - P477	Sst - P477	Sh - 2485	Calc - P2151 Ferr - 540
N ≥ 4	And - 804 And - 804 And - P3405		Chrt - 410	Sst - P672	Sh - 132 Sh - 172/2 Sh - 410 Sh - 404 Sh - P1418	Cal - 804 Cal - 804

Figure 2.4: Experimental design matrix

3. INVESTIGATION

The investigation procedure involved the location of sites on each identified road, at which both distressed areas (usually in the outer wheel track) and sound areas occurred in close proximity. Usually the failed area occurred in the outer wheel track (OWT) and the sound area could be located in the adjacent inner wheel track (IWT) which facilitated direct comparison of the performance of good and bad structures with minimal material variation between the sites. Some of the roads performed so well that no distressed areas were evident. As it was equally important to evaluate these roads, the investigation was carried out at sites on these roads which were representative of the overall road performance.

It was considered impractical to locate borrow materials from which the roads were constructed in order to evaluate whether any change in the materials had taken place since construction, as the variability of natural gravels is typically so large that subtle changes in the material properties would not be confidently identified. Samples were thus collected from the centre-line (CL) area (ostensibly untrafficked and with a relatively consistent moisture content), or on narrower roads where the centre-line showed obvious signs of trafficking, samples were collected from between the wheel tracks (BWT), for comparative testing.

The lane showing the most distress was sampled in all cases as this was considered to be representative of the heavier traffic.

Full descriptions of the location of each site are provided in the detailed investigation reports[32-44] and summarised in Appendix A.

3.1 FIELD EVALUATION

In the field the condition of each road in the vicinity of the site was described in terms of TRH 6[51] and the riding quality of each section of road was also measured. The rut depth was measured under a 2 metre straight edge using a wedge. The performance of the road was rated in the field on a scale of 1 (good) to 5 (poor). The drainage was rated on a scale of 1 (good) to 3 (poor).

In situ testing at each point (three points per site) consisted of a DCP test to a depth of 800 mm (on some roads this was not possible because of the pavement strength or the presence of excessively coarse material within the structure) and the determination of the in situ density and moisture content of each layer of the pavement. The densities for this work were carried out using a Campbell CPN-2 nuclear gauge. Comparison of the results with earlier sand replacement test[52] results showed that provided the gravimetric moisture content was used to calculate the dry density from the nuclear wet density, the results of the nuclear method were at least comparable with, and sometimes better than, those of the sand replacement method. The actual moisture contents determined by the nuclear method were shown to be statistically different from the gravimetric method and of no practical use[52].

It was also noted that the moisture content samples (4 to 5 kilograms) required oven-drying for up to 7 days before the constant weight situation was achieved.

Representative bulk samples of the base (90 to 100 kg), subbase and selected layers where they existed (45 to 50 kg) and subgrade (45 to 50 kg) were collected from each site.

The pavement profile, layer thicknesses and materials in each test hole were fully described[53] and these are provided in the detailed reports for each road together with the pavement performance evaluation.

3.2 LABORATORY INVESTIGATION

All of the samples collected were returned to the laboratory, individual bags were thoroughly mixed and the material quartered and prepared according to TMH 1[54] for both routine and non-routine, specialised testing.

The following tests were carried out on each base sample:

i) Atterberg limits and linear shrinkage
ii) Particle size distribution
iii) Compaction characteristics
iv) CBR strength
v) Durability mill testing
vi) Density/moisture/strength relationships

Methods i) through iv) followed the standard TMH1[54] procedures, the Durability Mill test was carried out according to Sampson and Netterberg[55] and the density/moisture/strength relationships were determined by testing the CBR strength at various combinations of density and moisture.

The samples from the lower layers were tested similarly except that less work was done on the moisture/density/strength relationships and no Durability Mill testing was carried out.

During testing of the Cape and Natal samples discussions indicated that the plasticity index carried out on the material passing the 0,075 mm sieve was a useful indicator of material performance. This testing was consequently carried out on most of the samples from the Cape and Natal.

The test results from all the materials are fully tabulated and discussed in the relevant reports dealing with each of the roads investigated[32-44] and are not included in this report. The statistics of the important material properties are, however, summarised in Appendix B.

It is clear from the results in Appendix B that very wide ranges were measured in all of the tests. This indicates that the findings of this research are applicable over a wide range of materials.

3.3 PERFORMANCE CLASSIFICATION

Although the performance of each section of road investigated was rated in the field, problems were encountered when using this rating in the analyses. The main problem was that many of the roads had been resealed and problems which may have occurred in the past were masked. Ruts and patches were filled and covered, cracks were sealed and not visible and the riding quality was improved. On the other hand, older roads which had not been resurfaced or properly maintained may have rated badly on the basis of visible cracking and rutting despite having carried more traffic. These roads were not rated high purely on account of their age as the time that cracking and deformation started could not be estimated.

Based on the visible evidence and traditional classification of distress[51] a totally incorrect rating may have been given. Old roads with a cracked seal and significant rutting and ravelling may have cost very little to maintain, whilst the newly sealed roads may have had extensive patching and costly maintenance. Although, it was not possible for this project, it is suggested that the performance of low volume roads is best classified on the basis of the cost of maintenance which is necessary to ensure that the structural integrity of the road is retained.

The performance needs to be related to the age of the road and the cumulative traffic which the road has carried. A young road rated as good may perform poorly in the long term compared to an old road which has carried significant traffic and is now in need of rehabilitation. This aspect is difficult to quantify on a one-off visual basis.

For the purpose of this research, the following factors were considered in the evaluation of the performance.

Rutting

Rutting is not necessarily an important nor reliable indicator of performance (unless they are the result of excessive strain due to inadequate strength as opposed to densification of the material through traffic compaction). Although deep ruts can result in ponding of water and deterioration in the safety conditions of the road, it is considered that ruts of up to 50 or 60 mm are not necessarily unacceptable on low volume roads, particularly if the road is on a grade . However, if the surfacing associated with the ruts is cracked, this is a significant problem and timely maintenance is necessary.

The rutting observed during the field work was attributed to poor compaction of the base, subbase and subgrade, particularly the subgrade at depth. Comparison of the densities in the outer and inner wheel tracks with those beneath the centre-line showed that some rutting was attributable to the base but this was generally a small proportion. Deep ruts were typically the result of poor construction control, improvement of which would reduce the potential to rut significantly. It has recently been shown[56] that provided the moisture content of the material to be compacted is correct (close to the critical moisture content), very few roller passes are necessary to achieve a high degree of compaction (typically one or two).

An attempt to analyse rutting in terms of a standard rut parameter (mm/million Equivalent standard axles) resulted in values typically in excess of the base thickness. This is the result of trying to use compaction-related rutting as an indicator of traffic-related deformation and also trying to extrapolate parameters used for traditional roads to very lightly trafficked roads.

The use of rutting as a maintenance or rehabilitation trigger condition[57] or performance evaluation tool for low volume roads is considered to be unsatisfactory. Similarly the use of rutting in relation to the traffic which has been carried by the road to predict the ultimate carrying capacity (for a 20 mm rut depth) is open to criticism. Although this is the basis for most mechanistic analysis procedures, there is always doubt as to whether the rut is a result of subgrade strain, base or subbase densification or post-construction bedding-in of the materials.

Cracking

The presence of cracks need not necessarily be related solely to the pavement performance. While it is accepted that a weak base can result in cracking of the surfacing, it should be noted that high pavement deflections, volumetric movement of the subgrade or fill, ageing and fatigue of seals, poor bond between the seal and base, poor construction, excessive moisture in the pavement and settlement could all result in cracking of the surfacing. These problems may not be related to the performance of the base in any way and yet still result in the performance of the road being classified as poor.

Shearing

Shearing of the base and underlying layers is a direct result of the shear strengths of the material being exceeded. Shallow base failures are easily recognised in test pits and are clear evidence of unacceptably weak bases. However, in many cases, the outer wheel track fails during excessively wet periods and is patched. It is seldom, during an investigation of this type, that a base failure is actually observed and it is difficult to relate existing patches to the cause or location of the distress.

Ravelling

Ravelling, and eventually potholing, always results in a poor classification of the performance of the road due to the poor riding quality and aesthetics. Routine maintenance can usually restore the road to an acceptable condition and the performance classification is thus not necessarily a true representation of the structural capacity of the road. Ravelling is usually the end-result of surface cracking which need not necessarily be associated with deficiencies in the base course.

Bleeding

Bleeding is normally a sign of problems with the road surfacing or upper base. It typically arises as a result of excessive heavy vehicles, poor construction or punching of the surfacing stone into the top of the base. However, on lightly trafficked roads, bleeding is considered to be more acceptable and, where maintenance is likely to be prolonged, is often advisable as the extra bitumen assists in maintaining the integrity of the seal. Bleeding is typically a functional and not a structural deficiency but can be directly related to the performance of the base course.

Drainage

Because of the importance of drainage in roads, this was rated separately from the performance. Most of the problems observed on the roads, however, could be attributed to drainage deficiencies. The drainage was rated on the basis of the ability of the road and adjacent areas to adequately shed rain water by the presence of appropriate drains and the condition of the drains in terms of maintenance. In addition, the basic ground-water conditions which could result in poor subsurface drainage conditions were assessed.

Bearing the preceding discussion in mind, the field performance ratings were subjectively adjusted to take the age, traffic, and maintenance history into account as far as possible. While the deficiencies of this are recognised, no other mechanisms for evaluating the functional performance were considered suitable. The structural performance was evaluated from the DCP. The measurement of deflection bowls at each site and evaluation of the in situ stiffness of each base course would have been an improvement on the DCP but even this would not take the seasonal variation of strength into account without regular and repeated testing. This was considered logistically impractical for this type of large-scale investigation.

The optimum solution to this problem would be to monitor the sections over an extended period, including measurements of deflection and seasonal variation of moisture and strength within the base course.

The performance was rated for the short section of road in the area directly surrounding the site sampled. The high variability of the materials along the road resulted in significant variation in performance. Sites which were typical of the general performance of the road were selected for sampling. The performance criteria could then be related to the material, moisture and construction characteristics at that site. The rating used a 5 point scale with 1 being very good (minimal defects) and 5 being very poor (badly distressed).

4. DISCUSSION OF FINDINGS

The findings of the investigation are discussed in this section. It should be noted that these findings are based on the examination of 57 roads with a wide range of material types, traffic conditions and climatic characteristics.

Although the prime objective of the investigation was to evaluate the base course materials and develop performance-related specifications for low volume roads, the base performance cannot be assessed in isolation and the influence of the other pavement layers needs to be taken into account. It is thus necessary to discuss aspects relating to the surfacing and base-support layers in the holistic context of the pavement performance including functional and structural characteristics as well as effects of the subgrade and other layers.

4.1 BASE

The bases investigated during the project consisted mostly of natural gravels, although some crushed stone was used in the Cape Province and a number of treated gravels were used in the Transvaal (10 sections) and some sections were treated with ionic soil stabilisers in Natal. The treated sections in the Transvaal all had between 2 and 3 per cent of added stabiliser (lime, cement, lime-slag and "wallcrete" were used) and can thus be classified as being mostly "modified" as opposed to "cemented" in most cases[58]. It was noted during the investigation that most of the treated sections had become badly to totally carbonated[59] supporting the fact that they had been "modified"..

The investigation has shown that the achievement of high densities during construction is critical to ensure satisfactory performance. Low densities lead to rutting, and theoretically have a higher capacity for water ingress and retention, more interparticle abrasion and degradation and generally a greater propensity for the pavement to deteriorate. The highest density economically and practically achievable[60] should be strived for and perhaps some form of compaction aid should be employed to assist the compaction process. It has been clearly demonstrated in the individual reports[32-44] that the strength of many of these materials has a greater density dependence than moisture dependence.

The average compactions obtained for the various provinces are summarised in Table 4.1.

Table 4.1: Average densities of base by province

Province	Average density	Range of densities
Orange Free State	99.5	87 - 104
Transvaal	97.2	88 - 105
Cape	98.7	91 - 106
Natal	100.3	96 - 106

It can be seen that the average densities are all similar although the Transvaal is a little lower. This is probably the result of the specification for light pavement structures in the Transvaal requiring only a compaction of 95 per cent of Mod AASHTO in the base.[61]

It is interesting to note that the average densities in Natal are the highest of the 4 provinces. This could be the result of SPP's in a number of roads. These products can effectively reduce the surface tension in certain soils[62] and improve their compactability. The average compactions obtained are, however, generally good.

The maximum densities achieved in all the provinces are very similar (between 104 and 106 per cent) indicating that this is probably the maximum density achievable under normal compaction and traffic densification processes. It does mean that it is possible to calculate the potential rutting which could be attributable to the base should lower densities be achieved during construction. However, the recent work[56] relating compatibility to the compaction moisture content shows that there is no excuse for not getting a high density.

The determination of density using nuclear techniques should always be carried out in conjunction with gravimetric moisture content determinations. TMH 1[54] explicitly states that moisture measurements on ferruginous materials or materials containing chemically bound water need to be compensated using gravimetric determinations. Results obtained during this project have shown that the nuclear moisture can vary between 40 per cent below and 90 percent above the gravimetric determination for materials as diverse as granites, shales, ferricretes and norites. The importance of using gravimetric moisture contents for construction cannot therefore be overemphasised. As discussed previously, it is equally important that the moisture determination is actually carried out after the sample has been dried to a constant mass. As this varies from material to material, frequent checking is necessary.

It is interesting to note that the average moisture regimes of all the roads investigated (Appendix B), irrespective of the climatic region in which they occurred, were considerably wetter than predicted by the models of Emery[30,63]. This investigation has shown that the average rating for drainage of all the roads is between fair and poor and this could indicate why the in situ moisture contents are higher than predicted. Although surface drainage was considered as a stratification factor (good/fair and poor) in the experimental design of Emery's work[63], subsurface drainage was left as an uncontrolled variable. The results and interpolation of the findings should thus theoretically not be influenced by drainage.

The average ratio of field to predicted moisture content (using Emery's equation 3[30]) for all the samples was 127,6 per cent with a range of 32 to 334 per cent. The averages in the four provinces were 115, 138, 127 and 132 per cent for the Cape, Free State, Transvaal and Natal respectively. The in situ moisture content can therefore not be related to the rainfall or any other climatic parameter. It is also independent of material as the material properties are incorporated in the prediction model for the equilibrium moisture content. It is interesting to note that the Cape results are the lowest, as most of the roads were in the coastal areas, many of which are classified as having rain through most of the year.

The average ratio of field to optimum moisture content for all the roads investigated was 89,5 per cent. For all bases in a wet climatic area ($I_m > 0$) this value should be less than 60 per cent (less than 56 per cent in arid areas)[30]. Emery's models were developed from samples collected from typical provincial roads throughout southern Africa, mostly constructed to traditional standards. It would thus appear that the models are not fully applicable to marginal materials or thin pavement structures. These aspects should be noted when using the models in the design process, particularly for unsoaked CBR designs where an unexpectedly high risk of failure may occur.

Materials with a wide range of plasticities and particle size distributions have been investigated during the project. The average plasticity index of all the base samples tested was 7,4 with a range of non-plastic to 20,5. Exclusion of the non-plastic values (taken as zero for analysis purposes) from the analysis resulted in an average value of 9,3, considerably higher than the TRH14[3] recommendation but within the range of most recommended relaxations[21]. A summary of certain relaxed limits indicates that plasticity index values between 8 and 12 are satisfactory (up to 15 for pedocretes). Similar results were found for the grading analysis data where the average grading modulus was 1,86 (range 0,63 to 2,63). The average percentage passing the 37,5 mm sieve was 96 but the range of results varied between 66 and 100 per cent indicating that a number of the roads had extremely high percentages of coarse material. The average percentages passing the 0,425 and 0,075 mm sieves were 39 and 21 respectively (ranges of 12 to 82 and 4 to 68) indicating that the majority of the materials were very fine and well outside current specifications. The high average percentage passing the 0,425 mm sieve signifies that most of the samples tested would be rejected on the basis of the current criterion that this should not exceed 35 per cent[55,64]. In spite of these material deficiencies, the average performance of all the sections tended towards good.

The conclusion from the results obtained is that materials not complying with the traditional requirements in terms of these parameters should not be rejected for use in lightly trafficked roads without careful consideration. Aspects such as, whether large stones or high plasticity prevail, which will make construction difficult or affect the surfacing adhesion should, however, be considered. Similarly very fine materials with little aggregate appear to detrimentally affect the surfacing/base adhesion.

The primary objective of good road design is to provide pavement layers which are capable of supporting the applied loads without shearing or undergoing excessive non-recoverable plastic strains over their design lives. In addition, the base layer should have adequate stiffness to distribute the applied loads sufficiently to protect the underlying layers. The main criteria for pavement layers are therefore the strength, the ability to maintain this strength over time (ie durability) and the variation of strength with time (mostly seasonal moisture influences). The average laboratory-determined soaked CBR strengths at 100 per cent Modified AASHTO density of the base course materials investigated in this project was 71 (range 9 to 232). The average unsoaked CBR at the same density was 94 and the soaked CBR at 95 per cent compaction (Proctor effort) was 27. It is clear that most of the materials have lower strengths than the currently specified minimum CBR of 80. In addition the general density dependence of strength is clearly illustrated.

Despite the average moisture content of the base courses being higher than predicted, the average in situ strength of the bases (equivalent CBR from the DCP) was 105 per cent (range 19 to 480). It is thus clear that the soaked CBR is very conservative with respect to the possible degree of wetting up of the material in situ. An evaluation of some of the materials tested indicated that the increase in moisture of CBR samples during the 4 day soaking period was highly density dependent and could be very high (Table 4.2).

Table 4.2: Increase in moisture content during soaking for CBR test

Density	Ratio of moisture content after soaking to OMC				
	Number of samples	Mean	Standard deviation	Minimum	Maximum
Mod AASHTO	20	1,287	0,161	1.17	1,70
NRB	20	1,474	0,170	1,25	1,88
Proctor	20	1,720	0,264	1,30	2,34

Theoretically, it could be postulated that the water absorption would be a function of the particle size distribution and hence the density achievable under a given compaction effort. In fact, there was a strong relationship between the water absorption at the different densities and the individual samples.

Testing of the durability of the materials has indicated some interesting results. Very few of the materials investigated complied with the currently recommended requirements of the Durability Mill test (DMI) and Fineness Product[55,64]. However, equally few of the problems noted in the field could be directly attributed to degradation of the material in service. Examination of the average fineness products of all the materials showed values of 289, 300 and 275 for the outer and inner wheel tracks and centre-line respectively. This indicates that, on average, only minor degradation of the materials has occurred under traffic with less than a ten per cent change in the fineness product. The corresponding durability mill indices are 428, 475 and 429 respectively. This is indicative of the potential of the materials to undergo significantly additional degradation should the traffic increase or the moisture regime deteriorate. The consistency between the fineness moduli and the DMI values shows that the basic philosophy pertaining to these tests as indicators of durability is sound.

The above discussion supports the interim conclusion[65-68] that durability problems are, in general, unlikely to affect lightly trafficked roads to the same extent as those carrying heavy traffic. The generation of excessive fines in a base layer will affect the density and permeability properties, normally for the better, unless the fines produced are excessively plastic. However, should the material become soaked, high pore water pressures can build up and the strength will reduce dramatically under load. Despite an intentional bias to include a large number of basic igneous rocks in the investigation, the fines generated in the durability mill test were predominantly of low plasticity.

4.2 SURFACING

Although the project objectives do not include an investigation of the life and effectiveness of the different types of seals (these have been investigated separately in a SABITA sponsored project[69]), they are obviously closely associated with the overall performance of pavements constructed with marginal materials. They have been discussed in the individual detailed investigation reports[32-44] and are not discussed in detail in this report.

Roads consisting of almost every type of surfacing commonly used in South Africa were investigated. These ranged from sand seals, thin and thick slurries, single, double and Cape seals to asphalt. Sand seals were commonly identified as the first surfacing in many cases with a subsequent application of single seals.

A number of important interrelationships between the surfacing and base (and pavement structure as a whole) arise from the use of marginal materials in the base.

- The adhesion between the base and seal on weak and fine-grained materials can be a problem. A number of the finer grained materials showed distinct layers of loose material beneath the surfacing. This resulted in easy separation of the seal from the base. When a deep prime penetration occurred this tendency was decreased and the upper layer of the base was considerably strengthened. It is thus recommended that a non-viscous, deep-penetrating prime is used on weak bases or those which are fine grained or may generate fine sandy material with time.

- Large stones in the base material should not be allowed to protrude or show through the top of the compacted base. Numerous cases of potholes, associated with the presence of large stones which affected the seal, were observed. Most binders quickly lose their adhesion to the large stones, cracks form and ready access of water in the areas adjacent to the stones is permitted. The low density often found adjacent to large stones (the roller is supported by the stones and cannot compact the adjacent material effectively) exacerbates this situation. It is recommended that should the presence of large stones in the upper base course be unavoidable, a modified bitumen is used to enhance the adhesion of the seal to the large stones and allow more flexibility between the stones and the surfacing.

- It was evident during the investigation that the hardening of the bitumen binder with time resulted in a decreased flexibility of the seal with concomitant cracking under high deflections (usually seasonal). This was particularly in evidence on those older roads with low DSN_{800} values which can be expected to have high deflections. The use of durable, flexible binders is thus recommended on low volume roads.

- Related to the above recommendation is the necessity for regular and thorough maintenance, particularly on roads with thin structures and high deflections. It is recommended that either dilute emulsion fog sprays or reseals are scheduled regularly enough to avoid the surfacing reaching the stage where deflections will result in cracking. It is critical when using marginal materials in the base that all surfacing distress such as cracking and ravelling is maintained immediately. The moisture/strength relationship of these materials, which is generally far more critical than that of traditional materials, results in significant weakening of the pavement on water ingress.

- One aspect common to almost all the successful surfacings on the roads investigated was the presence of a slightly high binder content. Some bleeding was invariably evident but under the prevailing traffic was not considered to be of major consequence and assisted in retaining the integrity of the surfacing. It is recommended that slightly high bitumen application rates are used as a matter of course for light pavement structures.

4.3 LOWER LAYERS

The pavement layers beneath the base both affect and are affected by the base. It is these layers which provide a platform on which the base is compacted (ie a reaction to the compaction effort). After construction the base protects the lower layers from being overstressed.

Forty seven per cent of the roads investigated during the project had no subbase or selected layers whilst 14 per cent had both subbase and at least one selected layer (often remnants of previous gravel wearing course layers). It is notable that the average performance of the roads constructed directly on the subgrade was no worse than those with a subbase. Sixty two per cent of both types of road had performance rated as two or better. Four per cent of the roads without a subbase and six per cent of those with a subbase were classified as poor. It would thus appear that for lightly trafficked roads, the South African subgrade conditions often make the importation of layers other than the base redundant. Seven hundred millimetres of imported gravel was measured on one road which had an average in situ subgrade CBR in excess of 20.

An analysis of the subgrade conditions of the 57 roads investigated showed that the average soaked CBR strength at Modified AASHTO compaction was 50 per cent with a range of 3 to 181. At Proctor compaction, the average was 21 with a range of one to 73. The average unsoaked CBR at Mod AASHTO density was 79 with a range of 3 to 220. It is clear that ripping and compaction of the in situ materials (preferably in more than one layer) will, in many cases, obviate the need for the importation of other material , which is often of poorer quality than the in situ material.

The water-table in South Africa is generally deep, with only localised areas of shallow and perched water-tables[70]. This is illustrated by the average moisture content of all the subgrades investigated. The average ratio between actual subgrade field moisture content and optimum moisture content was 1,02 with a range of 0,39 to 2,03 (Figure 4.1). In order to take the material type into account the ratio between the predicted field/optimum moisture ratio (equation 15 in ref 30) and the actual field/optimum ratio was evaluated. Although there was significant scatter, the average for all the roads was 1,01 indicating that the prediction model is accurate but has a high error of estimate (Figure 4.2). It is thus clear that certain roads were very dry whilst others were very wet at the time of sampling. Most of the sampling took place between August and October of their respective years which is the dry season for all of the roads except some in the Cape Province. It is therefore unlikely that the high moisture contents were the result of sampling during the wet season, although it is recommended that further work is carried out in this regard.

One imported layer on the compacted subgrade would thus appear to suffice for most lightly trafficked pavements on reasonable subgrades. The practice of importing layers of various strengths onto strong subgrades often results in poor pavement balance (Section 4.7).

In order to evaluate the requirements of layers beneath the base course, a number of detailed mechanistic analyses of the pavement structures investigated in this project were carried out for another project[71]. The full results are not included in this report but some of the conclusions are summarised below:

- The mechanistic analyses generally indicate higher lives than the actual lives of the pavement. This is partly the result of the actual lives being calculated from the current cumulative traffic and the rut depth, such that the actual life will be the cumulative traffic at which a rut depth of 20 mm will develop. Modified E-modulus values based on the model given by Emery (equation 37 in reference 30) mostly give better results than the standard recommended E moduli for the South African

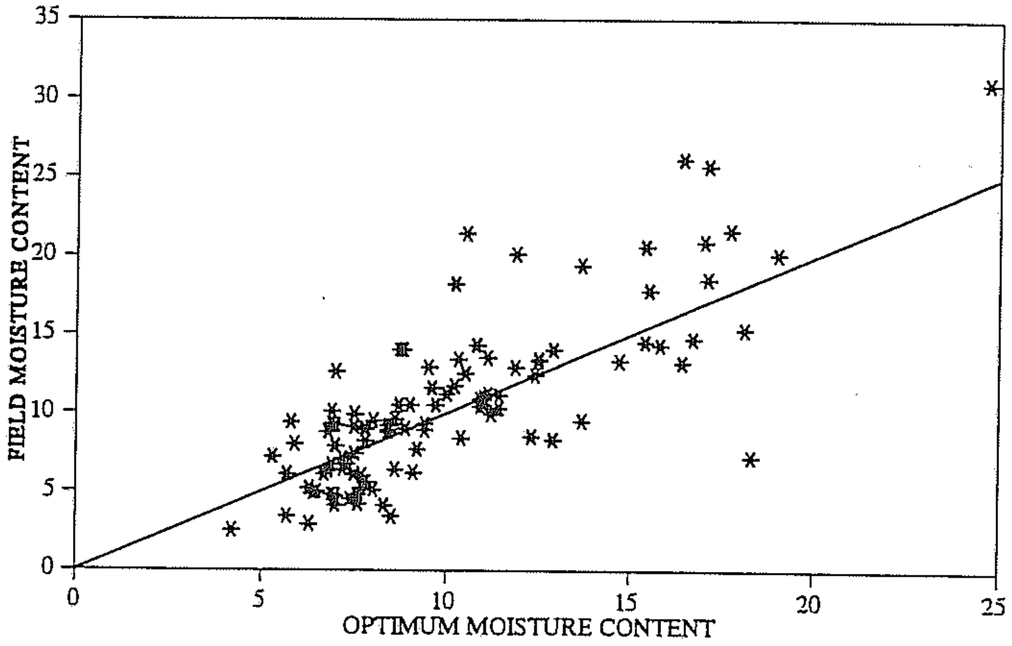

Figure 4.1: Subgrade moisture content versus optimum moisture content

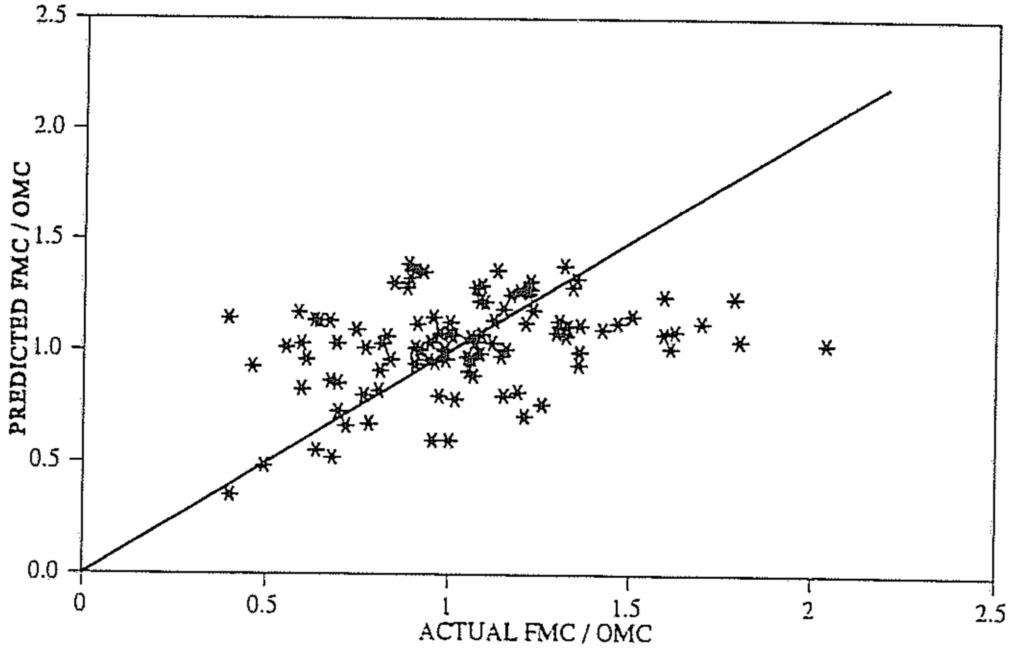

Figure 4.2: Predicted versus actual field moisture content (Model 15 in Ref 30)

mechanistic analysis method[72]. The E moduli and c and ϕ values for the low quality materials all appear to be significantly under-estimated. The linear analysis also fails to approximate the actual behaviour of the pavement in many cases, with the biggest problem being thick base courses and strong subgrade layers. Accurate saturation ratios under the pavement should be obtained as the predicted life of the pavement is strongly affected by this parameter.

- In general the roads with stabilised bases have performed badly, the most likely explanation for this is that most of the samples were carbonated and hence their strengths had returned to that of the equivalent unstabilised material. In addition, the maximum dry density of stabilised materials is typically less than that of the untreated material. During the design process for the road, the base would have been assumed to have a high strength and with the support of the underlying layers would be taking the majority of the loading. That load is now being transferred into the subbase or subgrade and these layers are probably being over-stressed.

- Many of the roads have performed well despite their light structures but most of the roads have large rut depths due to poor compaction (mostly in the subgrade) and very thin pavement layers. This implies that the construction of low volume roads is not being controlled as carefully as major roads, while the material and design standards are being lowered.

- Certain spurious results were obtained in the analyses, particularly when the pavement balance is poor. For instance, by increasing the thickness of the base, the structural capacity of the subgrade was found to decrease. This work is continuing but shows that the pavement balance is more than just a research tool and is perhaps more important than is generally appreciated. It could also be a function of the stress-dependent behaviour of the natural materials which was not accounted for in the analyses.

4.4 DRAINAGE

A critical aspect of the use of marginal materials in lightly trafficked roads is the influence of moisture on the materials. The importance of investigating the moisture/strength relationships has already been emphasised in this report. However, even the highest quality materials, when saturated, will produce high pore water pressures under load and thus often have unacceptable shear strengths at critical times. This was clearly illustrated by Road P477 in the Cape Province[67] which had a crushed stone base complying in all respects with traditional TRH 4 requirements (for G4) and yet still failed where high moisture contents resulting from poor drainage occurred.

The rating of the effectiveness of the drainage at each site indicated that the majority of the areas investigated were averagely to poorly drained (28 per cent good; 30 per cent average; 42 per cent poor). The very important aspect of regular and adequate maintenance of the drainage structures which were installed was often overlooked which exacerbated the condition. This is apparently a major *educational need* where the necessity for good maintenance and consequences of not carrying this out regularly and timeously should be clearly demonstrated to the maintenance teams. Many otherwise satisfactory drains were filled with stones and dense vegetation whilst shoulders often had poor cross-falls, were uneven, held windrows from grader maintenance and/or were thickly grassed. This resulted in an infiltration of water adjacent to the pavement and potential weakening of the pavement structure.

Cuttings were particularly troublesome areas and it is recommended that in cuttings, effective sub-surface drains or higher quality materials are utilised in order to reduce the necessity for continual maintenance.

It is also recommended that roads using marginal materials are raised above the natural ground level so that the bottom of the base course is at least 0,75 m in order to facilitate the retention of low moisture contents in the critical pavement layers. If imported layers are to be minimised, side drains should be constructed to limit the potential height of standing water to a depth of 750 mm below the base course.

Emery[63] evaluates the risk of the road reaching a premature terminal condition using probabilistic theory. It is assumed that an unsoaked subgrade CBR is used for the design and the probability of this being exceeded on wetting up is determined. The relationship between CBR strength and moisture content was used to model the variation of E-modulus with moisture content. This was then used in mechanistic analyses to determine the probability of premature failure.

4.5 CONSTRUCTION

The investigation has clearly shown that the achievement of high densities is critical to ensure good performance. Low densities lead to rutting and theoretically have a higher capacity for water ingress and retention, more particle abrasion and degradation and a generally greater propensity for the pavement to deteriorate. The highest density economically and practically achievable should be strived for. It is possible to predict the maximum degree of compaction for any material based on certain standard indicator test results[50] and provided the moisture content is correct[56], this density should be achievable without excessive compaction effort.

If the material has a grading or properties such that a high degree of compaction will be difficult, some form of compaction aid could be employed to assist with the compaction. The strong dependence of strength on density of many of the materials tested has been clearly demonstrated from the laboratory test results.

The benefit of achieving densities higher than those at which the laboratory CBR was determined can be significant. A laboratory CBR of 40 at 95 per cent Mod AASHTO compaction may result in an effective field CBR greatly in excess of 40 if the material is compacted to a density of 98 or 100 per cent Mod AASHTO. The actual increase achieved would be related to the strength/density sensitivity of any particular material.

The determination of density for construction control using nuclear techniques should always be carried out in conjunction with gravimetric moisture content determinations as discussed earlier. Full quality and construction control, possibly more than normally specified, must be carried out.

In order to reduce the effect of moisture ingress and consequent rutting in the outer wheel path, the possibility of differential compaction should be investigated. In this way the centre-line and inner wheel track areas should be compacted to the specified 97 or 98 per cent of modified AASHTO density but the outer wheel path should have additional compaction to try and achieve a density in excess of 100 per cent. Should the achievement of high densities be difficult the outer wheel track area should be concentrated on.

4.6 PERFORMANCE

The investigation has clearly shown that significantly reduced pavement structures using materials which would not normally be considered as base course quality can perform successfully under lightly trafficked conditions in South Africa. The problems of rating the performance of lightly trafficked pavements have been discussed previously . Despite these, the adjusted five point field rating was used and resulted in most of the roads being classified as having a satisfactory to good performance (40 per cent good; 23 per cent good to average; 39 per cent average; 17 per cent average to poor; 4 per cent poor). These roads have all given a number of years service and can all be considered to have been more cost-effective than their unpaved equivalents. When the influence of road user cost and aspects such as dust reduction (the effect on crops and road users), the quality of agricultural produce, etc are considered, these roads are highly beneficial.

The average Present Serviceability Index (PSI) of the roads varied between 1,2 and 3,2 with corresponding values for the Quartercar Index (QI) of 14 to 85. Sixty two per cent of the roads would thus be considered to have a good riding quality for lightly trafficked (Category C) roads, thirty three per cent a warning riding quality and only five per cent to have a poor riding quality[57]. This is considered to be highly satisfactory for roads of this class. With careful maintenance this situation could be significantly improved.

4.7 STRUCTURAL CHARACTERISTICS

It is interesting to note that nearly all of the roads investigated so far are structurally sound. The superposition of DCP adequacy curves (for a future 10 000 E80's, significantly more than the design traffic of most of the roads) on the redefined layer strength diagrams[72,73] indicates that in every case the shear strengths of the pavement layers are adequate and no structural problems with the pavement should be expected provided that the roads do not wet up significantly. All but about 9 of the roads were structurally capable of carrying over 50 000 E80,s and many could even carry over 500 000 E80's in their present moisture conditions.

The relationships used for the DCP adequacy curves are of course primarily intended for well balanced pavement structures. It should be noted that ten per cent of the roads investigated were classified as well-balanced (29 per cent were poorly balanced) and the use of the adequacy curves is thus only an indication of their potential carrying capacity.

Although the shear strengths of the layers within the pavements are apparently adequate, the elastic properties may still allow for high deflections and unless the surfacings are particularly flexible under all environmental conditions, cracking may occur. This will obviously exacerbate the problem as moisture will then have even easier access to the pavement layers.

It is clear from many of the roads that thin structures with low DSN_{800} values (the lowest recorded was 45) can prove satisfactory for lightly trafficked conditions. It is, however, interesting to note that the lowest class design in the TRH4 catalogues[2], if converted to DCP CBR values at its worst condition only has a DSN_{800} of 71 and yet this is theoretically capable of carrying at least $0,2 \times 10^6$ standard axles. This structure assumes, of course, that the pavement is well balanced.

The road with a DSN_{800} of 45 was in Natal and had carried 16 000 E80's over a period of 5 years. The performance was rated as average with some longitudinal cracking in the outer wheel track and a maximum rut depth of 20 mm. It is interesting that the life obtained from the DCP analysis[72] assumes a maximum rut depth of 20 mm. This aspect is discussed in more detail in the following section.

4.8 RELEVANCE OF TRADITIONAL CONCEPTS

The traditional concepts of failure criteria and residual life require some modification or a different form of interpretation for lightly trafficked roads. The standard criteria for identifying trigger conditions (roughness or rut depth)[57] are probably over-conservative for very lightly trafficked roads. It is considered that a rut depth of 20 mm is not necessarily critical for a lightly trafficked road provided that the surfacing is still in an uncracked condition, water will not stand in the ruts and the rutting is not the result of shear-induced strains. Similarly a PSI of 1,5 (warning condition which approximates a QI of about 70 counts/km) on a paved road is significantly better than the average roughness of an equivalent unpaved road (usually 80 to 100 counts/km). Discussion with road users indicates that a poor paved road (provided it is not potholed) is preferable to an average unpaved road. An analysis of the total life-cycle cost of the two alternatives is required to make a decision an any particular road. However, it is important that a data base of the cost of maintaining roads constructed with marginal materials is developed in order to model the life-cycle costs accurately.

The concept of remaining life is also considered to be inappropriate for lightly trafficked roads consisting of natural gravels. Unless water is allowed to accumulate in the pavement structure, most natural gravels increase in strength (stiffen) with time as they densify and remould[74] . The repeated loading of a pavement has two effects on the material:

- densification through compaction;
- a change in the properties of the material, primarily the grading through crushing and abrasion, but possibly the plasticity through the release of fines.

The former process results in stiffening (strain hardening) of the pavement with a concomitant increase in the load bearing capacity whilst the latter results in a decrease of the shear strength.

Unless the latter process predominates (which appears to be most unlikely in typical low volume roads), fatigue failure of granular materials is highly unlikely. The cohesion of granular materials (C) is mostly negligible as it is primarily the result of surface tension or soil suction forces. Very little interparticle bonding occurs without a reasonable percentage of clay minerals. The angle of internal friction (ϕ), however, is strongly dependent on the density and increases as the compaction and particle interlock increases.

The concept of residual life of granular pavements then becomes a dilemma - as the DSN_{800} increases with traffic densification the pavement becomes stronger and less prone to water penetration. The residual structural capacity of a granular pavement layer is a function of the factor of safety of that layer. This is estimated from a model based on the principal stresses, the cohesion and angle of friction and a constant which depends on the moisture conditions[50]. Unless the moisture conditions deteriorate, this factor of safety will increase with densification. If the ruts are filled the new calculated structural capacity of the base layer will thus also be increased.

Rehabilitation of pavements with granular materials should therefore be restricted to levelling courses and rehabilitation of the bituminous surfacing. The filling of ruts with a coarse slurry and the application of a thin bituminous surfacing will result in a road which is probably "better than new". This assumes that the old surfacing is not cracked in such a manner that reflective cracking and similar problems control the life of the pavement.

4.10 RISK

There is no doubt that the risk of premature failure through unexpected environmental conditions will be increased if marginal materials are used. This risk can, however, be managed by ensuring that the construction quality is well controlled and drainage measures are implemented and maintained. Using the risk analysis method described by Emery[30] it is possible to evaluate the probability of the pavement wetting up and hence the probability of premature failure.

An important aspect of increased risk is the public awareness. The public need to be informed of the economic benefits which can be achieved (ie the savings) but at the same time, the increased risk needs to be explained. As well as the public acceptance of this increased risk, political acceptance needs to be obtained.

4.10 VARIABILITY

Traditional material and construction quality criteria are used to ensure that only 5 to 10 per cent of the road reaches a terminal condition at the design life. The use of lighter pavements and poorer materials with a possibly higher variability, will result in an increased proportion of the pavement becoming distressed. Hence more careful construction control and sharper maintenance are essential to ensure good performance.

4.11 MAINTENANCE

The importance of adequate, appropriate and timeous maintenance has been emphasised throughout this document. The maintenance must also be carried out to a high standard. Many cases have been observed where, for example, potholes have been filled with "soil" obtained from the side of the road which is poorly compacted and surfaced with a poorly designed cold premix. Very soon after the maintenance operation, the patches begin slipping and shearing, allowing the ingress of water and exacerbation of the problem in the area.

The maintenance activities should concentrate on sealing of cracks, patching of ravelled areas and potholes, shaping and clearing of the shoulders and maintenance of the drainage measures. New appropriate trigger or intervention standards need to be developed for roads constructed with marginal materials. This type of maintenance can be labour intensive and is a good opportunity to create local employment (and small businesses). The lengthman system, where local residents are appointed to retain a defined section of road to a given standard is very useful in these situations. The development of light maintenance techniques should also be investigated.

Preventative maintenance in terms of timely resealing is also very necessary to ensure that the pavement does not reach a stage where routine maintenance becomes excessive.

4.12 TIME EFFECTS

The sites which were investigated early in the project were revisited during the final stages of the project and the condition compared with the original one to see whether deterioration had occurred. The results of some of the roads are summarised in Table 4.3.

It is clear that some of the roads have hardly deteriorated further whilst others have developed significant ruts and the cracking has become more serious. It is important that this aspect of the investigation is continued in order to evaluate the deterioration process and rates. A comprehensive data base to back this exercise up has been developed.

Table 4.3: Summary of condition of some roads at beginning and end of project

ROAD No	ORIGINAL CONDITION 1989 - 1990			CONDITION DURING REVISIT FEB 1994		
	RUT	CRACK	OTHER	RUT	CRACK	OTHER
467	10	1	Bl/2,	6	3	Good
540	14	5	Bl/2	27	5	Good,SL,EB
804/3*	5	1	Bl/2	3	1	Bl/2, EB
410/0,9	7	1	Bl/3	10	1	Bl, EB
132*	8	5	Bl/4	6	5	Patched, EB
421*	15	5	Shoving	20	5	Failing
518	15	5		12	4	Very good
646	5	1	Bl/4	6	1	Good
804/19	0	1	Bl/2, EB	6	1	Bl/2, EB
804/11	13	3	Bl/5	14	4	EB,Start PH
466/16	10	3	Bl/5	6	3	Good

SL = Stone loss, EB = Edge break, Bl/2 = Bleeding degree 2, PH = Pothole

5. RECOMMENDED MATERIAL REQUIREMENTS FOR BASES

One of the primary objectives of this project was to develop material specifications which would allow the use of lower quality materials than typically specified in bases for lightly trafficked roads with an appropriate degree of confidence. It is considered that this class of road will become increasingly important in future. In order to conserve good quality construction materials which are becoming scarcer and more costly, to minimise road user costs and provide a standard of road which meets the aspirations of the future commuter and township resident, appropriate specifications for the materials and structural design of lightly trafficked paved roads are urgently required.

This project concentrated on the requirements of base materials as it is these which are the most costly and probably the most important components of the pavement as the potential life of the surfacing is highly dependent on the quality and strength properties of the base layer. It is interesting to note that not one of the pavement structures investigated was classified as shallow[13] indicating that the base contributes limited strength to the pavement structure, most of its capacity being mobilised at depth.

Three aspects need to be addressed regarding the performance of the base. These are:

- the bearing capacity of the material under any single applied load;
- the ability of the material to retain that bearing strength with time (ie durability);
- the ability of the material to retain the bearing strength under various environmental influences.

The test results obtained were evaluated with the purpose of fulfilling these needs. A number of multiple correlation analyses were carried out in order to establish which of the individual factors in the data base affected the performance of the pavements in a statistically significant way. A summary of some of the traditionally important material parameters with their correlation coefficients and levels of significance is provided in Appendix C. The parameters not included in the summary are those which were duplicated by other parameters (eg many of the grading parameters) and those with very low correlation coefficients. One hundred and thirteen sets of results from the wheel tracks and another 53 sets of results ostensibly representing the untrafficked road were available for the analysis.

Appendix C shows that seven of the material or climatic parameters investigated correlate significantly (at the 5 per cent level ie there is only a 5 per cent probability that the correlation has arisen by chance) with the performance of the roads. These parameters are the field to optimum moisture content ratio, drainage, traffic, in situ wet density, Weinert N-value, relative compaction and gravimetric moisture. The grading coefficient[75] was the next most significant parameter with a significance of 10 per cent. It is notable that five of the parameters which correlated well were related directly to the moisture content. The compaction and traffic are both results of the analysis technique where the performance of the centre-line area was invariably rated as good whilst the traffic was zero and the compaction was typically lower than the rest of the road. Both correlations were positive indicating that as the traffic and compaction increase, the performance deteriorates. The former direct relationship was anticipated while the latter (in effect an inverse relationship) was somewhat unexpected but can be explained by the analysis method.

In view of these spurious results, a second analysis was carried out in which only the trafficked areas of the road were included (the centre-line results were omitted). The results are summarised in Appendix D. Similar results to those for all the sites were obtained although the significance of all the parameters identified above decreased (mostly a result of the smaller sample size). The best significance of correlation was at the 0,7 per cent level whilst only three parameters had values less than ten per cent. These were the ratio of field/optimum moisture content, the in situ wet density and the drainage rating. The compaction was only significant at the 13 per cent level.

A further analysis on the results of the outer wheel track samples only produced a slight deterioration of the correlations with four properties having significant correlations, the best at a level of 3,2 per cent (Appendix E). The significant correlations at the ten per cent level were in situ wet density, compaction, drainage and ratio of field to optimum moisture contents. The return of the compaction as a significant variable is indicative of the rutting in the outer wheel tracks being associated with the poorer roads.

The correlation analysis of all the test results shows that none of the standard indicator tests has any correlation with performance. As discussed previously, the grading coefficient was significant at a level of 10 per cent and the bar linear shrinkage at 15 per cent. The soaked CBR at Proctor density showed some correlation (17 per cent) but the traditional gradings, plasticity and soaked CBR at Mod AASHTO had correlation coefficients significant at between 20 and 85 per cent levels. The latter result is not unexpected as there are inherent problems with the CBR test and there is the ubiquitous problem of relating the CBR to the various moisture contents at which traffic may have caused damage to the pavement. It is interesting to note that the grading coefficient and bar linear shrinkage were also the best of the indicator tests for predicting the performance of unpaved wearing course materials[75].

The same basic patterns were found for the results from both the wheel tracks and the outer wheel track only.

The fact that the performance of the roads depends primarily on the moisture-related parameters is indicative of the influence of drainage on roads in the longer term. This also indicates that the moisture parameters determined during a one-off investigation of road problems are probably not always indicative of the worst possible conditions. This was confirmed by attempting to correlate plasticity and CBR results combined with drainage/moisture with performance. None of these analyses resulted in significant correlations.

The materials tested had a wide range of values for most of the individual properties as shown in Appendix B. In terms of these results the following observations were made:

Grading: None of the traditional grading parameters correlated significantly with the performance of the roads. The best correlation obtained from the grading parameters was for the grading coefficient[75] which was significant only at the 10 per cent level. It can be concluded that although it was developed for unpaved wearing course materials it appears to be more effective for materials for paved roads than any of the traditional grading parameters. Parameters such as the grading modulus and percentage passing the 0,075 mm sieve had correlation coefficients of 0,01 to 0,08 (between a 29 and 84 per cent probability of arising by chance).

Examples of the lack of correlation between grading parameters and performance are shown in Table 5.1 and graphically in Figures 5.1 to 5.5.

Table 5.1: Poor correlation between grading parameters and performance

Road No	Performance	Age (years)	Percentage passing 0,075 mm	Grading modulus	Traffic
P1418	Fair to good	16	28 - 35	1,65 - 1,83	29 200
P1352	Fair	26	21 - 28	1,29 - 1,38	94 900
P390	Poor	22	15 - 16	2,08 - 2,06	112 240

It is clear that road P1352 has performed particularly well considering its age and traffic compared with road P390 which has a much better particle size distribution (on the fine side of a G4) but has performed poorly under slightly more traffic. It should be noted that the drainage of P390 was poor. Road

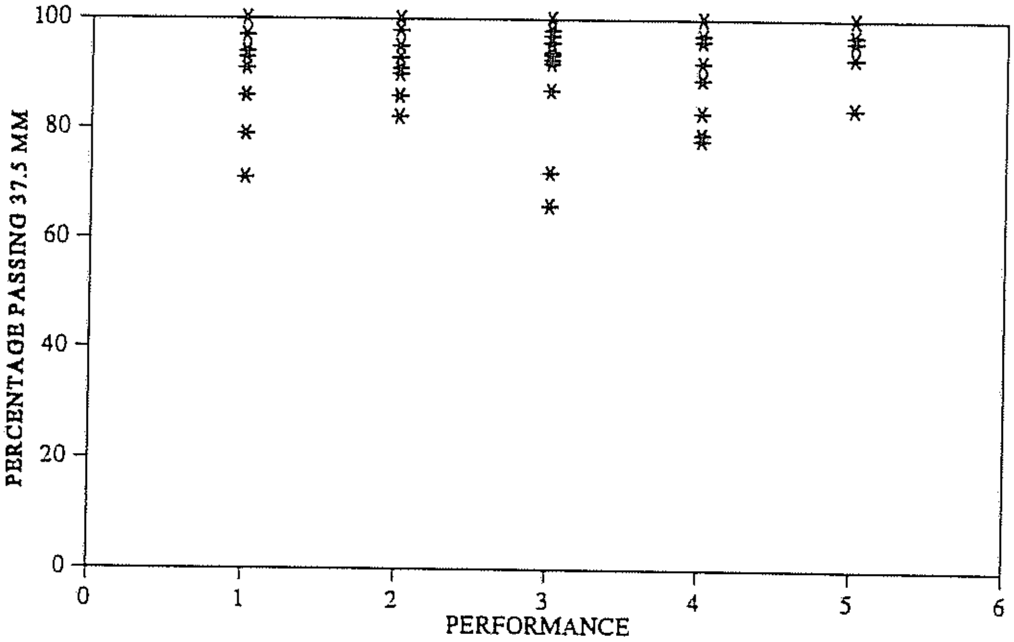

Figure 5.1 Performance versus percentage passing 37.5 mm sieve

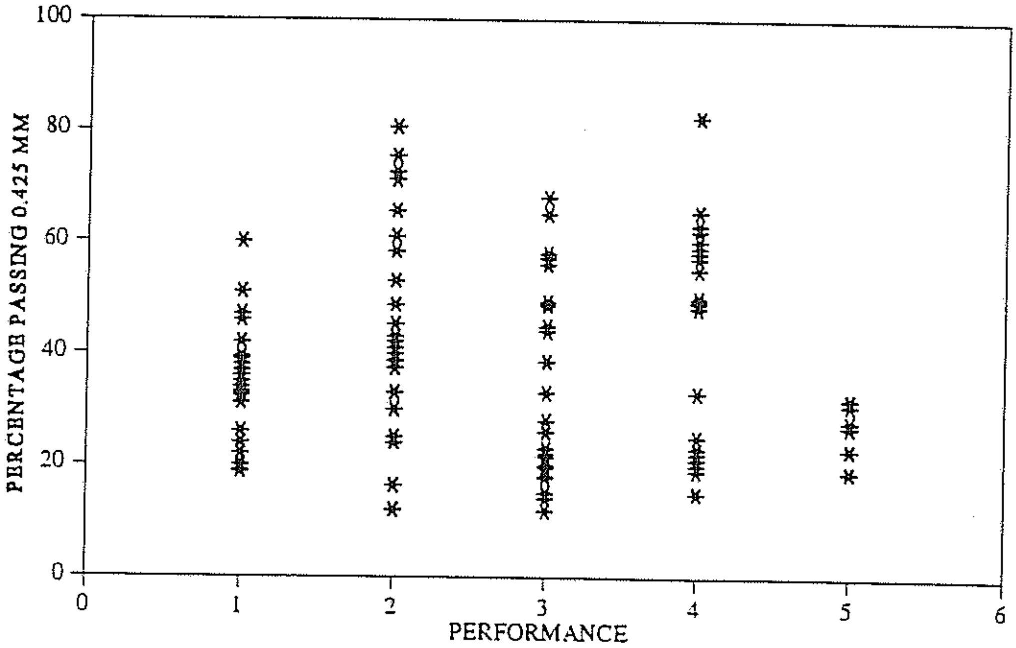

Figure 5.2 Performance versus percentage passing 0.425 mm sieve

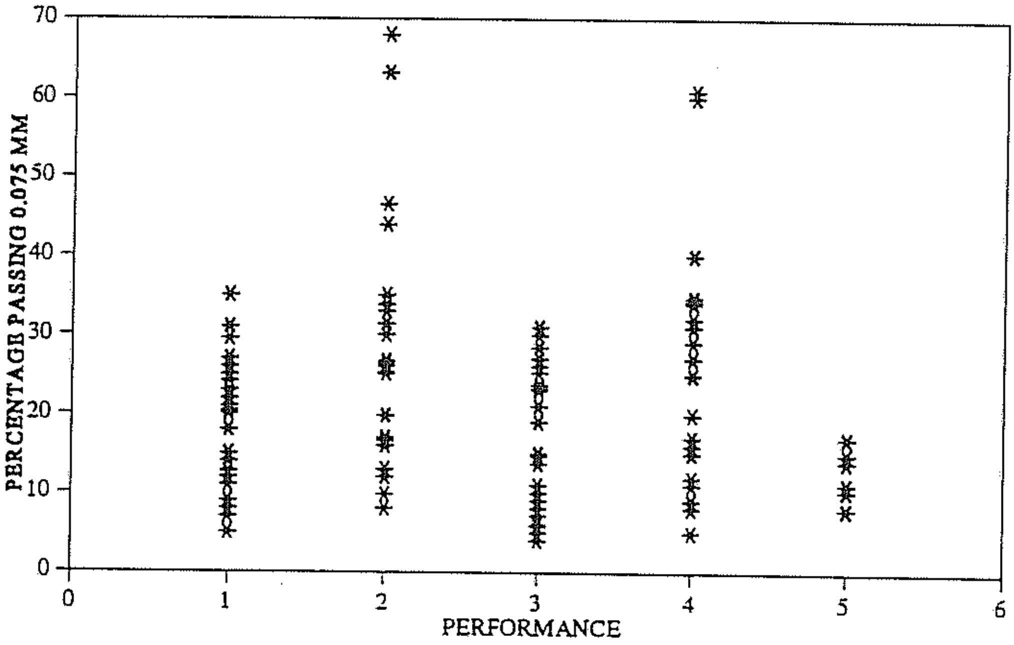

Figure 5.3 Performance versus percentage passing 0.075 mm sieve

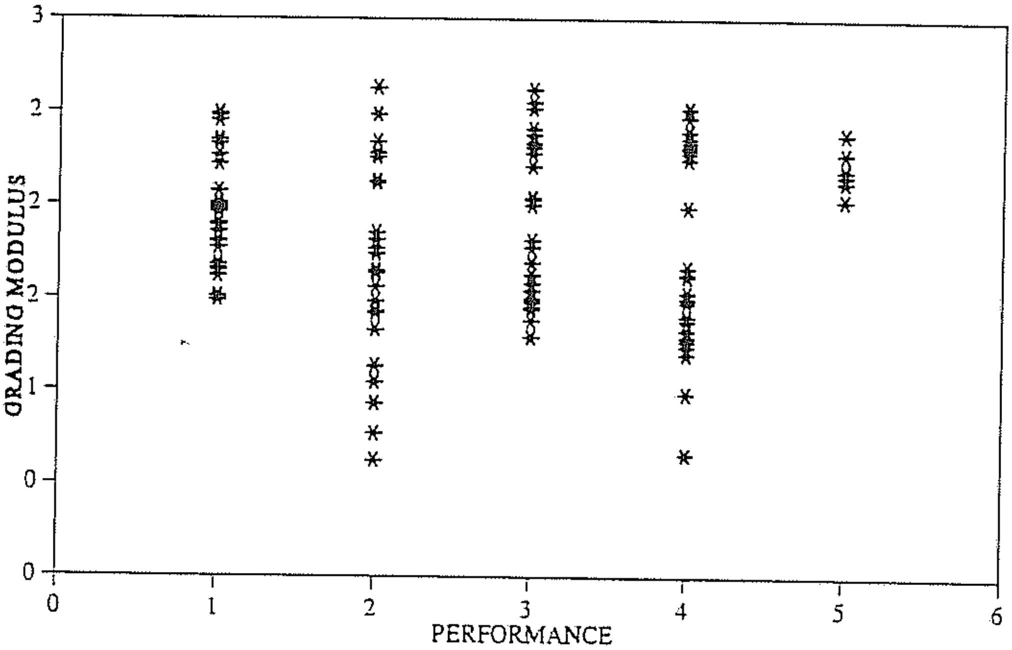

Figure 5.4 Performance versus grading modulus

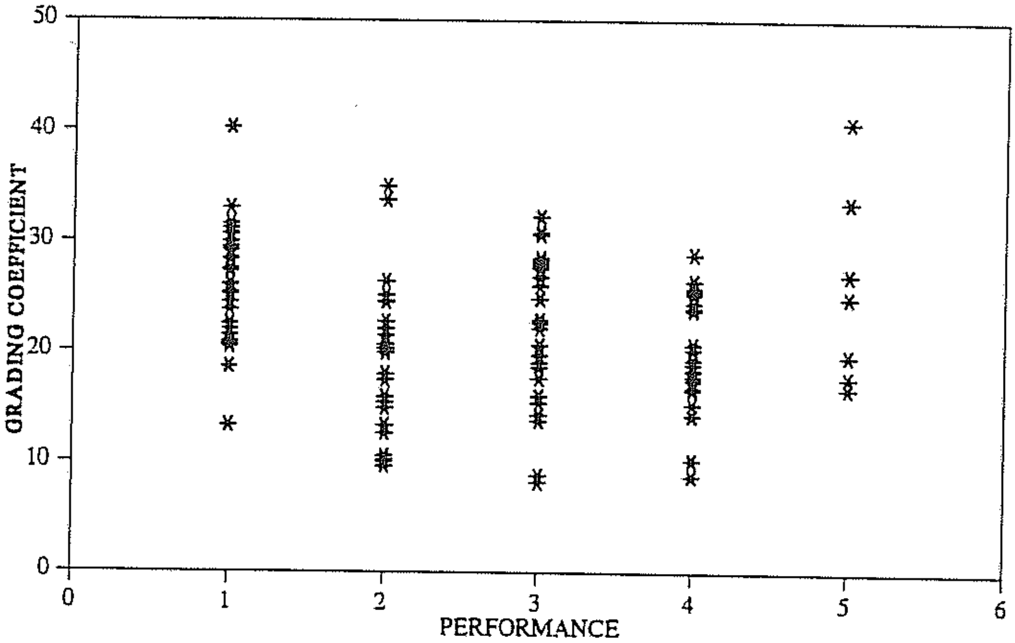

Figure 5.5 **Performance versus grading coefficient**

P1418 has a significantly worse grading than the other two roads but has performed well under the light traffic carried so far.

Plasticity: The plasticity index had correlation coefficients of between 0,016 and 0,070 (significance 51 to 86 per cent) indicating little relationship between the plasticity and performance. Road P477 with almost no plasticity (non-plastic to PI 2) had failed badly whilst Roads P1418 and P2753 with PI's of between 9 and 12 had performed well.

The bar linear shrinkage correlated the best of all the plasticity parameters with a correlation coefficient of 0,115 (significant at the 15 per cent level. For this reason the weighted bar linear shrinkage was correlated against the performance. This resulted in a correlation coefficient of 0,127 (significant at the 11 per cent level. Other combinations of parameters eg weighted plasticity index were evaluated all with no success.

The poor correlations between the plasticity parameters and performance are shown graphically in Figures 5.6 and 5.7.

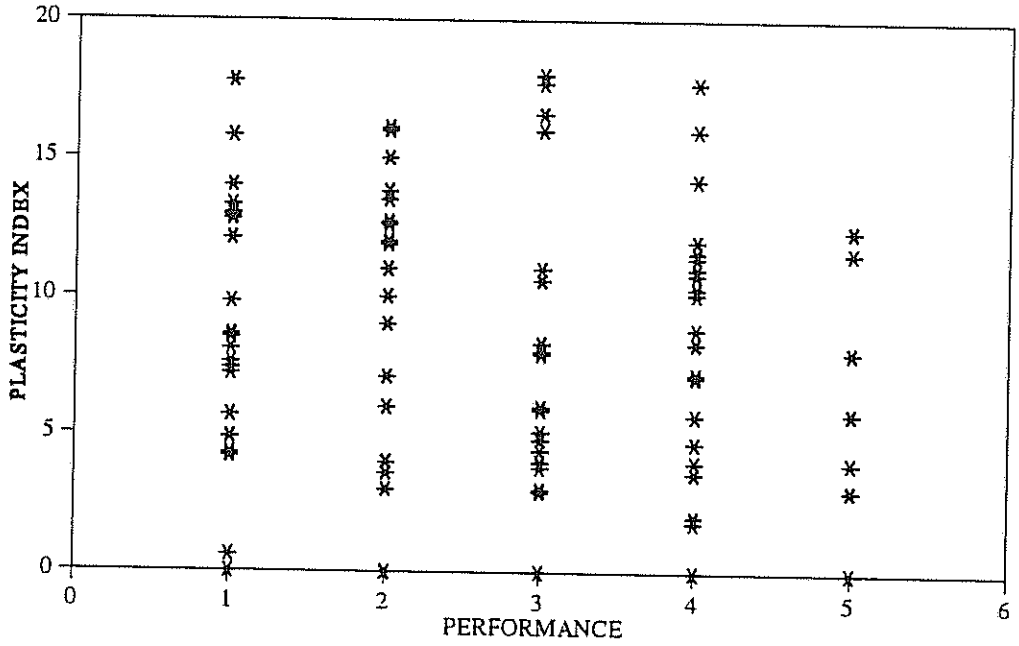

Figure 5.6 Performance versus plasticity index

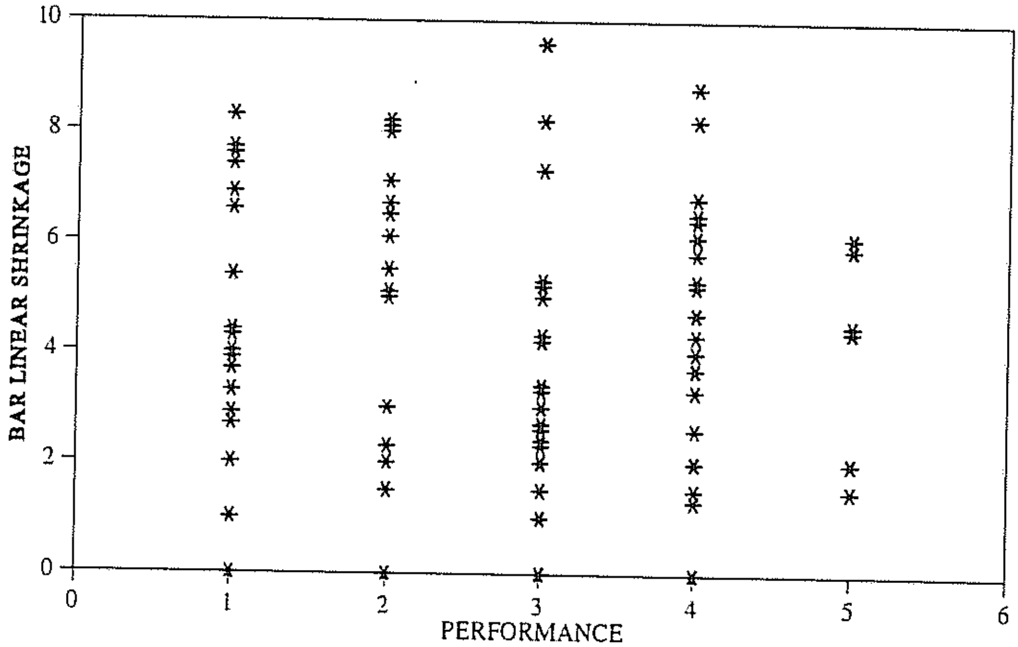

Figure 5.7 Performance versus bar linear shrinkage

Strength: Neither the in situ nor laboratory CBR's of the base material showed significant correlation with performance (negative correlation coefficients of 0,073 to 0,123). The average laboratory soaked CBR at 100 per cent Mod AASHTO density for all the roads was 71 per cent which is marginal by traditional standards. However, the range was 9 to 232 with 63 per cent of the samples having a CBR less than 80 per cent and 36 per cent having values less than 50 per cent. Thirty six per cent of the samples had unsoaked CBR strengths of less than 80 at 100 per cent Mod AASHTO density and 16 per cent had values less than 50 per cent. The average in situ CBR strength (estimated from the DCP) was 105, indicative of the relatively dry nature of the bases with respect to OMC. However, 56 per cent of the in situ CBR's were less than 80 and 28 per cent were less than 50 per cent.

Plots of various strength measurements against the performance are shown in Figures 5.8 to 5.11.

Durability: Neither the fineness product nor the durability mill criteria showed any significant correlation with performance (r= 0,106 to 0,116). Very few of the sections passed the current criteria for durability[64]. Some sites which had performed well had DMI values as high as 500. Plots of the fineness products and Durability Mill Indices against the performance of all the roads are shown in Figures 5.12 and 5.13.

It is thus clear that the performance of marginal quality materials in lightly trafficked roads depends to a far greater extent on the drainage and seasonal moisture variations than on the quality of the material.

Based on the foregoing discussion several different approaches to the analysis were pursued in an attempt to correlate some of the parameters investigated with the performance.

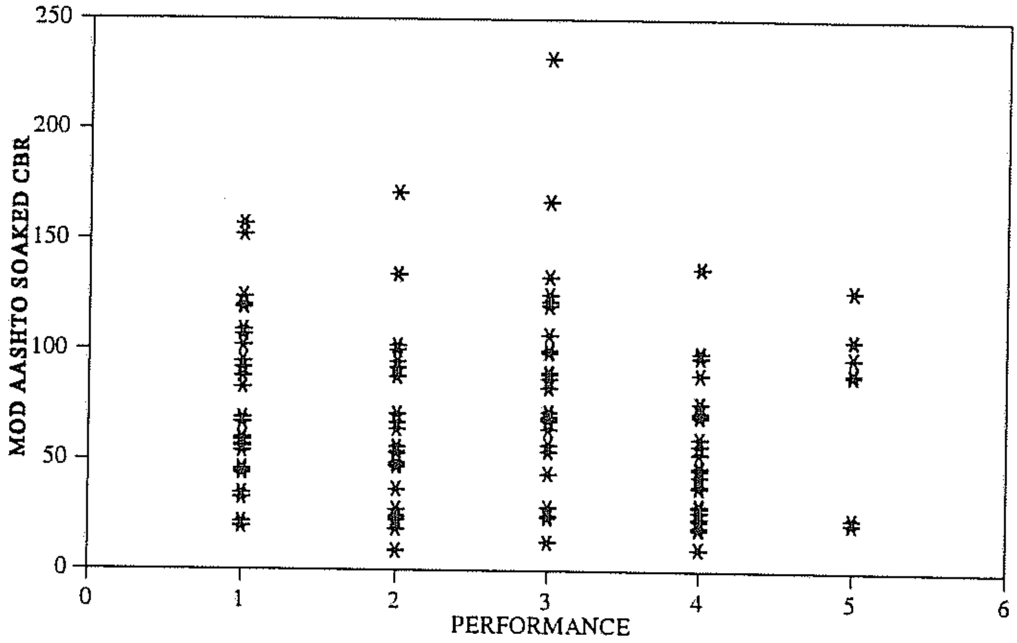

Figure 5.8 Performance versus Mod AASHTO soaked CBR

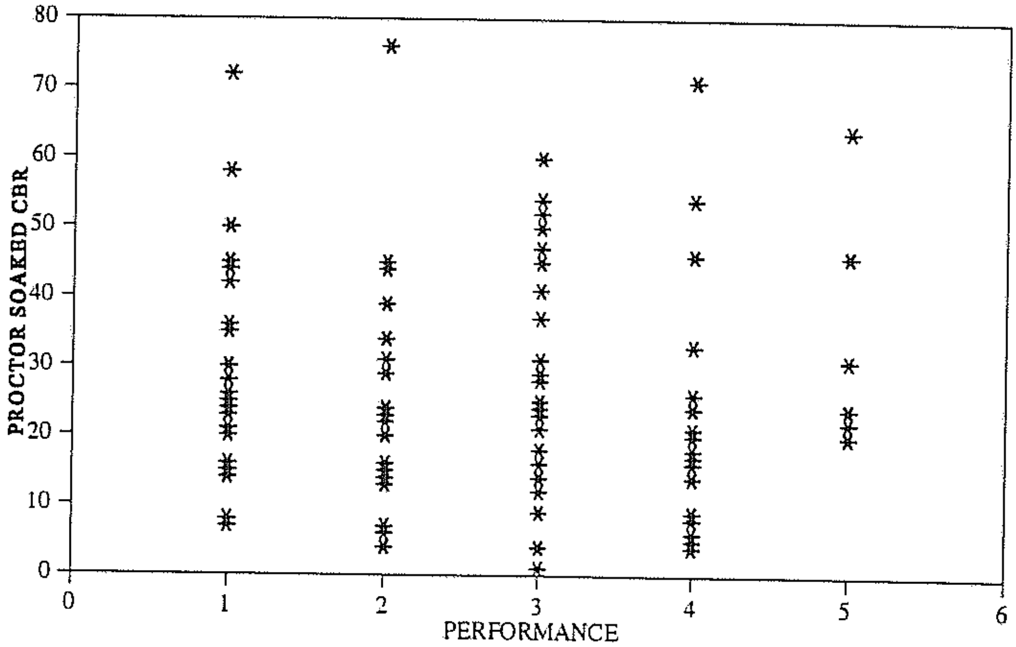

Figure 5.9 Performance versus Proctor soaked CBR

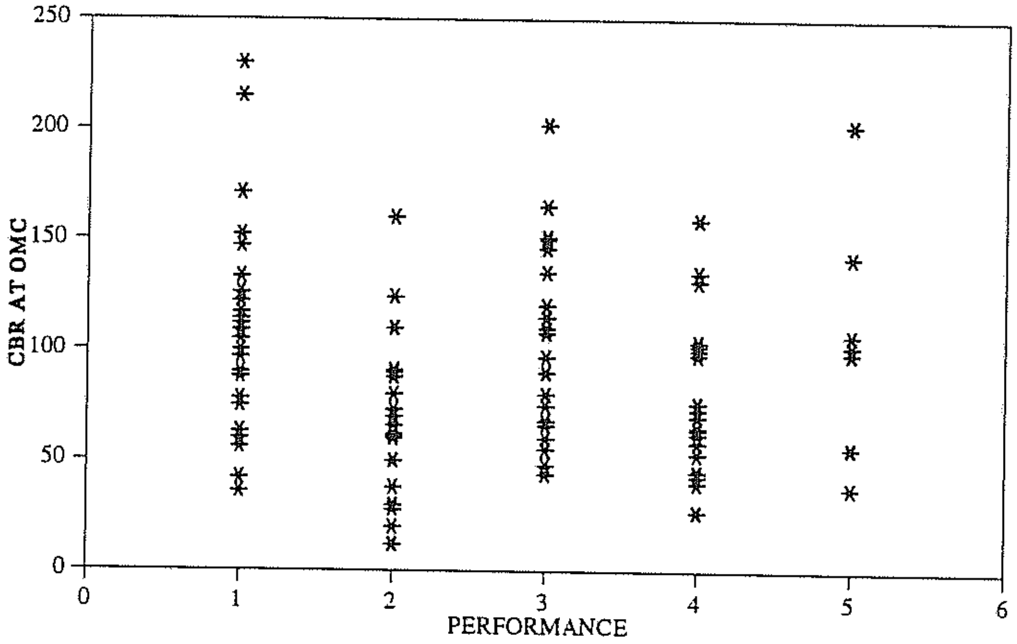

Figure 5.10 Performance versus CBR at OMC

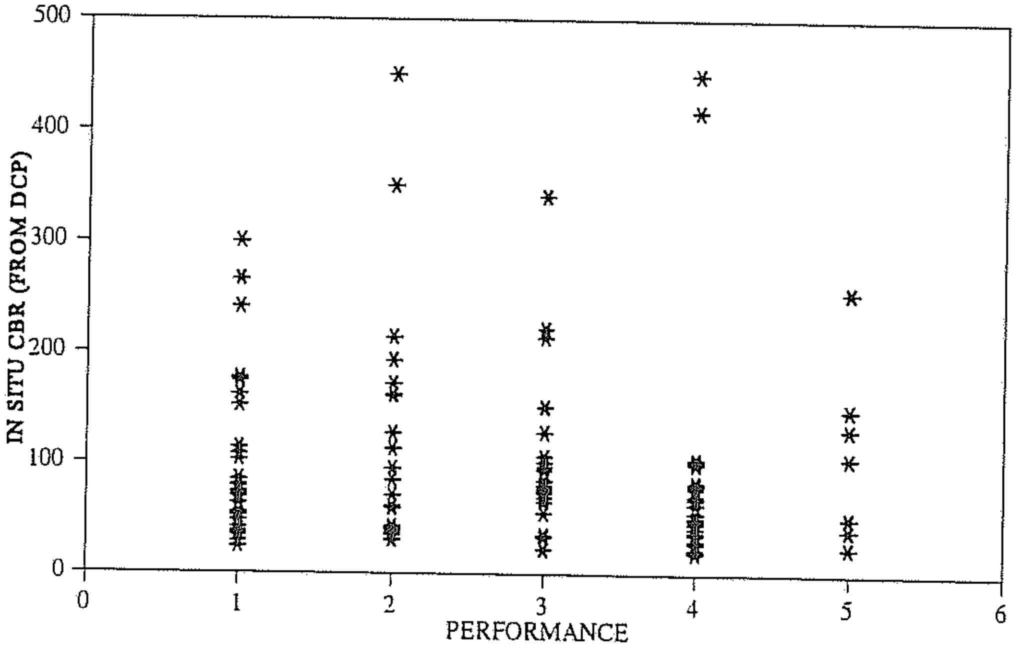

Figure 5.11 Performance versus in-situ CBR (from DCP)

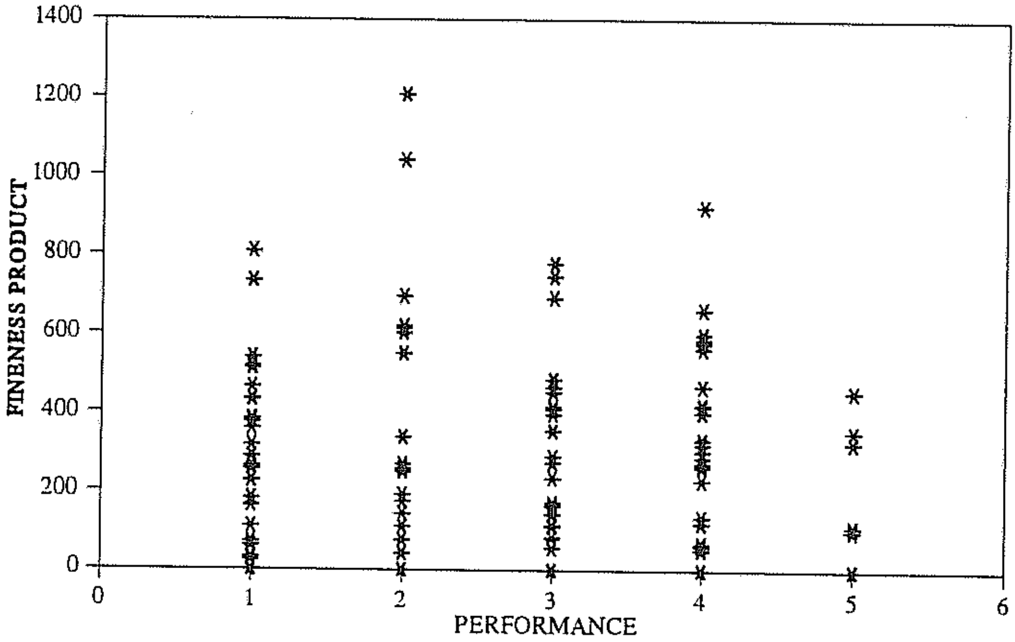

Figure 5.12 Performance versus Fineness Product

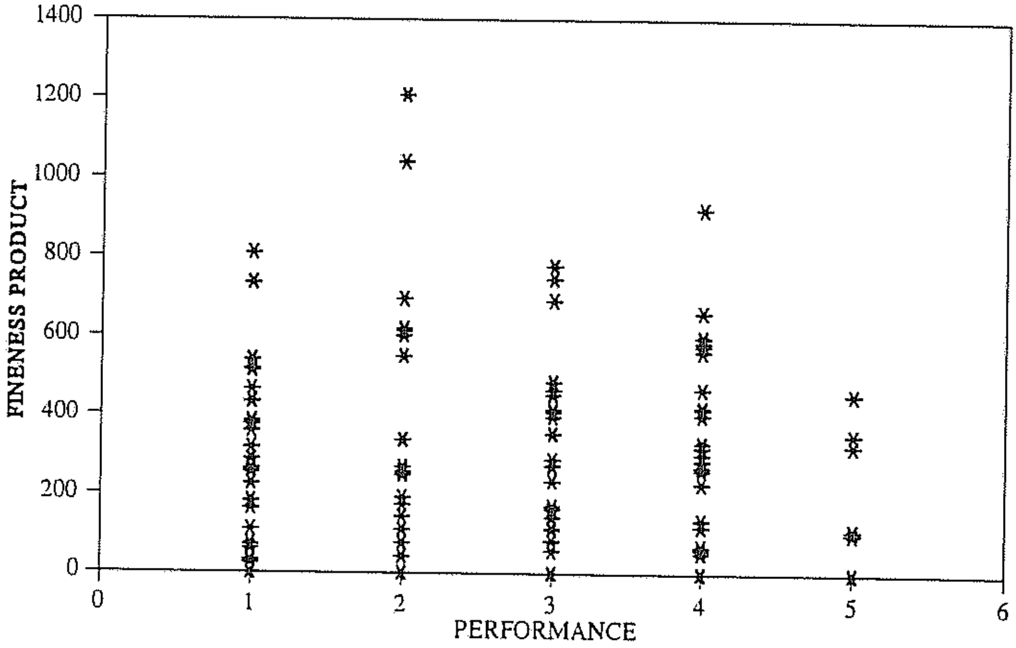

Figure 5.13 Performance versus Durability Mill Index

Drainage sub-sets

The data was split into subsets on the basis of drainage. Analyses similar to those shown in Figures 5.1 to 5.13 were carried out on each of the drainage categories, but no trends could be observed. Typical examples of plots for the in situ base CBR and soaked CBR at 100 per cent Mod AASHTO density in the good drainage subset are shown in figures 5.14 and 5.15.

Material group subsets

The performance of the different material subsets was then analysed to investigate whether there were any trends by material group. It was clearly noted that any material group could give any performance (Figure 5.16) and that the material properties did not correlate significantly with performance within any material group (Figure 5.17 to 5.20).

It was considered imprudent to start combining subsets (eg traffic and drainage) as the sample sizes would then have become too small for meaningful results.

Multiple regression analyses by subsets were carried out but, as was to be expected from the initial correlation matrix, no significant models were obtained.

Finally, the performance was rated as good (ratings 1 to 3) and poor (ratings 4 and 5) and a discriminant analysis was carried out. In this technique, a number of variables are combined to form a model which discriminates between those materials which perform well and those which do not. The results of this analysis did not discriminate the performance on the basis of material parameters.

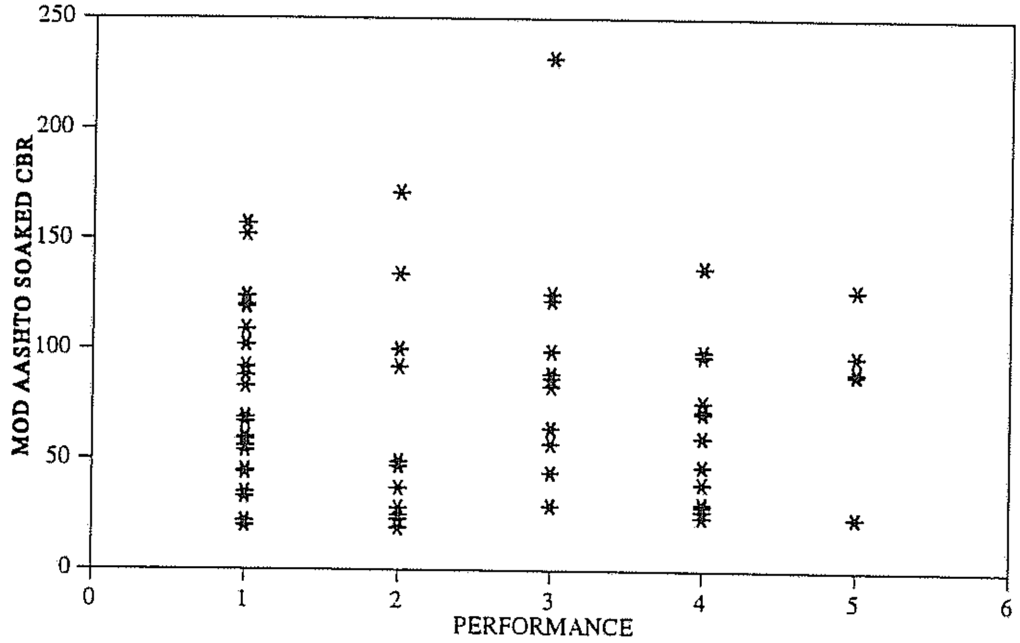

Figure 5.14 Performance versus CBR for roads with good to average drainage

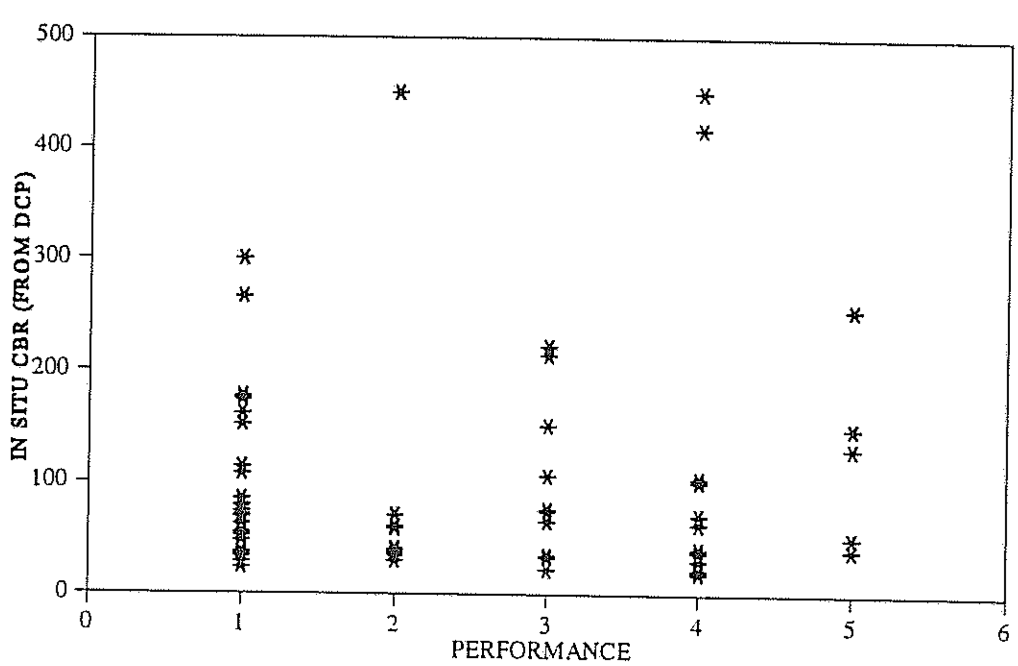

Figure 5.15 Performance versus in situ CBR for roads with good to average drainage

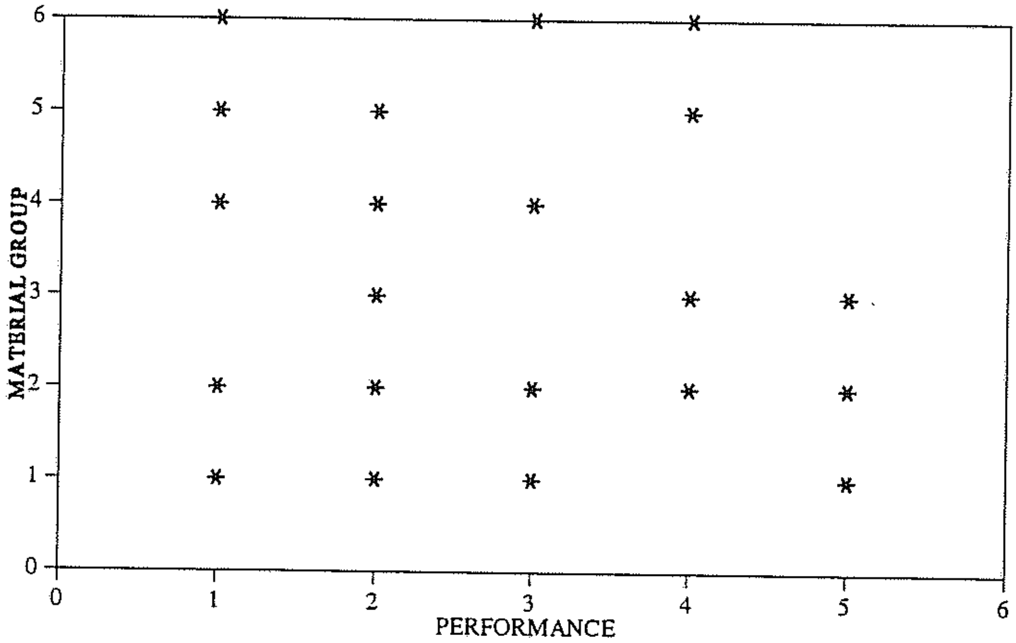

Figure 5.16 Material group versus performance for roads with good to average drainage

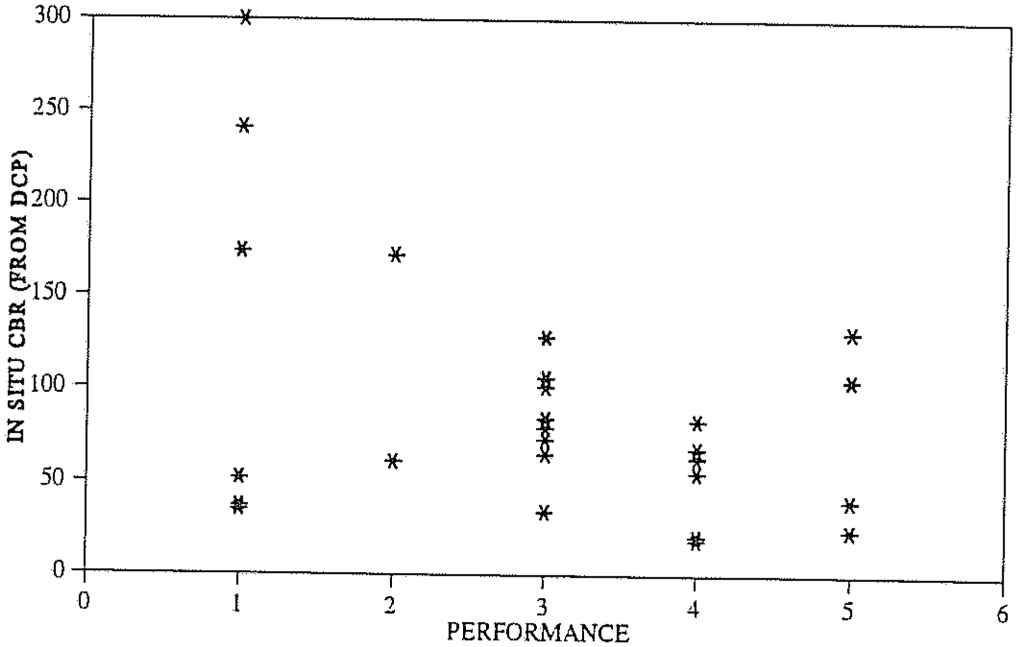

Figure 5.17 Performance versus in situ CBR for acid crystalline materials

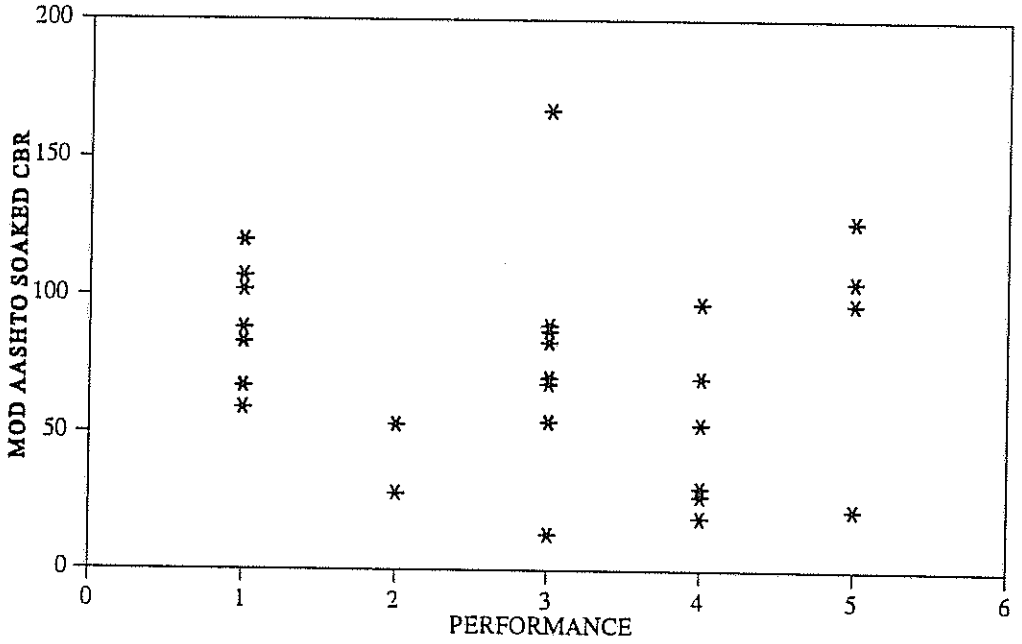

Figure 5.18 Performance versus Mod AASHTO CBR for acid crystalline materials

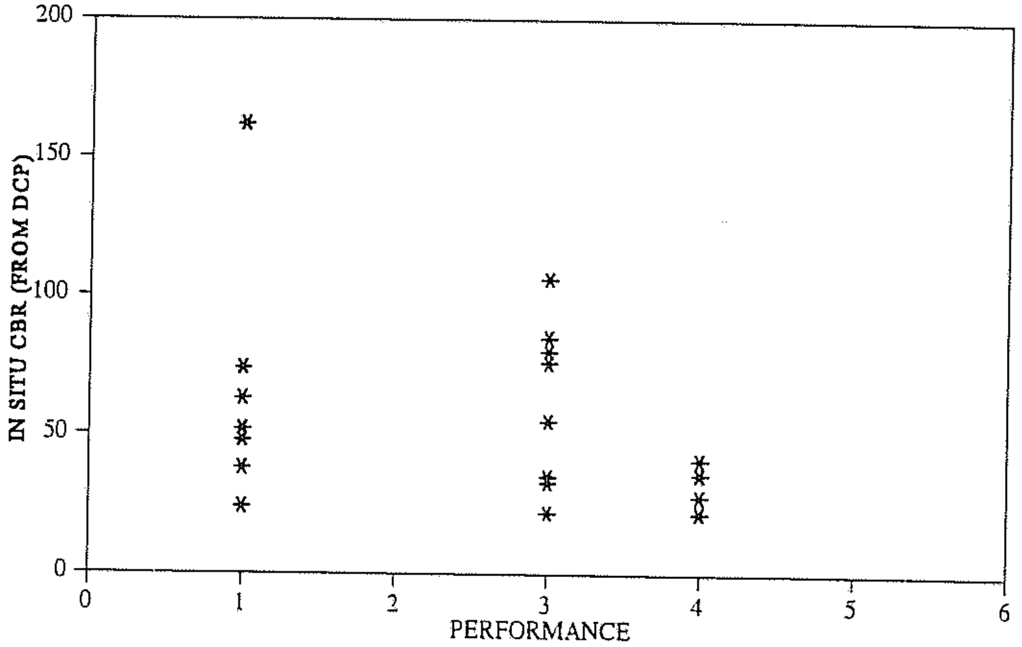

Figure 5.19 Performance versus in situ CBR for pedocretes

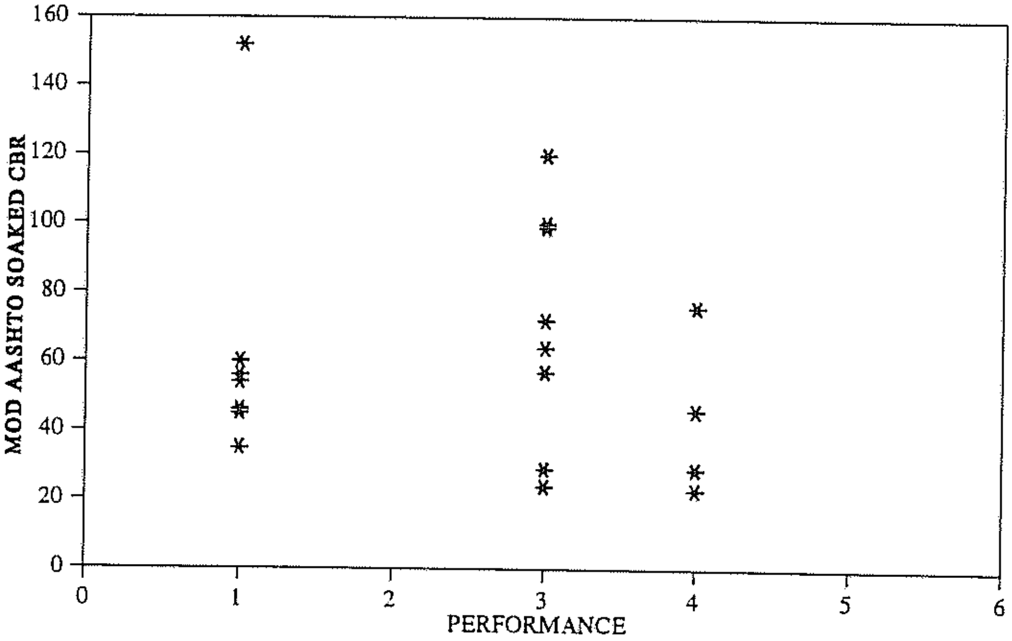

Figure 5.20 Performance versus Mod AASHTO CBR for pedocretes

6. RECOMMENDATIONS

The design of lightly trafficked roads using marginal materials in the base course needs to follow a holistic approach with attention being paid to compatibility between the pavement structure, the materials used, the type of surfacing, construction processes and control and the associated drainage.

Many of the traditional specifications and philosophies applicable to roads appear to be deficient when marginal materials are used in thin pavement structures. The application of relatively few standard axle repetitions apparently results in different physico-mechanical processes to those occurring in more heavily trafficked pavements. Existing structural analysis techniques for roads are considered to be inaccurate for low volume or lightly trafficked roads and appropriate modifications need to be developed. The data collected during this project will provide a suitable data base to allow a re-evaluation of design procedures specifically for lightly trafficked roads.

It is extremely important that the quality of materials used during construction and the construction process is well controlled, perhaps even more so than for roads constructed of traditional processed materials where the material variation is potentially far less. Densities, for instance, must be achieved in the road to ensure successful performance. The question of material variability raises a number of important points, the main one being the effect of variable optimum moisture contents on routine compaction. It has been repeatedly noted that certain areas with significantly different OMC's are often under-compacted in comparison with adjacent areas on some roads. This may be due to the moisture content selected for compaction on the job lot being too high or too low for those materials in isolated areas and under the standard compaction, the specified densities are not obtained in these areas.

Problems are encountered with the comparison of test results from various places within a pavement and even more so between borrow pits and roads because of the lack of data concerning material and test variation, repeatability and reproducibility. It is strongly recommended that values for these parameters are obtained in order to evaluate differences statistically with any degree of confidence.

The success of this type of project depends on an accurate assessment of the traffic. It is thus imperative that accurate traffic data is used in the analyses. Currently, very little good information regarding the type, axle loads, seasonal variation and effects of traffic on low volume roads is available. This deficiency needs to be addressed urgently.

A similar problem exists with performance classification. Current methods of evaluating performance and trigger conditions are inappropriate for low volume roads. Research into other/improved mechanisms for performance evaluation is necessary. It is recommended that this should involve the total cost of maintaining the road to a prescribed standard taking into account preventative maintenance.

The strength of the material in the base at the prevailing environmental conditions is the major material parameter affecting the performance of low volume paved roads. However, in addition to determining the absolute strength of a material, it is important to evaluate the strength/moisture/density relationships. It is recommended that the moisture and density dependence of the materials is evaluated carefully so that a full understanding of the potential performance of the material under the possible moisture conditions which may occur, is obtained. This is especially true for the density as this is an area which is often not controlled to the required limits in these roads.

The moisture contents measured in the field were mostly considerably higher than those predicted by the currently available models which were developed on traditional provincial roads. Methods of correcting these models for light pavement structures with marginal materials need to be developed. This needs to be related to the seasonal variation in moisture and strength in pavements particularly in the outer wheel track areas of roads.

The use of flexible, durable surfacings is recommended in order to accommodate high deflections, provide a good adhesion to potentially soft bases and large stones and to retard the ageing process. This needs to be associated with a high degree of appropriate and timeous maintenance of the road surface and drainage structures.

It is recommended that follow up investigations are carried out to evaluate the seasonal variation of moisture and its effect on the in situ strengths and moduli of selected roads. At the same time the long term pavement performance of light pavement structures can be monitored and evaluated. The large data base has a lot of potentially useful results and it is recommended that further development of this data is carried out.

Despite the large data base it has not been possible to isolate any particular test or material parameter which will predict the performance of paved roads. It is thus recommended that provided the drainage is carefully designed and controlled, the pavement is raised above the general ground level or potential standing water level (at least 0,75 m below the bottom of the base course), all the pavement layers are compacted to as high a density as possible (between 97 and 106 per cent Mod AASHTO) and the pavement is adequately maintained, an in situ CBR of 60 will be adequate for most low volume road pavements. This would be for traffic up to 100 000 E80's.

7. CONCLUSIONS

Many roads specifically designed for light traffic volumes have been constructed in South Africa using marginal materials and reduced pavement structures. Most of these have provided an adequate level of service for the specific situation with a number of additional advantages. These include conserving gravel wearing course materials, reducing maintenance costs compared with the unpaved alternative, reducing vehicle operating costs and providing a sound structure for future upgrading of the road.

In order to optimise the use of marginal materials a holistic approach to pavement design, material selection, construction and maintenance is necessary. This will allow thin pavement structures to be constructed using materials with properties outside the traditional specifications.

An analysis of data collected from 57 different sections of lightly trafficked road constructed with marginal base course materials in South Africa has shown that the properties of the materials used in the roads have little influence on the performance of the pavement structures in comparison with the effects of inadequate drainage. The prevalence of excessive moisture within the pavement structures results in problems almost irrespective of the quality of the materials within the pavements.

In terms of the specification of material properties for lightly trafficked roads, extensive analysis of the large data base compiled has shown that no material property will predict the performance of the road, without taking into account the drainage. In situ CBR values of less than 30 have performed well whilst other roads with in situ CBR values in excess of 400 have performed poorly. Provided the pavement is well drained, well constructed and properly maintained, an in situ CBR value of 60 at not less than 98 % Mod AASHTO density will prove adequate for roads carrying up to at least 100 000 E80's.

The primary requirements of satisfactory low volume roads are that the pavement is well drained, the construction quality is very tightly controlled, high compaction standards are achieved in all layers and the road is timeously and effectively maintained.

A conclusion which can be drawn from this project is that significantly more degradation can be tolerated in lightly trafficked roads than is permissible in standard designs without undue deterioration of the road occurring. No durability requirements are necessary for lightly trafficked roads. However, should the traffic increase or the life of the road be extended without upgrading, overstressing of the structure can be expected.

8. REFERENCES

1 SOUTH AFRICAN BITUMEN AND TAR ASSOCIATION. Social development issues: road needs in developing areas. SABITA Project Report ARP/J, SABITA, Cape Town, 1993.

2 COMMITTEE OF STATE ROAD AUTHORITIES. Structural design of interurban and rural road pavements. TRH 4, CSRA, Pretoria, 1985.

3 COMMITTEE OF STATE ROAD AUTHORITIES. Guidelines for road construction materials. TRH 14, CSRA, Pretoria, 1985.

4 COMMITTEE OF STATE ROAD AUTHORITIES. Standard specifications for Road and Bridge Works. CSRA, Pretoria, 1987.

5 WRIGHT, B, EMERY SJ, WESSELS, M AND WOLFF, H. Appropriate standards for effective bituminous seals: cost comparisons of paved and unpaved roads. Technical note RDT/1/90, DRTT/SABITA, Pretoria, 1990.

6 TRANSVAAL PROVINCIAL ADMINISTRATION. Standard specifications for road and bridge works. TPA, Pretoria, 1973.

7 VAN DER WALT, N. Materiale Handleiding. Orange Free State Roads Dept. Manual, Bloemfontein, 1973

8 PROVINCIAL ADMINISTRATION OF THE CAPE OF GOOD HOPE. Materials Manual, Department of roads, Provincial Administration of the Cape of Good Hope, Cape Town, 1983.

9 NATAL PROVINCIAL ADMINISTRATION. Materials Manual. NPA, Pietermaritzburg, Natal, ca 1985.

10 PATERSON, WDO AND MARAIS, GP. An evaluation of low standard pavements in the south western Transvaal. The Civil Engineer in South Africa, September 1980, pp 233-238.

11 NETTERBERG F AND PAIGE-GREEN, P. Pavement materials for low volume roads in southern Africa: A review. Proc Annual Transportation Convention, Vol 2D, SAICE, Pretoria, 1988.

12 RICHARDS, RG. Proceedings of a colloquium on lightly trafficked roads held at NITRR on 25 January 1977. NITRR Report RP/1/77, NITRR, CSIR, Pretoria, 1977.

13 KLEYN, EG AND VAN ZYL, GD. Application of the dynamic cone penetrometer (DCP) to light pavement design. Report L4/87, Transvaal Roads Department, Pretoria, 1987.

14 WOLFF, H, VAN ZYL, GD, PAIGE-GREEN, P AND EMERY, SJ. The development of a structural design catalogue for low volume roads. Proc Ann Transp Convention, Vol 3B, Pretoria, 1993.

15 DEPARTMENT OF TRANSPORT. Towards appropriate standards for rural roads: Discussion document. Research Report RR 92/466/1, Department of Transport, Pretoria, 1993.

16 BOTSWANA MINISTRY OF WORKS AND COMMUNICATIONS. Road design manual. Ministry of Works and Communications, Gaborone, Botswana, 1982.

17 NETTERBERG, F. Calcrete in road construction, NITRR Bulletin 10, CSIR, Pretoria, 1971.

18 SPOTTISWOODE, BH. Design and construction of a low-cost road at the West coast. Proceedings Annual Transportation Convention, Volume 3, August 1982.

19 STRAUSS, PJ AND HUGO, F. Innovations in design and construction of a low volume road on windblown sands. Transport Res Record, No 641, 1977, pp 52-61.

20 JOUBERT, G. Paaie in die operasionele gebied. Proceedings Symp Low Volume Roads, Windhoek, SAICE/SARF, 1982.

21 MAREE, JP. Die werkverrigting van ligte padplaveisels in die westelike Oranje-Vrystaat. MIng Skripsie, Universiteit van Pretoria, 1992.

22 TRANSVAAL PROVINCIAL ADMINISTRATION. Pavement design manual. Manual Li/78, Transvaal Roads Department, TPA, Pretoria, 1978

23 MEYER, AH AND HUDSON, WR. Preliminary guidelines for material requirements of low volume roads. Proc 4th Int Conf Low Volume Roads, Transportation Research Record, No 1106, Transportation Research Board, Washington, DC, 1987, pp 260-267.

24 PAIGE-GREEN, P AND NETTERBERG, F. Requirements and properties of wearing course materials for unpaved roads in relation to their performance. Transportation Research Record, 1106 (Vol 1), Transportation Research Board, Washington, 1987, pp 208-214.

25 WEINERT, HH. The natural road construction materials of southern Africa. H and R Academica, Cape Town, 1980.

26 PAIGE-GREEN, P. Tillite and other strata of the Dwyka Formation. in Engineering geology of southern Africa: Vol 3. (Edited by ABA Brink), Building Publications, Pretoria, 1983.

27 PAIGE-GREEN, P. Innovative application and modifying of local materials for road building. Interim Report IR 93/286/1, Department of Transport, Pretoria, 1994.

28 SCHULZE, BR. The climates of South Africa according to the classifications of Köppen and Thornthwaite. S A Geographical Journal, V 29, 1947, pp 32-42

29 SCHULZE, B R. The climate of South Africa according to Thornthwaite's Rational Classification. S A Geographical Journal, V 40, Dec 1958, pp31-53.

30 EMERY, SJ. The prediction of moisture content in untreated pavement layers and an application to design in southern Africa. Bulletin 20, DRTT, CSIR, Pretoria, 1992.

31 WEATHER BUREAU. Climate of South Africa: Climate statistics up to 1984. Report WB40, Department of Environmental Affairs, Pretoria, 1986.

32 PAIGE-GREEN, P. The use of marginal base course materials in some roads in the Orange Free State. Interim Report IR 88/033/1, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

33 PAIGE-GREEN, P. The use of marginal base course materials in three low volume roads in the Transvaal. Interim Report IR 88/033/2, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

34 PAIGE-GREEN, P. The use of marginal base course materials in three low volume roads in the western Transvaal. Interim Report IR 88/033/3, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

35 PAIGE-GREEN, P. The use of marginal base course materials in some low volume roads in the Transvaal. Interim Report IR 88/033/4, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

36 PAIGE-GREEN, P. The use of marginal base course materials in three low volume roads in the eastern Transvaal. Interim Report IR 91/201/1, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

37 PAIGE-GREEN, P. The use of marginal base course materials in three sections of low volume road in the eastern and western Transvaal. Interim Report IR 91/201/2, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

38 PAIGE-GREEN, P. The use of marginal base course materials in three sections of low volume road in the western Transvaal. Interim Report IR 91/201/3, Division of Roads and Transport Technology, CSIR, Pretoria, 1992.

39 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in the Cape Province: Part 1. Interim Report IR 91/201/5, Division of Roads and Transport Technology, CSIR, Pretoria, 1993.

40 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in the Cape Province: Part 2. Interim Report IR 91/201/6, Division of Roads and Transport Technology, CSIR, Pretoria, 1993.

41 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in the Cape Province: Part 3. Interim Report IR 91/201/7, Division of Roads and Transport Technology, CSIR, Pretoria, 1993.

42 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in Natal: Part 1. Interim Report IR 91/201/9, Division of Roads and Transport Technology, CSIR, Pretoria, 1994.

43 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in Natal: Part 2. Interim Report IR 91/201/10, Division of Roads and Transport Technology, CSIR, Pretoria, 1994.

44 PAIGE-GREEN, P AND BAM, A. The evaluation of marginal base course materials in low volume roads in Natal: Part 3. Interim Report IR 91/201/11, Division of Roads and Transport Technology, CSIR, Pretoria, 1994.

45 BOSMAN, J. Goederevloei op Suid Afrikaanse paaie en die invloed daarvan op padbeplanning en ontwerp. PhD Thesis, University of Pretoria, Pretoria, 1988.

46 VAN ZYL, GD, BOSMAN, J, BESTER, PJ AND VORSTER, B. Characteristics of heavy vehicles on Transvaal roads. Report, DPVT C/235, DRTT, CSIR, Pretoria, 1993.

47 BESTER, PJ. Personal communication, 1994.

48 KLEYN, EG. Aspekte van plaveiselevaluering en -ontwerp soos bepaal met behulp van die dinamiese kegelpenetrometer. M Ing verhandeling, Universiteit van Pretoria, 1984.

49 DE BEER, M. Personal communication, 1994.

50 MAREE, JH. Aspekte van die ontwerp en gedrag van padplaveisels met korrelmateriaalkroonlae. PhD thesis, Universiteit van Pretoria, 1982.

51 COMMITTEE OF STATE ROAD AUTHORITIES. Nomenclature and methods of describing the condition of asphalt pavements. Technical Recommendation for Highways (TRH) 6, CSRA, Pretoria, 1985.

52 PAIGE-GREEN P AND HADDOW, P. A comparison between gravimetric moisture determinations and those from a nuclear density meter. Proc Annual Transportation Convention, Vol 2C, Pretoria, 1992.

53 JENNINGS, JE, BRINK, ABA AND WILLIAMS, AAB. Revised guide to soil profiling for civil engineering purposes in southern Africa. The Civil Engineer in South Africa, 15, 1, 1973, pp 3-12.

54 COMMITTEE OF STATE ROAD AUTHORITIES. Standard methods of testing road construction materials. Technical Methods for Highways (TMH) 1, CSRA, Pretoria, 1987.

55 SAMPSON, L R AND NETTERBERG, F. The durability mill: A new performance-related durability test for base course aggregates. The Civil Engineer in South Africa, September, 1989, pp 287-294.

56 SEMMELINK, CJ, GROENEWALD, M AND DU PLESSIS, EG. The optimization of compaction specifications for different pavement layers. Project Report PR 91/199. Department of Transport, Pretoria, 1994.

57 COMMITTEE OF STATE ROAD AUTHORITIES. Bituminous pavement rehabilitation design. Technical Recommendation for Highways (TRH) 12 (Draft), NITRR, CSIR, Pretoria, 1986.

58 COMMITTEE OF STATE ROAD AUTHORITIES. Cementitious stabilizers in road construction, Technical Recommendations for Highways (TRH) 13, CSRA, Pretoria, 1986.

59 PAIGE-GREEN, P, NETTERBERG, F AND SAMPSON, LR. The carbonation of chemically stabilised road construction materials: guide to its avoidance, Project Report PR 89/146/1, Department of Transport, Pretoria, 1990.

60 SEMMELINK, C. The effect of material properties on the compatibility of some untreated roadbuilding materials. PhD Thesis, University of Pretoria, 1991.

61 VAN ZYL, GD AND KLEYN, EG. Beleid en riglyne vir die betering van ligte plaveisels. Verslag LO 2/84, Transvaal Roads Department, Directorate Materials, 1984.

62 PAIGE-GREEN, P. Innovative application and modification of local materials for road building: Interim report. Interim Report, IR 93/286/1, Department of Transport, Pretoria, 1994.

63 EMERY, S J. Prediction of moisture content for use in road design. PhD thesis, University of Witwatersrand, Johannesburg, 1985.

64 SAMPSON, LR. Recommended durability tests and specification limits for base course aggregates for road construction. Project Report PR/88/032:1102, South African Roads Board, Pretoria, 1990.

65 PAIGE-GREEN, P. Interim recommendations on the use of marginal base course materials in low volume roads. Interim Report IR 88/033/5, Division of Roads and Transport Technology, CSIR, Pretoria, 1991.

66 PAIGE-GREEN, P. Interim recommendations on the use of marginal base course materials in low volume roads in the Transvaal. Interim Report IR 91/201/4, Division of Roads and Transport Technology, CSIR, Pretoria, 1992.

67 PAIGE-GREEN, P. Interim recommendations on the use of marginal base course materials in low volume roads in the Cape Province. Interim Report IR 91/201/8, Division of Roads and Transport Technology, CSIR, Pretoria, 1993.

68 PAIGE-GREEN, P. Interim recommendations on the use of marginal base course materials in low volume roads in Natal. Interim Report IR 91/201/12, Division of Roads and Transport Technology, CSIR, Pretoria, 1994.

69 SOUTH AFRICAN BITUMEN AND TAR ASSOCIATION (SABITA). Appropriate Standards for Bituminous Surfacings for low volume roads, SABITA, Cape Town, 1992

70 PARTRIDGE, TC. Some aspects of the water table in South Africa. Proc 4th Reg Conf Africa Soil Mech Foundn Engng, Vol 1, Cape Town, 1967, pp 41-44.

71 P PAIGE-GREEN, COETZER, K, GROENEWALD, M, VAN HUYSSTEEN, S AND LEA, J. Appropriate specifications for use of locally available materials for road building in rural areas. Interim Report IR 93/263/1, Department of Transport, Pretoria, 1994.

72 JORDAAN, GJ. Analysis and development of some pavement rehabilitation design methods. PhD Thesis, University of Pretoria, Pretoria, 1988.

73 KLEYN, EG AND SAVAGE, PF. The application of the pavement DCP to determine the bearing properties and performance of road pavements. Proceedings of the International Symposium on Bearing Capacity of Roads and Airfields. Trondheim, Norway, 1982.

74 MARAIS, GP, MAREE, JH AND KLEYN, EG. The impact of HVS testing on Transvaal pavement design. Proc Ann Transp Convention, Vol 3H, Pretoria, 1982.

75 COMMITTEE OF STATE ROAD AUTHORITIES. The structural design, construction and maintenance of unpaved roads. Technical Recommendations for Highways, No 20, CSRA, Pretoria, 1990.

Appendix A: Summary of locations of sites investigated

Road No	Kilometre point	Region or District
TRANSVAAL		
D467	1.66	Rustenburg
D540	1.5	Benoni
D410	5.88	Rustenburg
D410	0.92	"
P172/2	13.62	"
D132	0.91	"
D804	3.0	"
D404	0.675	"
D421	2.45	Lydenburg
D514	10.25	"
D736	5.9	"
D466	21.2	Ermelo
D466	16.2	"
D390	3.4	"
D2485	5.8	Rustenburg
D804	8.45	"
D804	11.1	"
D804	19.4	"
HI-1	16.5	Kruger Park
H-6	6.95	"
S-114	5.0	"
S-3	8.0	"
D646	9.5	Ermelo
D518	15.2	"
D466	27.6	"
ORANGE FREE STATE		
S191	8.2	Bethlehem
S65	6.74	"
S65	57.8	"
S63	17.8	"
P13/2	30.11	Senekal
S18	1.3	Bethlehem
S43	2.9	Heilbron
S796	1.7	Bethlehem

Road No	Kilometre point	Region or district
CAPE		
P1418	2.26	Bree River
P1351	5.93	Western Cape
P2151	2.0	West Coast
P1532	2.55	South Cape
P390	6.14	"
P390	8.97	"
P3405	0.99	Kimberley
P672	70.03	Drakensberg
P477	30.15	Algoa
P477	45.3	"
P2738	0.25	East London
P2753	1.3	"
NATAL		
P169	2.15	Estcourt
P10/1	50.1	"
P10/2	10.55	"
P102	2.0	"
P220	2.0	Vryheid
P326	6.1	Eshowe
P39	9.5	Newcastle
P39	20.7	"
P39	23.3	"
D594	2.2	Port Shepstone
P197/3	6.8	Umkomaas
P500	0.6	Camperdown

Appendix B: Selected summary statistics of base course data collected

Property	No of samples	Mean	Standard deviation	Minimum	Maximum
In situ wet density	166	2238	145	1915	2610
Field moisture (%)	166	8.61	4.11	1.0	23.4
Compaction	166	98.5	3.94	87	106
Thickness	166	142	43.0	50	290
Maximum dry density	166	2094	140.2	1664	2406
Optimum moisture content	166	9.40	3.107	4.4	19.6
Field/optimum moisture ratio	166	89.48	25.64	20.24	191.2
Plasticity index	166	7.4	5.45	0	20.5
Passing 37,5 mm(%)	166	96.2	7.03	66	100
Passing 26,5 mm (%)	166	91.4	10.36	53	100
Passing 2,0 mm (%)	166	54.1	18.7	17	91
Passing 0,425 mm (%)	166	38.8	16.6	12	82
Passing 0,075 mm (%)	166	20.7	12.2	4	68
Grading modulus	166	1.86	0.45	0.63	2.63
Grading coefficient	166	22.7	6.92	8.2	40.8
Fineness product	163	288.5	247	0	1209
Durability mill index	162	444.5	325	0	1356
CBR at OMC	145	93.8	41.2	12	300
Soaked CBR at Mod AASHTO	166	70.9	39.5	9	232
Soaked CBR at Proctor	151	27.2	16.8	1	80
DSN_{300}	152	205	161.5	45	1132
DCP CBR (base)	164	105	92	19	480
Traffic (x 1000 E80)	166	112	199	2.19	1046
Age (years)	166	10.3	8.5	2	45
Rainfall (mm)	166	734.8	186.6	265	1224
Quartercar index (counts/km)	147	29.8	24.6	14	85
Cracking	146	2.2	1.46	0	5
Rut depth (mm)	144	7	9.8	0	67
Performance	166	2.22	1.25	1	5
Drainage	166	2.13	0.83	1	3

Appendix C: Correlation of various base properties with performance (all sites)

Property	Correlation coefficient	Significance level
Gravimetric moisture	0.171	0.028
Maximum dry density	0.025	0.746
Optimum moisture content	0.609	0.610
In situ wet density	0.244	0.003
In situ dry density	0.130	0.122
Relative compaction	0.193	0.024
Field/optimum moisture ratio	0.294	0.001
Liquid limit	0.053	0.529
Plasticity index	-0.016	0.858
Bar linear shrinkage	0.115	0.146
Per cent passing 26,5 mm sieve	-0.013	0.872
Per cent passing 4,75 mm sieve	0.038	0.657
Per cent passing 0,425 mm sieve	0.065	0.404
Per cent passing 0,075 mm sieve	0.084	0.282
Grading modulus	-0.067	0.392
Grading coefficient	-0.127	0.104
Fineness product	0.116	0.193
Durability mill index	0.106	0.237
CBR at OMC	-0.073	0.419
Soaked CBR at Mod AASHTO	-0.117	0.190
Soaked CBR at Proctor	-0.123	0.167
Drainage	0.264	0.001
Rainfall	0.119	0.128
Weinert N-value	-0.198	0.011
DSN_{800}	0.028	0.785
In situ CBR (from DCP)	-0.092	0.257
Traffic	0.253	0.002

Appendix D: Correlation of various base properties with performance (only wheel tracks)

Property	Correlation coefficient	Significance level
Gravimetric moisture	0.104	0.332
Maximum dry density	0.100	0.346
Optimum moisture content	-0.099	0.355
In situ wet density	0.230	0.029
In situ dry density	0.155	0.145
Relative compaction	0.159	0.134
Field/optimum moisture ratio	0.283	0.007
Liquid limit	-0.078	0.466
Plasticity index	-0.070	0.511
Bar linear shrinkage	0.102	0.298
Per cent passing 26,5 mm sieve	-0.074	0.451
Per cent passing 4,75 mm sieve	0.009	0.929
Per cent passing 0,425 mm sieve	0.014	0.887
Per cent passing 0,075 mm sieve	0.022	0.826
Grading modulus	-0.019	0.843
Grading coefficient	-0.137	0.159
Fineness product	0.053	0.591
Durability mill index	0.092	0.348
CBR at OMC	-0.084	0.451
Soaked CBR at Mod AASHTO	-0.104	0.351
Soaked CBR at Proctor	-0.086	0.445
Drainage	0.193	0.082
Rainfall	0.004	0.974
Weinert N-value	-0.083	0.459
DSN_{300}	-0.175	0.115
In situ CBR (from DCP)	-0.156	0.162
Traffic	0.157	0.158

Appendix E: Correlation of various base properties with performance (outer wheel track only)

Property	Correlation coefficient	Significance level
Gravimetric moisture	0.132	0.382
Maximum dry density	0.113	0.455
Optimum moisture content	-0.006	0.970
In situ wet density	0.316	0.032
In situ dry density	0.233	0.119
Relative compaction	0.290	0.050
Field/optimum moisture ratio	0.254	0.088
Liquid limit	-0.071	0.639
Plasticity index	-0.058	0.701
Bar linear shrinkage	-0.072	0.635
Per cent passing 26,5 mm sieve	0.039	0.793
Per cent passing 4,75 mm sieve	0.066	0.658
Per cent passing 0,425 mm sieve	0.047	0.750
Per cent passing 0,075 mm sieve	0.011	0.942
Grading modulus	-0.044	0.767
Grading coefficient	-0.064	0.666
Fineness product	0.030	0.838
Durability mill index	0.062	0.678
CBR at OMC	-0.067	0.653
Soaked CBR at Mod AASHTO	-0.121	0.415
Soaked CBR at Proctor	-0.186	0.196
Drainage	0.264	0.064
Rainfall	0.055	0.707
Weinert N-value	-0.121	0.403
DSN_{aco}	-0.145	0.314
In situ CBR (from DCP)	-0.114	0.432
Traffic	0.110	0.448