CHAPTER 6
DERIVATION OF MECHANISTIC STRUCTURAL DESIGN CRITERIA

6.1 Introduction

This chapter addresses the derivation of the design criteria for the mechanistic design of surface mine haul roads. The structural performance categorisation introduced previously is used as a guide to the efficacy of the various existing haul road designs. Stresses and strains generated from the multi-layer elastic solution for the particular road test section are then compared with the structural performance categorisation to established suitable design criteria.

Construction material elastic moduli are assessed in terms of both the TRH14 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction are derived. The catologue of modulus values facilitates the adoption of the technique without the need for separate tests to determine suitable modulus values, unless construction materials differ significantly from those analysed. An optimum structural design is then sought through consideration of the response of each pavement layer to the applied loads and the limiting design criteria previously assessed.

6.2 Derivation of Limiting Design Criteria

Two design criteria were proposed with which to assess the structural performance of mine haul roads, namely factor of safety (FOS) for the two uppermost layers and vertical compressive strain for each layer below the top layer. As discussed in Chapter 5, the FOS does not appear to correlate with the structural performance classification. Mine test site roads exhibiting good structural performance do not necessarily exhibit correspondingly high layer FOS values, the latter being a function of the ultimate strength of each layer, which is normally not mobilised, the depth of the wearing course layer an the choice of depth at which the FOS is calculated. It is thus concluded that the FOS design criteria in the upper layers is not applicable to haul road design. Other design criteria may be more appropriate, particularly the vertical strain criterion. In the absence of any definitive criterion for the wearing course, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality wearing course gravel would appear most appropriate, based on those mine sites wearing course layers exhibiting adequate structural performance.

Figure 6.1 relates the vertical compressive strain measurements taken at each mine site; those mine sites exhibiting poor performance and an associated excessive deformation/maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. When the maximum vertical strain is analysed in conjunction with the structural performance of the road (based on the product of performance index and daily traffic repetitions) as can be seen in Figure 6.2, as the structural performance index of the road is increased at a particular level of traffic volume, the maximum recorded strains in the pavement layers then decrease. Similarly, for a given performance index, increasing traffic volumes can be associated with lower maximum strain (and thus deformation) values. By plotting a maximum strain envelope (for a minimum satisfactory performance index of 7), the maximum allowable strain recommended for various traffic volumes and required performance levels is given by Equation [6.1];

$$\varepsilon_{max} = \exp^{(8{,}2 - 0{,}007.KT.I)} \qquad [6.1]$$

where ϵ_{max} = maximum allowable vertical compressive microstrain
KT = daily tonnage hauled on road (kt)
I = performance index (1-10)

Since the majority of mines' monthly tonnage lies in the region of 300kt, and using a performance index of 7 it is evident that an upper limit of 2000 microstrain should be placed on layer strain values in this case. A similar value is adopted for public road construction (Maree and Freeme, 1981) applicable to similar materials as are used in mine haul road construction, together with a strain reduction for increased standard axle repetitions and maximum allowable deformation. The Asphalt Institute (1973) design method for airport pavements subject to loads up to 1580kN recommend a maximum subgrade strain of between 2548-1422 microstrain for between 100 and $1x10^6$ repetitions. The 2000 microstrain limit

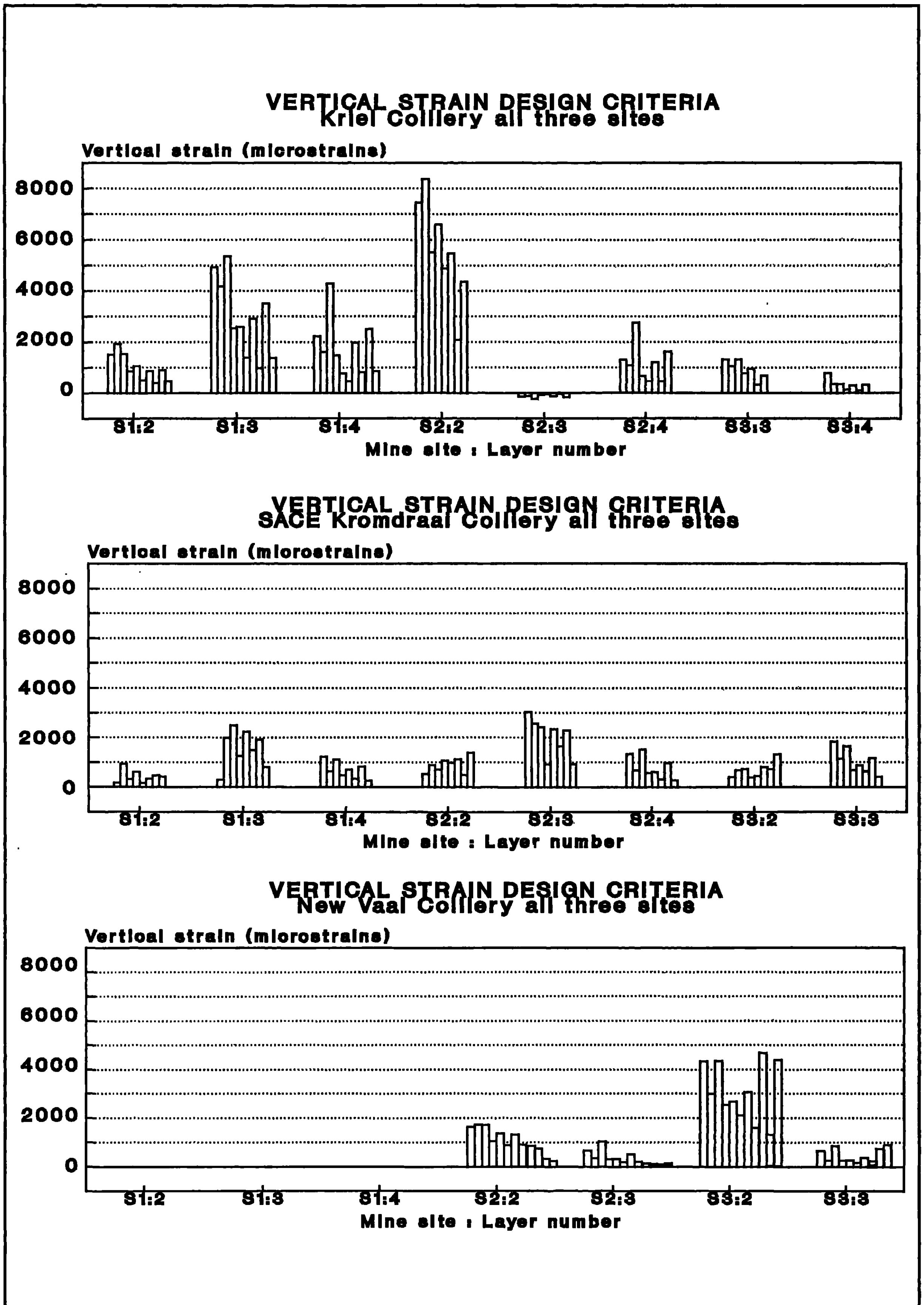

Figure 6.1 Vertical Strain Measurements at all Mine Sites

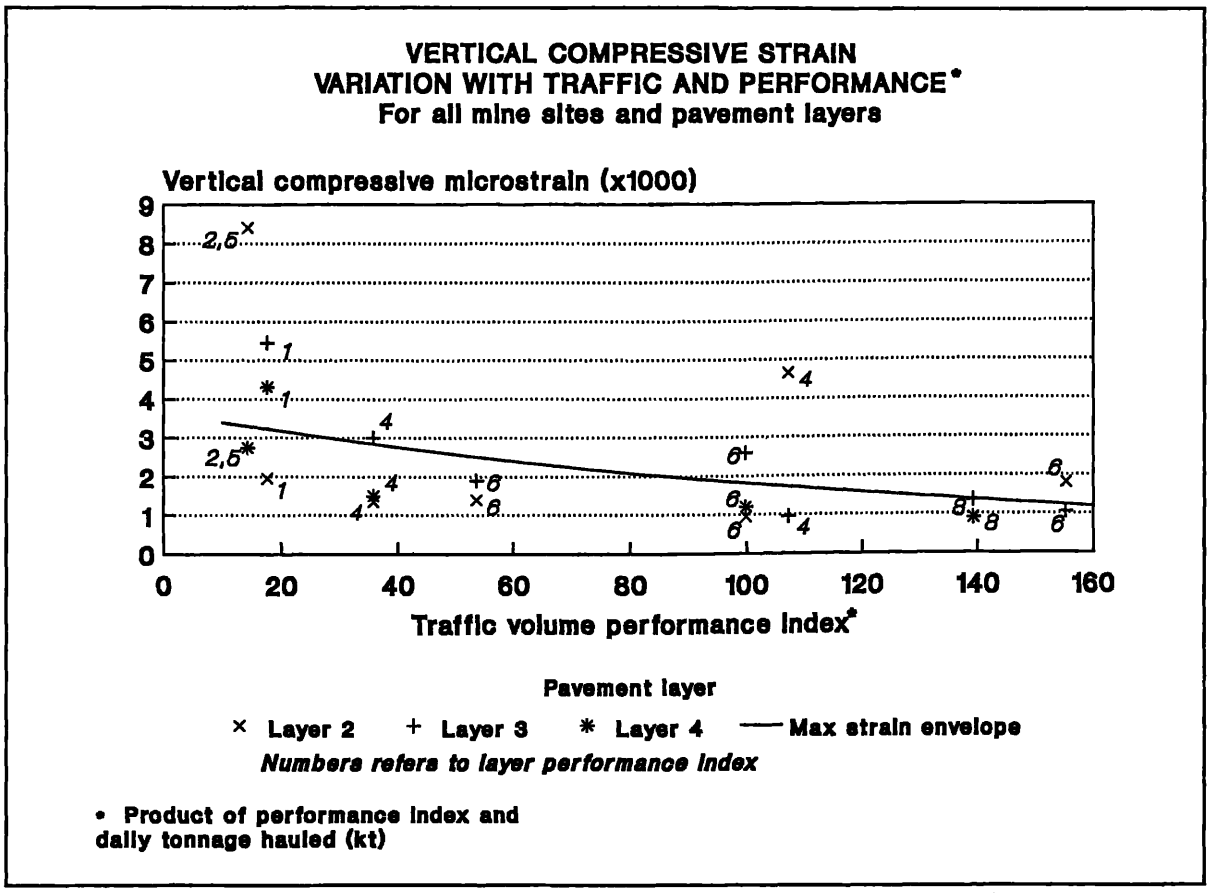

Figure 6.2 Maximum Vertical Compressive Strain Variation with Traffic and Structural Performance Index

is thus motivated as a design criteria for mine haul roads, based on typical traffic volumes and required performance index. Where traffic volumes are lower and/or poor structural performance is acceptable (short term roads) the maximum strain limit can be accordingly reduced following Equation [6.1].

6.3 Selection of Effective Elastic Modulus Values

The strains induced in a pavement are a function of the effective elastic modulus values ascribed to each layer in the structure. In order to facilitate mechanistic design of mine haul roads, some indication of applicable moduli values are required for the practical application of the method. This was achieved by considering the individual layer modulus values generated by the mechanistic analysis of existing pavements and comparing these values to established modulus values and the associated material classification.

For each test site analysed, each layer exhibited a range of effective elastic modulus values, dependant on the specific material used for road construction. Current data relating the range of moduli for granular materials, classified following CSRA TRH14 guidelines (Committee of State Road Authorities, 1985) is presented in Table 6.1. A classification for (amongst other materials) untreated gravel materials and dumprock is proposed in CSRA TRH 14. In all, six material groups are recognised, in descending order of strength and quality for roadbuilding purposes, from a G1-G3 (high quality graded crushed stone), G4-G6 (natural gravels), G7-G10 (gravel soil) to (DR) dumprock. Classification is based on material grading, Atterberg limits, CBR, swelling and field compaction characteristics. A summary of the applicable material characteristics for G1 to G10 and dumprock materials is presented in section 6.3 as they apply to haul road construction.

Tables 6.2-6.4 summarise the moduli values and associated classification for the materials used in each site pavement construction whilst Figure 6.3 presents the information graphically. As can be seen the modal material classification (ignoring in-situ material) is that of a G4-G6 gravel or low quality gravel where local mine ferricrete is used. The imported material used in the New Vaal construction does not differ significantly from this classification. It would therefore seem prudent to adopt blanket modulus values for these material types. A modulus range of 150-200MPa is proposed for G4-G6 gravels when used in wearing course and 75-100MPa for the same material when used in a base or sub-base layer. These values are slightly lower than the average values reported by SARB (1993), thereby accommodating local deviations from the standard material, compaction, stress softening effects, the presence of water and poor support from sub-grade materials. Values for the moduli of the in-situ sub-grade material are very much site and material specific and range from 17MPa to 388MPa and often exhibit stress softening. The use of DCP derived CBR values as outlined in section 4.2.4 may provide the most tractable approach in ascertaining suitable modulus values for this material. Data in Tables 6.1 and 6.5 may be used in conjunction with the CBR data to determine modulus values for these poorer quality (G7-G10) sub-grade materials.

The use of the DCP to investigate the structural performance of haul roads has been limited to the generation of balance profiles, CBR values for each layer and seed modulus for the

Table 6.1 Suggested Moduli Ranges (MPa) for Granular Materials (After Freeme, 1983 and updated by SARB, 1993)

CODE	MATERIAL DESCRIPTION	ABBREVIATED SPECIFICATION (CSRA, 1985)	OVER CEMENTED LAYER SLAB STATE	OVER GRANULAR LAYER OR EQUIVALENT	WET STATE (GOOD SUPPORT)	WET STATE (POOR SUP-PORT
G1	High quality crushed stone	86 - 88 % ARD impermeable	450 (250 - 1 000)	150	50 - 250	40 - 200
G2	Crushed stone	100 to 102 % Mod AASHTO	400 (200 - 800)	100 - 400	50 - 200	40 - 200
G3	Crushed stone	98 - 100 % Mod AASHTO	350 (200 - 800)	100 - 350	50 - 150	40 - 200
G4	Gravel base quality	CBR $\nless$ 80 PI $\ngtr$ 6	300 (100 - 600)	75 - 350	50 - 150	30 - 200
G5	Gravel	CBR $\nless$ 45 PI $\ngtr$ 10 - 15	250 (50 - 400)	40 - 300	30 -200	20 - 150
G6	Gravel low quality subbase	CBR $\nless$ 25	225 (50 - 200)	30 - 200	20- 150	20 - 150
Poisson's ratio 0,35						

Table 6.2 Layer Modulus and Classification for Kriel Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)	415	368	39	17	117	51	4175	29	421	2557	173	328
S Deviation σ (MPa)	110	98	9	2	60	15	801	10	156	150	49	109
TRH14 classification	G4	G4	G8	G8	G6	G7	Rock layer	G8	G4	Rock layer	G6	G5

Table 6.3 Layer Modulus and Classification for Kromdraai Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)	247	1113	49	99		337	116	129	55	517	144	
S Deviation σ (MPa)	88	354	19	31		47	44	31	3	154	28	
TRH14 classification	G5	?	G8	G6	No data	G4	G6	G6	G7	G4	G6	

Table 6.4 Layer Modulus and Classification for New Vaal Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)					197	32	73		144	32	168	
S Deviation σ (MPa)					51	16	26		29	7	54	
TRH14 classification					G6	G8	G7		G6	G7	G6	

Table 6.5 Suggested Modulus of Sub-grade Materials (after SARB, 1993)

CODE	SOAKED	MATERIAL	EFFECTIVE E-MODULUS (MPa)	
	CBR		WET STATE	DRY STATE
G7	$\nless$ 15	Gravel-soil	20 - 120	30 - 200
G8	$\nless$ 10	Gravel-soil	20 - 90	30 - 180
G9	$\nless$ 7	Gravel-soil	20 - 70	30 - 140
G10	$\nless$ 3	Gravel-soil	10 - 45	20 - 90

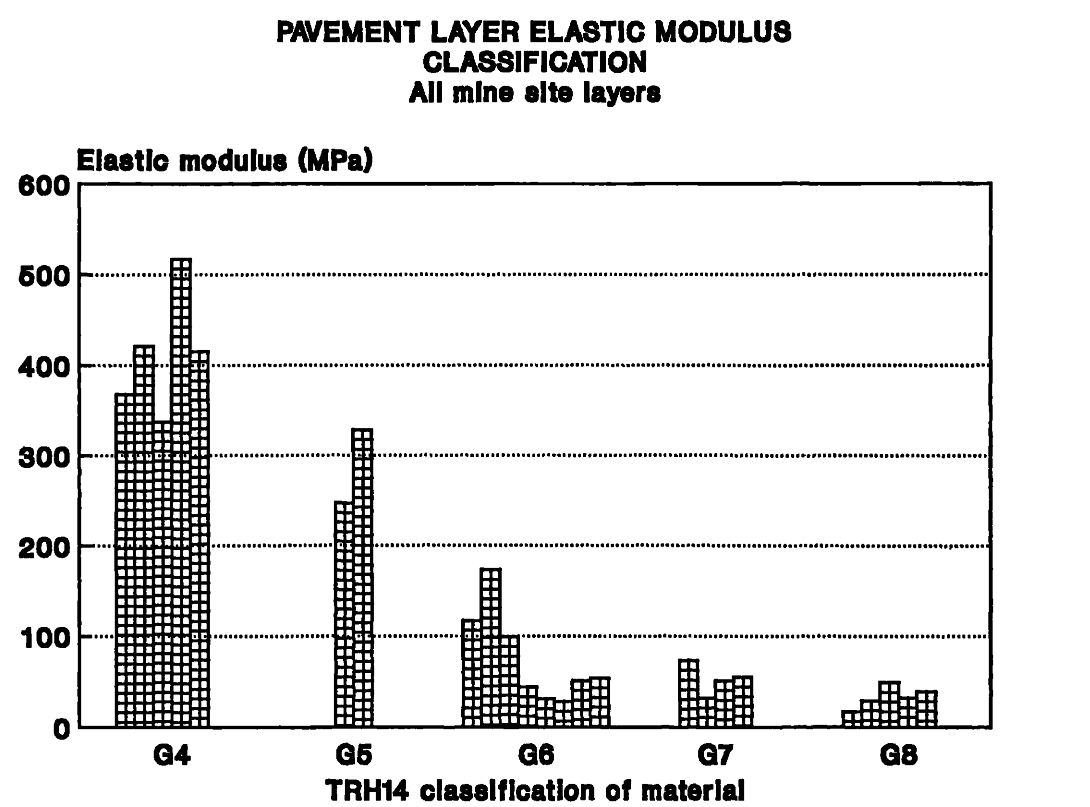

Figure 6.3 Range of Elastic Modulus Values Encountered for Various Material Classifications

multi layer elastic analysis. It has been shown in section 4.2.4 that the balance profile has limited application in the design of mine haul roads since one of the most efficient and structurally sound designs incorporates a rock layer at a shallow depth resulting in a poorly balanced shallow strength profile. In general terms the strength balances to be avoided are those of inverted structures and, to a lesser extent, poorly balanced deep. Both are associated with excessive vertical strains in the pavement.

The empirical relationship used to determine the seed modulus for the mechanistic model [Equation 5.2] has been reanalysed in the light of the final solutions for the layer modulus and the DCP penetration rate values (DN) as shown in Figure 6.4. Some trend is evident but the confidence limits calculated for the relationship are large and a solution within 80% confidence extends over two decades. The empirical relationship derived in this study for a 430kN wheel load and 630kPa contact stress is given in Equation [6.2].

$$\log(E_{eff}) = 2{,}281 - 0{,}3138(\log(DN)) \qquad [6.2]$$

The associated standard error of estimate is 0,487 and $R^2=68\%$. Data pertaining to the analysis is given in Appendix D4.

It is difficult to motivate for the existence of a direct relationship between effective elastic modulus and DCP penetration rate due to the very different testing techniques employed to derive different characteristic parameters for the same material (shear failure for DCP and elastic response for MDD). This is evident when the effective elastic modulus is plotted against the pavement layer CBR value derived from the DCP testwork, as shown in Figure 6.5. Thus the relationship proposed above should be used with caution, bearing in mind the limitations associated with its derivation.

6.4 Summary of Recommended Mechanistic Design Procedure

The optimal mechanistic structural design of a surface mine haul road embodies the selection of target effective elastic modulus values for the construction materials available and the

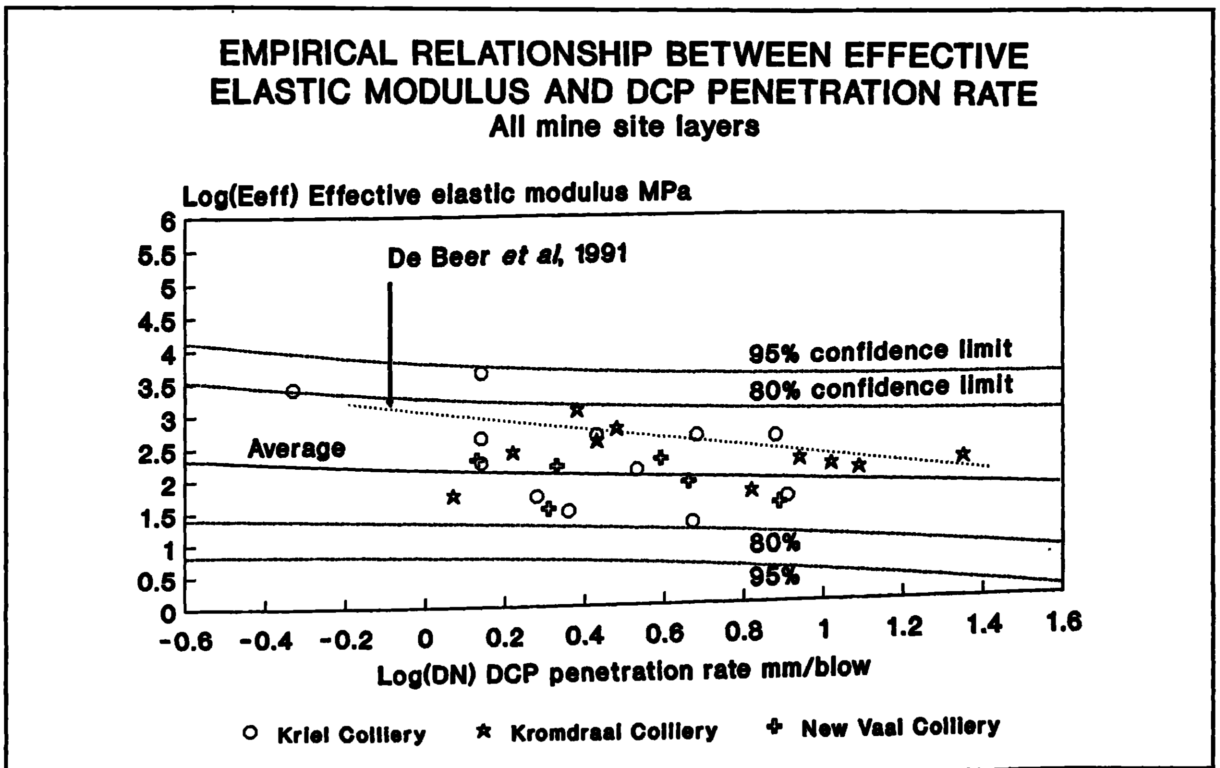

Figure 6.4 Empirical Relationship Between Effective Elastic Modulus and DCP Penetration Rate for Various Ultra-heavy Axle Loads.

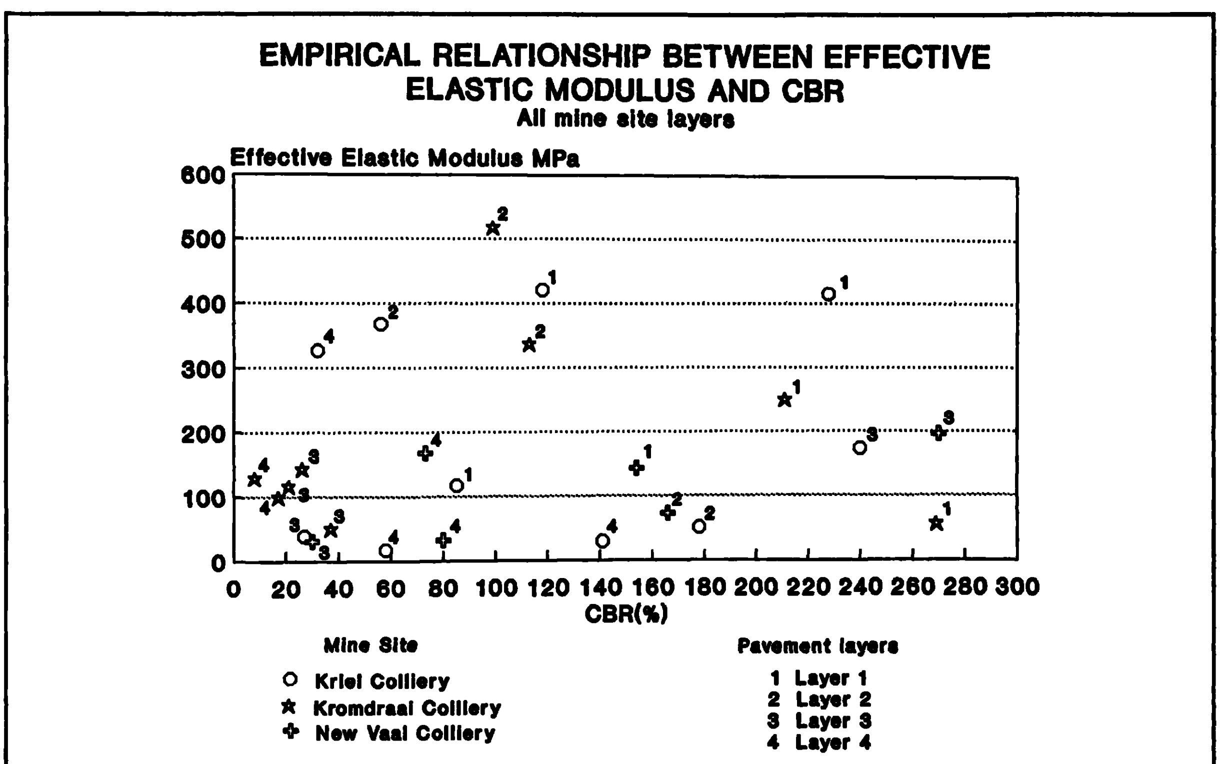

Figure 6.5 Relationship Between Effective Elastic Modulus and CBR for Various Ultra-heavy Axle Loads.

placement of those materials such as to optimise their performance both as individual layers and over the entire structure. Performance has been analysed in terms of minimum wearing course thickness and compaction and the limiting design criteria of vertical strain in the base, sub-base and sub-grade layers. In addition, of the various design options analysed at each mine test site, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness. These findings are examined as they appertain to the mechanistic structural design of mine haul roads.

Materials available on site for the construction of roads is derived from borrow pits or the pit itself. Borrow pit material comprises generally ferricrete and may be classified (following TRH14) as G4-G6. Material derived from in-pit working, typically sandstone parting, is classified as dumprock (DR). Selection criteria for these materials are analysed in terms of material grading, Atterberg limits, CBR, swelling and field compaction characteristics as a precursor to assigning target effective elastic modulus values to the material.

All natural materials will display a degree of inherent variability and a certain percentage of the population will exhibit poorer quality levels than those specified. TRH14 recommends that not more than 10% of the materials should have a quality level below the specification limit. These guidelines can be accepted for typical borrow pit material used in haul road construction, although poor quality materials may exceed the 10% limit. This deviation is accomodated by adopting the lower-bound modulus values reported in the Tables 6.1 & 6.5.

Grading

Construction materials classified following TRH14 should comply with the grading requirements given in Table 6.6. Recommendations regarding the design of roads with these materials (Freeme, 1983) limit G4-G5 to the road base and G6-G7 to the sub-base. However, the mechanistic analysis of road performance indicates that a G4-G5 gravel is suitable for base and sub-base layers in haul road construction. CSRA draft TRH20 (The Structural Design, Construction and Maintenance of Unpaved Roads), (Committee of State Road Authorities, 1990) guidelines in regard to recommendations for material selection in haul road construction are illustrated in Figure 6.4 in terms of the grading coefficient. This value should range between 16 and 34. In addition, a maximum material size of 75-100mm is recommended together with oversize index (percent retained on 37,5mm sieve) of ≤10%. The assessment of haul road functionality will provide confirmation of these recommendations as regards the specific requirements of mine haul road users. The remaining selection parameters are discussed in the following subsections.

Atterberg Limits

The Atterberg limits given in Table 6.7 apply to the soil fines (<0,425mm) of natural gravels (G4 and G5). In general, high plasticity material should be avoided due to the associated stress softening effect as discussed in Chapter 5.3. TRH20 recommendations are summarised in Figure 6.6 in which a shrinkage product value of between 100-365 (maximum preferably <240) is used. This value incorporates both the quantity of fines and the linear shrinkage of the material, similar approximate values derived from TRH14 recommendations for G4 and G5 materials are 90 and 150 respectively.

Bearing Strength and Swell

Bearing strength (7 day soaked CBR) and swell properties for typical construction materials are given in Table 6.8. TRH20 recommendations are limited to a bearing strength of CBR≥15 at ≥95% Mod AASHTO compaction after 4 days soaking, approximately equivalent to a G6-G7 material.

Field Compaction

In order to achieve the target effective elastic modulus values for the various categories of materials available for construction, filed compaction requirements should also be considered. These are given in Table 6.9, according to the pavement layer position of the particular material. In all cases the moisture content of the various materials employed should be the optimum for the compaction plant employed to ensure that during compaction, instability or excessive movement of the material is avoided.

Table 6.6 Grading Requirements for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	GRADING REQUIREMENTS	
G4	Sieve size (mm)	Percent passing by mass
	53,0	100
	37,5	85-100
	26,5	-
	19,0	60-90
	13,2	-
	4,75	30-65
	2,00	20-50
	0,425	10-30
	0,075	5-15
G5 and G6	Should have a maximum size of 63mm or two-thirds of the compacted layer thickness, whichever is the smaller. A minimum grading modulus* of 1,5 (G5) and 1,2 (G6) should be obtained.	
G7	Should have a maximum size, in place, after compaction, not greater than two-thirds of the compacted thickness of the layer. A minimum grading modulus* of 0,75 should be obtained.	
DR (Dumprock)	Should have a maximum size not more than two-thirds of the compacted thickness of the layer and this should not exceed 300mm per lift.	

* Grading Modulus is given by;

$$GM = \frac{P_{2,00mm} + P_{0,425mm} + P_{0,075mm}}{100}$$

where $P_{2,00}$, etc., denotes the percentage retained on the indicated sieve size.

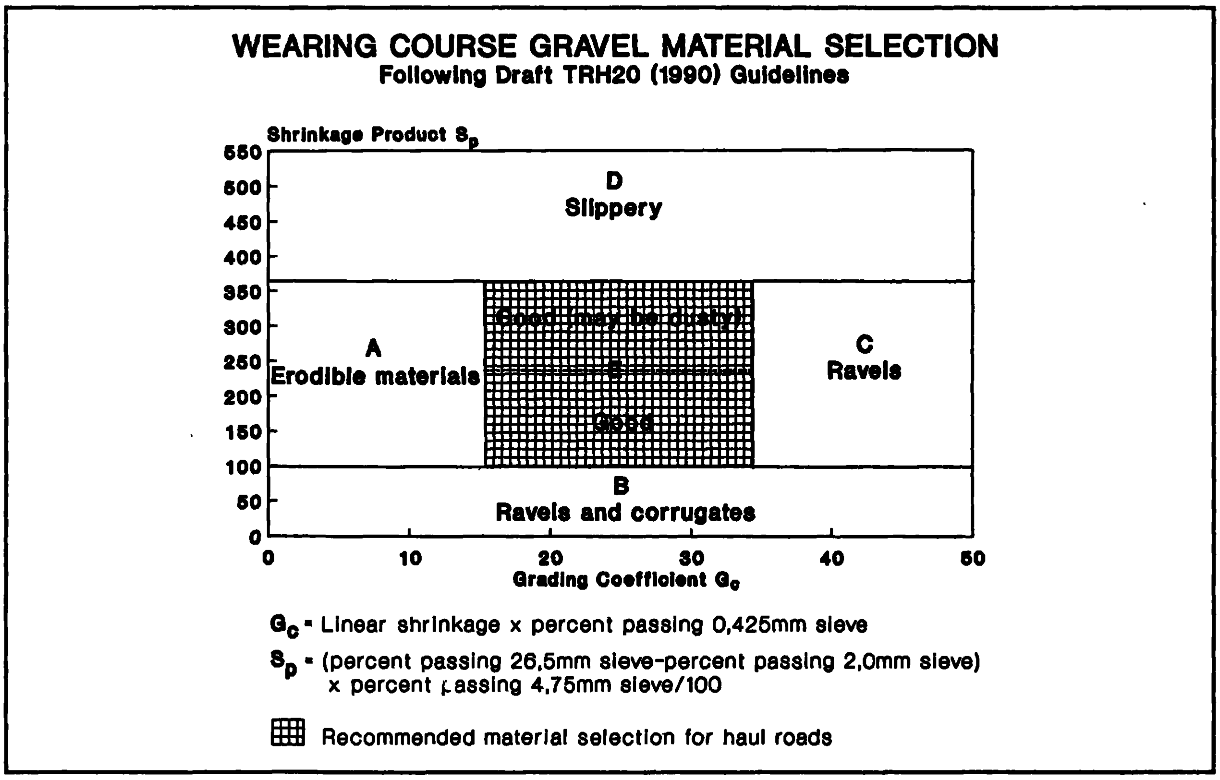

Figure 6.6 Relationship Between Shrinkage Product, Grading Coefficient and Performance of Haul Road Wearing Course Gravels (after CSRA, draft TRH20, 1990).

Table 6.7 Atterberg Limits for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	ATTERBERG LIMITS	
G3 and G4	Property	Value
	Liquid limit (max) Plasticity Index (max) Linear shrinkage (max) %	25 6 3
G5	Liquid limit (max) Plasticity Index (max) Linear shrinkage (max) %	30 10 5
G6 and G7	Plasticity Index (PI) should not exceed 12, or where a large course fraction is present, Plasticity Index is given by; $$PI = 3.GM + 10$$ Where Gm = Grading Modulus	

Table 6.8 CBR and Swell Properties for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	CBR AND SWELL PROPERTIES		
G3 and G4	Should have a CBR after soaking of not less than 80% at 98% Mod. AASHTO and a maximum swell of 0,2% at 100% Mod. AASHTO density		
G5	Should have a CBR after soaking of not less than 45% at 95% Mod. AASHTO and a maximum swell of 0,5% at 100% Mod. AASHTO density		
G6 and G7	PROPERTY	VALUE G6	VALUE G7
	Minimum CBR at 93 % Mod. AASHTO density.	25	15
	Maximum swell at 100 % Mod. AASHTO density	1,0	1,5

Table 6.9 Field Compaction Requirements for Haul Road Construction Materials (after CSRA TRH14, 1985).

PAVEMENT LAYER	CONSTRUCTION MATERIAL	RELATIVE COMPACTION
Base (upper and lower)	Natural gravel or gravel-soils (selected ferricrete) G4-G5 Dumprock (DR)	98% Mod. AASHTO Compaction is continued until movement under the roller is negligible
Subbase (upper and lower)	Natural gravel or gravel-soils (selected ferricrete) G5-G6	95% Mod. AASHTO
Selected layers	Natural gravel or gravel-soils (selected ferricrete) G5-G7	93% Mod. AASHTO

The strength of the in-situ material is also a critical factor in the structural design of a road. Values for the moduli of the in-situ sub-grade material are very much site and material specific and range from CBR 8% to 141%. The target effective elastic modulus for each of the material classifications considered above are given in Tables 6.1 and 6.5. A modulus range of 150-200MPa is proposed for G4-G6 gravels when used as a wearing course and 75-100MPa for the same material when used as a base or sub-base layer. These values are slightly lower than the average values reported by SARB (1993), thereby accommodating local deviations from the specified standards and poor support from sub-grade materials. For in-situ materials, a range of effective elastic modulus values from 17MPa to 388MPa were encountered, often exhibiting stress softening. Modulus values recommended for this material over a range of CBR values are given in Table 6.10. TRH20 recommends the in-situ material be ripped and mixed, water being added to achieve optimum moisture content if necessary. The material should then be compacted to 90% Mod AASHTO. Dump rock material, consisting of selected sandstone or parting is assigned a target effective elastic modulus value of 3000 MPa which is derived from consideration of a G2-G10 stabilised gravel layer in an uncracked state as reported by SARB (1993). Since relatively large rock material is specified in the rock layer (< 300mm or ⅔ of the specified layer thickness), although not stabilised the layer is nevertheless likely to exhibit high strength and stiffness.

Table 6.10 Effective Elastic Modulus Values for In-situ Materials.

CBR(%) OF IN-SITU MATERIAL	EFFECTIVE ELASTIC MODULUS* (MPa)	
	Wet state	Dry state
$CBR \geq 25$	105	135
$24 \geq CBR \geq 15$	85	135
$14 \geq CBR \geq 10$	65	120
$9 \geq CBR \geq 7$	55	95
$6 \geq CBR \geq 3$	45	65

* Effective elastic modulus values derived from Equation 6.2 and Table 6.5 (after SARB, 1993)

Recommendations regarding the structural design of surface mine haul roads are centred on the inclusion of a 500mm thick dumprock layer within the structure. The design proposed is based upon the findings of the mechanistic analysis of the Kriel Colliery site 3 road which incorporates a stabilised layer. The road comprises material common to other sites at Kriel but also a lime stabilised layer from 220mm to 460mm. The structural performance of the road is excellent as evidenced in Figure 5.7, the small deflection measured being due in most part to the resilience of the stabilised layer. Stabilisation techniques are expensive and the layers themselves subject to cracking if not adequately designed, thus the most tractable option is to use mine dumprock or parting material in place of the stabilised layer. The optimal location of this layer is immediately below the wearing course layer, thereby reducing deflections (and consequent deformation) in the lower layers to a minimum. Using this approach, a reduced structural thickness is realised without the attendant deformation and reduction in structural performance level that would otherwise be evident without a rock layer. The structural design, together with the associated minimum material specifications are depicted in Figure 6.7.

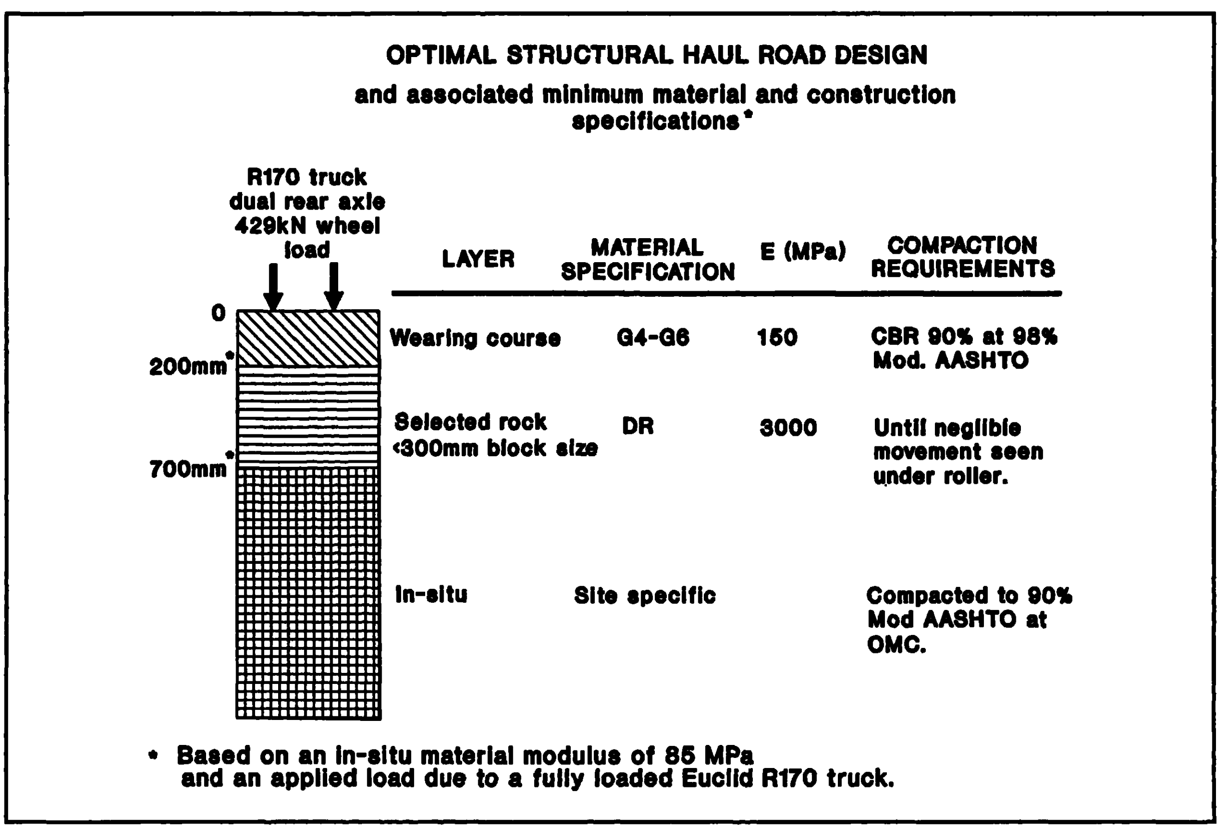

Figure 6.7 Optimal Structural Design Recommendations for Surface Mine Haul Roads.

The design criteria thus established together with the proposed target effective elastic modulus values for the various classes of materials locally available for haul road construction are applied to a typical structural design case study and the results discussed in the following Chapter.

CHAPTER 7

MECHANISTIC DESIGN OF A MINE HAUL ROAD - A CASE STUDY

7.1 Introduction

The design criteria derived from the mechanistic analysis of existing haul roads is used in this section to complete a comparative structural design for a road recently constructed at Kleinkopje Colliery. For comparative purposes, two design options are considered; the AMCOAL design based on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed optimal equivalent as derived and discussed in Chapter 6. Finally, the cost implications of the optimal design are analysed.

7.2 Roadbuilding Materials

The road is constructed in the Block 2 area of the mine where mining has already taken place, the road foundation is thus spoil material that has been tipped and dozed, together with the replacement of a top soil layer. Roadbuilding materials available on the mine were assessed by contractors (Loma Lab, 1992). The entire mine area is underlain by sedimentary sandstones, shales and carbonaceous seams of the Vryheid Formation Ecca Group of the Karoó Sequence. Transported and residual soils overlie the site. Details of borrow pit materials are presented in Figure 7.1 and Table 7.1.

As can be seen from the data presented in Table 7.1 the available material has consistently low Plasticity Indices (<10), low linear shrinkage (<5,5%), well graded character and of high density (2131kg/m^3 at 8.2% moisture content). This gives rise to good CBR values of 37% at 90% Mod. AASHTO and 90% at 98% Mod. AASHTO. Classification following TRH14 is generally G4-G6. The TRH14 classification suggests suitability from the point of view of public road construction. In mine haul road construction this material will be used to construct all the layers of the road, albeit at various levels of Mod. AASHTO compaction.

For comparative purposes, two design options are considered; the AMCOAL design based

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Table 7.1 Laboratory Classification Details of Borrow Pit Material

Test pit No.	Depth of layer (m)		Soil Description	Sieve Analysis						Liquid limit (%)	Plasticity index (%)	Linear shrinkage (%)	Grading modulus	CBR %					MOD AASHTO		TRH14	Suitability
	From	to		Percent passing										MOD AASHTO Density (%)				Swell at 90%	Density kg/m^3	Moisture content (%)		
				37,5	13,2	4,75	2,00	0,425	0,075					90	93	95	98					
BPA1	0,4	1,8	Gravel: ferruginous concretions	100	98	81	58	44	30	27	11	5,5	1,68	19	33	48	77	0,1	2091	9,1	G6	Lower subbase
BPA2	0,3	1,9	Gravel: ferruginous concretions	100	100	88	67	50	34	30	11	5,5	1,49	12	33	46	73	0,1	2053	10,0	G6	Lower Subbase
BPA3	0,4	2,0	Gravel: ferruginous concretions	100	97	67	48	36	16	17	5	2,0	2,00	20	36	52	84	0,0	2139	8,2	G5/G6	Subbase/base
BPA4	0,3	2,3	Gravel: ferruginous concretions	100	90	64	48	40	24	24	10	4,5	1,88	17	36	57	97	0,1	2119	7,7	G5	Subbase
BPA5	0,3	2,3	Gravel: ferruginous concretions	100	93	68	53	42	17	18	4	2,0	1,88	25	48	70	120	0,0	2214	7,0	G5/G4	Subbase/base
BPA6	0,6	2,0	Gravel: ferruginous concretions	100	96	77	59	44	24	21	8	3,5	1,67	18	32	45	72	0,1	2147	8,0	G5	Subbase
BPA7	0,3	1,4	Gravel: ferruginous concretions	100	98	74	60	49	24	21	8	3,5	1,68	22	37	50	86	0,1	2112	8,3	G5	Subbase
BPA8	0,5	1,5	Gravel: ferruginous concretions	100	94	70	57	48	19	20	8	3,5	1,80	23	41	60	100	0,1	2104	7,9	G5	Subbase
BPA9	0,5	1,7	Gravel: ferruginous concretions	100	93	71	49	44	19	22	7	3,0	1,95	22	43	67	115	0,2	2133	8,6	G5	Subbase
BPA13	0,4	1,6	Gravel: ferruginous concretions	100	96	69	50	37	21	22	10	4,0	1,88	21	36	50	82	0,0	2204	7,1	G5	Subbase
BPA16	0,3	1,4	Gravel: ferruginous concretions	100	100	93	77	61	41	27	5	2,0	1,21	20	34	48	80	0,0	2124	7,9	G6/G5	LSB/subbase

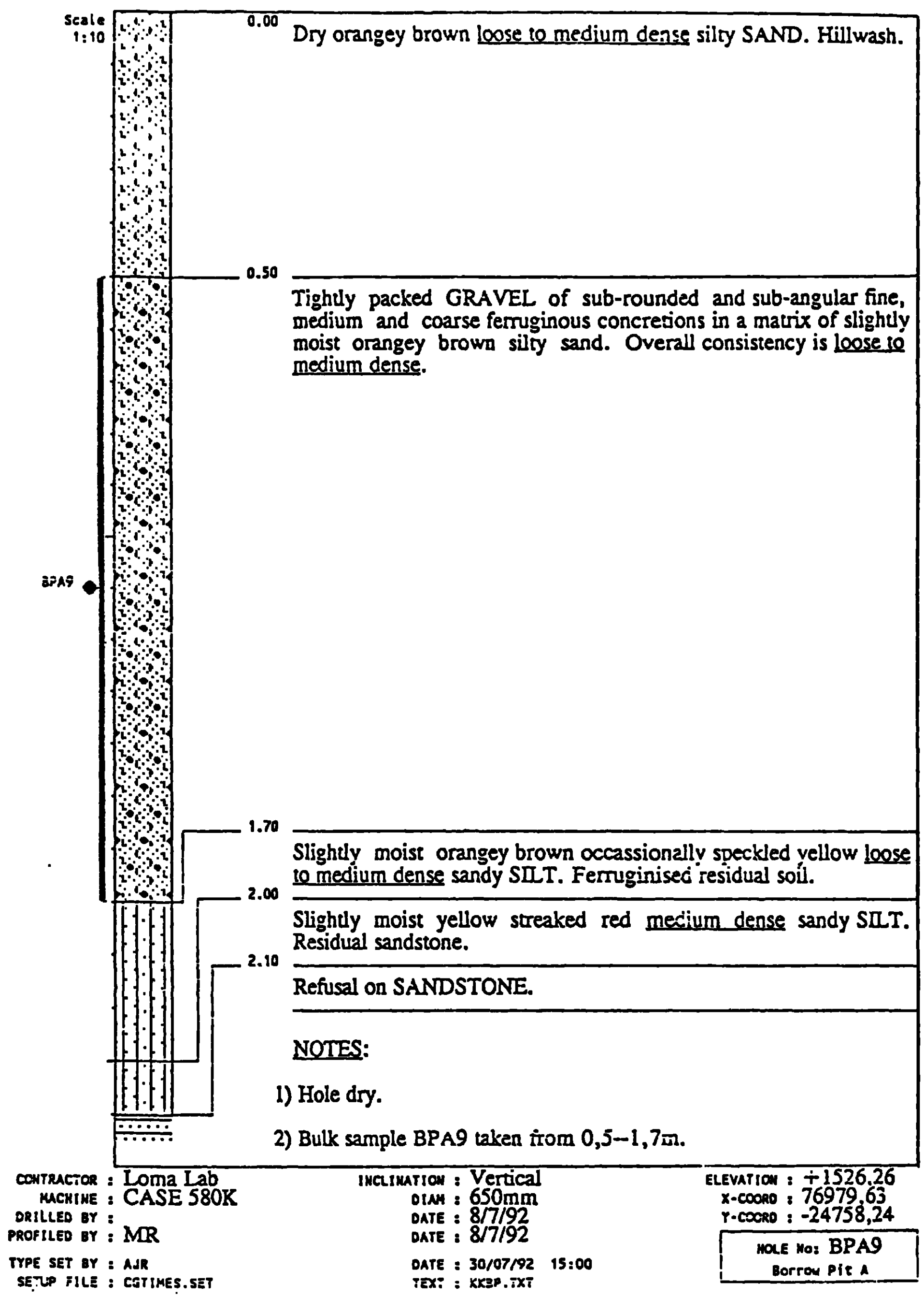

Figure 7.1 Soil Profile From Borrow Pit A, Kleinkopje Colliery (after Loma Lab, 1992)

on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed equivalent. It is assumed that in-situ and road construction material properties remain the same irrespective of the structural design technique adopted. For both options a minimum wearing course thickness of 200mm, compacted to a density of 98% Mod. AASHTO is adopted as recommended in the previous chapter. An Euclid R170 truck is used to assess the response of the structure to applied loads generated by a fully laden rear dual axle (429kN per wheel, 630kPa contact stress) and the assumption is made of no load induced deflections below 3000mm. The various design options are summarised in Figure 7.2.

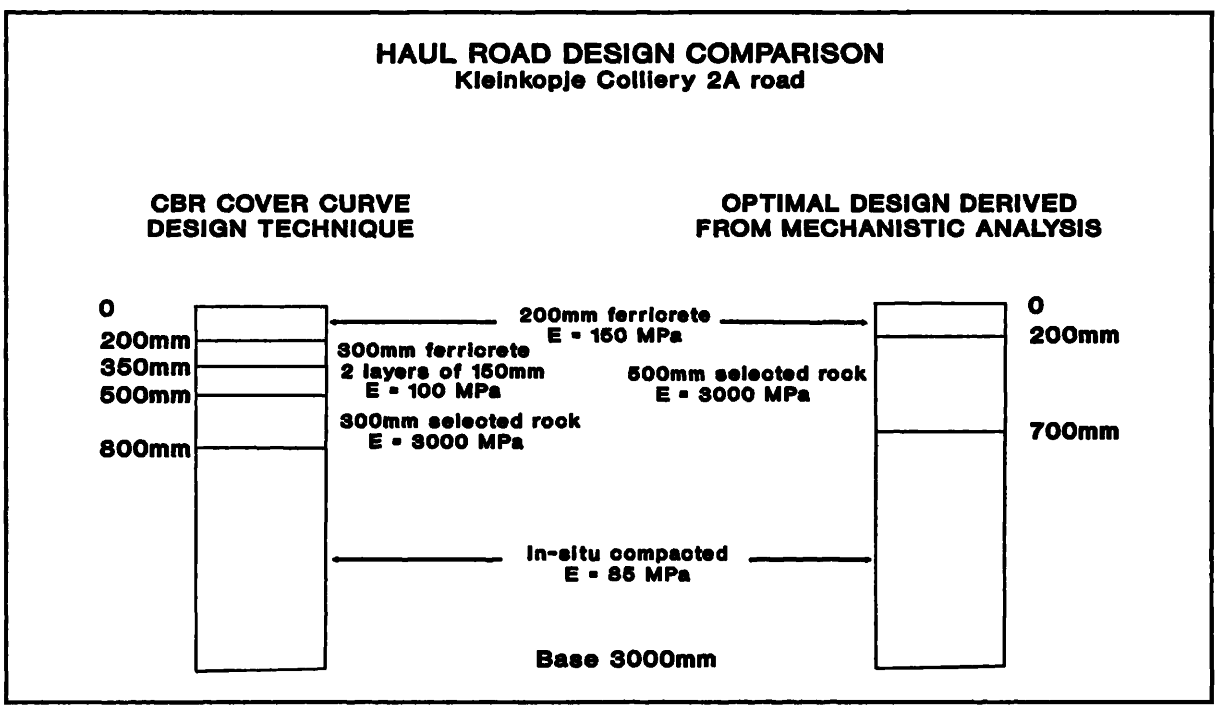

Figure 7.2 Haul Road Structural Design Options Investigated

7.3 CBR Cover Curve Design

The cover curve and layer strength diagram is given in Figure 7.3 for the Kleinkopje road, based on a compacted in-situ material CBR of 17% minimum. Structural design data is given in Table 7.2. The design was analysed mechanistically to determine the likely structural performance of the road in the light of those critical design factors previously

Table 7.2 CBR Structural Design Data

Layer	Layer Thickness (mm)	Mod. AASHTO compaction (%)	CBR achieved (%)	Assumed effective elastic modulus (MPa)*	Material description
1	200	98	90	150	Selected ferricrete G4/G5
2	150	95	50	100	Selected ferricrete G4/G5
3	150	93	35	100	Selected ferricrete G4/G5
4	300		>200	3 000	Selected sandstone, <300mm block size or < ⅔ layer thickness
5	In-situ		17	85	In situ compacted G7

* Values derived from Tables 6.1 and 6.10

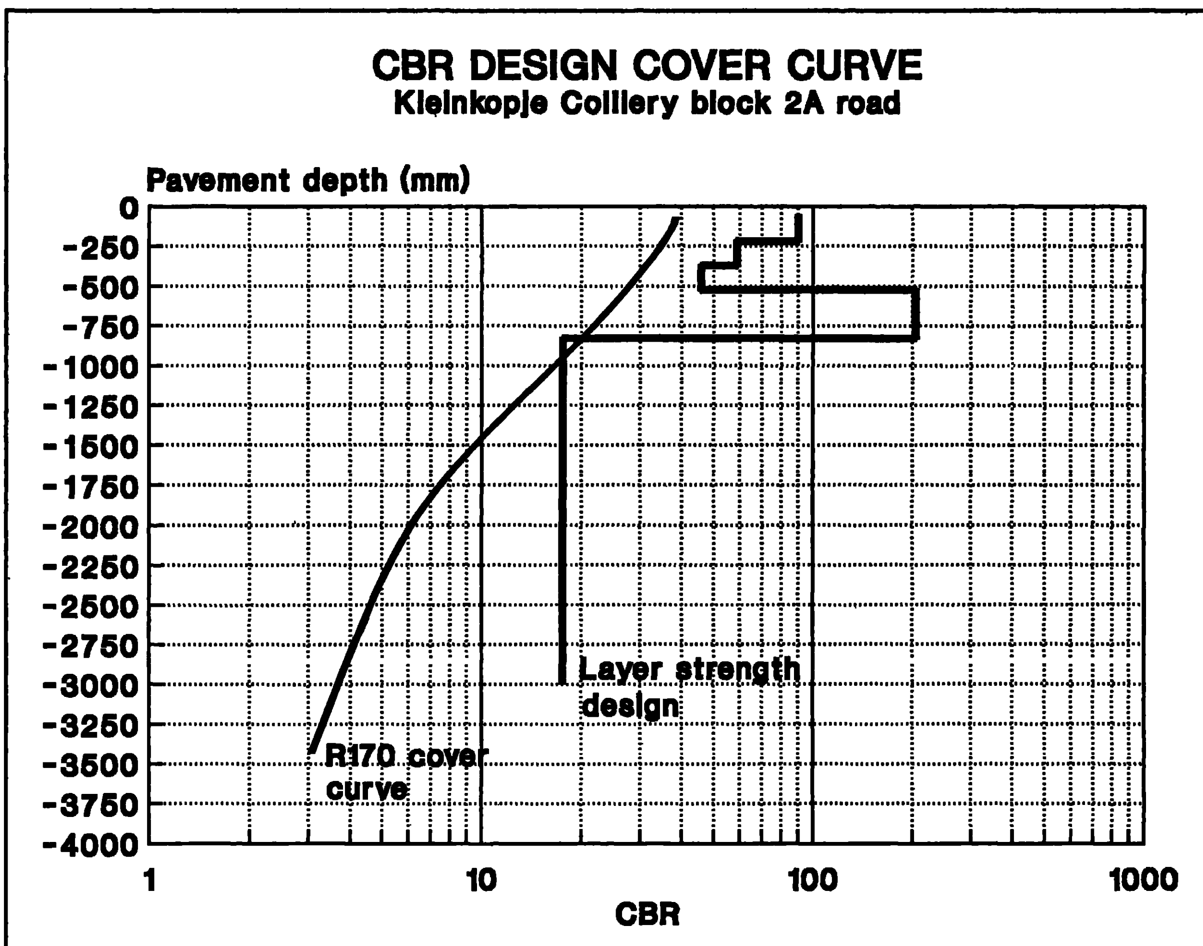

Figure 7.3 CBR Cover Curve For Kleinkopje Colliery Comparative Analysis

identified. In the case of Kleinkopje, a performance index of 7 was used in conjunction with 300kt monthly coal production which gave an upper limit to the load induced strains of approximately 2000 microstrain.

The data in Table 7.3 relates to the results of the mechanistic analysis of the CBR derived cover curve design. It is evident that excessive vertical compressive strains are generated in the top of layers 2 and 3. Strains in excess of 2000 microstrain are associated with an unacceptable amount of rutting and pavement deformation for this particular level of performance and traffic. Surface deflections generated by the applied load of 3,65mm do not appear excessive but when accompanied with the severe load induced strains, will eventually initiate structural failure. The comments made regarding the inapplicability and under-design apparent with the CBR design technique are borne out by these results, specifically the large vertical strains developed in the pavement as the design layer strengths approach the cover curve line. It is thus prudent to investigate design alternatives based on the results discussed in Chapter 6.

7.4 Optimal Haul Road Design

The design proposed is based upon the findings of the mechanistic analysis of existing haul roads. Of particular importance in this respect is the Kriel Colliery site 3 road which incorporates the stabilised layer. Whilst stabilisation techniques are expensive and the layers themselves subject to cracking if not adequately designed, the most tractable option is to use mine spoil rock material in place of the stabilised layer. The design adopted is depicted in Figure 7.2 and described in Table 7.4. The design is analysed mechanistically to determine the likely structural performance of the road in the light of the critical design factors previously identified.

The data in Table 7.5 relates to the results of the mechanistic analysis of the optimal design. It is evident that no excessive vertical compressive strains are generated in the structure, primarily due to the support generated by the shallow rock layer. Maximum vertical strains of 1505, 70 and 1078 microstrain are developed in layers 1, 2 and 3 respectively. Maximum

Table 7.3 Results of Mechanistic Analysis of Proposed CBR Based Design Technique

Kleinkopje CBR design assessment R170 rear full

	ELASTIC MODULUS	POISSONS RATIO	LAYER THICKNESS
1	150.	0.350	200.000 MM
2	100.	0.350	299.999 MM
3	2999.	0.350	299.999 MM
4	85.	0.350	2199.996 MM
5	29993.	0.350	SEMI-INFINITE

TWO LOAD(S), EACH LOAD AS FOLLOWS
TOTAL LOAD..... 428.96 KN
LOAD STRESS.... 629.86KPA
LOAD RADIUS.... 465.62 MM

LOCATED AT

LOAD	X	Y
1	0.000	0.000
2	1199.998	0.000

X-Y POINT(S)
X= 0.00 600.00
Y= 0.00 0.00

RESULTS REQUESTED FOR SYSTEM LOCATION(S)
DEPTH(S)
Z= 0.00 201.00 351.00 501.00 801.00

0.00 LAYER NO 1
DISPLACEMENTS
UZ 0.3650E+01 0.2304E+01
NORMAL STRAINS
EZZ 0.1860E-02 0.1095E-03

201.00 LAYER NO 2
DISPLACEMENTS
UZ 0.3115E+01 0.2348E+01
NORMAL STRAINS
EZZ 0.4593E-02 0.3983E-03

351.00 LAYER NO 3
DISPLACEMENTS
UZ 0.2437E+01 0.2227E+01
NORMAL STRAINS
EZZ 0.4235E-02 0.1074E-02

501.00 LAYER NO 4
DISPLACEMENTS
UZ 0.1907E+01 0.2054E+01
NORMAL STRAINS
EZZ 0.8003E-04 0.1464E-03

801.00 LAYER NO 5
DISPLACEMENTS
UZ 0.1867E+01 0.2025E+01
NORMAL STRAINS
EZZ 0.1394E-02 0.1407E-02

surface deflections are approximately 2mm, reducing to 1,52mm in the in-situ material at a depth of 700mm. Deflections at a similar depth for the CBR based design in the in-situ material (800mm) are reduced to 1,43mm (compared with 2,02mm). The proposed optimal design thus provides a better structural response to the applied loads as does the thicker CBR based design and, in addition, does not exceed any of the proposed design criteria for the particular performance index and traffic volume used in the analysis. The mechanistically designed road can accommodate a 25% increase in traffic volumes before the critical limiting vertical compressive strain is exceeded. Overdesign in this manner accommodates deviations from the insitu material modulus of 85MPa.

Table 7.4 Optimal Structural Design Data

Layer	Layer Thickness (mm)	Mod. AASHTO compaction (%)	CBR achieved (%)	Assumed effective elastic modulus (MPa)*	Material description
1	200	98	90	150	Selected ferricrete G4/G5
2	500		>200	3 000	Selected sandstone, <300mm block size or <⅔ layer thickness
3	In-situ		17	85	In situ compacted G7
* Values derived from Tables 6.1 and 6.10					

7.5 Cost Implications of Optimal Design

A cost comparison was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. Full details of the contractor unit and total costs for the construction of the road, based optimal (mechanistic) design approach, are given in Appendix E from data compiled by Purchase & Rowan (1993). This includes preliminary and general costs which are assumed not to vary with varying pavement structures and are thus not variables in this comparison context. It is also assumed that rock and borrow-pit material are within the free-haul distance of the construction site.

Table 7.5 Results of Mechanistic Analysis of Proposed Optimal Design

```
Kleinkopje optimal design assessment R170 rear full

        ELASTIC   POISSONS     LAYER
        MODULUS    RATIO      THICKNESS

  1       150.    0.350      200.000 MM
  2      2999.    0.350      499.999 MM
  3        85.    0.350     2299.995 MM
  4     29993.    0.350     SEMI-INFINITE

TWO  LOAD(S),EACH LOAD AS FOLLOWS                 LOCATED AT
TOTAL LOAD.....     428.96 KN                LOAD    X       Y
LOAD STRESS....     629.86KPA                  1   0.000   0.000
LOAD RADIUS....     465.62 MM                  2 1199.998  0.000

X-Y POINT(S)                           RESULTS REQUESTED FOR SYSTEM LOCATION(S)
X=     0.00   600.00                   DEPTH(S)
Y=     0.00     0.00                   Z=  0.00 201.00 701.00

0.00  LAYER NO  1
      DISPLACEMENTS
       UZ   0.2072E+01 0.1555E+01
      NORMAL STRAINS
       EZZ  0.1505E-02 0.3127E-03


201.00  LAYER NO  2
      DISPLACEMENTS
       UZ   0.1579E+01 0.1644E+01
      NORMAL STRAINS
       EZZ  0.7030E-04 0.2137E-04

701.00  LAYER NO  3
      DISPLACEMENTS
       UZ   0.1520E+01 0.1620E+01
      NORMAL STRAINS
       EZZ  0.1078E-02 0.1077E-02
```

The variable costs taken into account are those of the volume and area of materials required and the associated costs of placing and compaction. Costs are analysed under two categories; preliminary and general costs and haul road construction costs. Preliminary and general costs are assumed to remain constant for the purposes of the analysis and amount to R410 000, or R164 000 per kilometre of road. Road drainage, berm construction and finishing are also assumed to remain constant irrespective of the design chosen.

Table 7.6 summarises the amounts and cost of the various activities as they apply to the CBR and optimal mechanistic-based designs. From an analysis of the construction costs for each design it is seen that a cost saving of R155 060, or 25% could be realised by adopting the

Table 7.6 Cost Comparison of Design Options (Excluding Preliminary and General Costs).

CBR-BASED DESIGN			OPTIMAL DESIGN		
ACTIVITY	**AMOUNT**	**COST (R)**	**ACTIVITY**	**AMOUNT**	**COST (R)**
Compaction of in-situ	27000m² 230m³	9 720 1 256			
Compaction and treatment of road-bed	4 050m³ 6 480m³	8 465 16 913	Compaction of in-situ	10530m³	22 008
Place and compact rock fill layer	7 300m³	39 858			
Place and compact rock layer	18 750m³	102 375	Place and compact rock fill layer	8 760m³	47 830
Place and compact sub-base layer	9 375m³	108 468			
Place and compact base layer	9 375m³	108 468			
			Place and compact rock base layer	31 250m³	170 625
Place and compact wearing course	12 500m³	144 625	Place and compact wearing course	12 500m³	144 625
Finish, including drains and berms	1000m³	8 670	Finish, including drains and berms	1 000m³	8 670
	7500m³	56 175		7 500m³	56 175
	2,5km	7 650		2,5km	7 650
TOTAL		**612 643**			**457 583**

mechanistic-based optimal design, by virtue of the reduced material volumetric and compaction requirements. In terms of total construction cost (including preliminary and general costs), a 15% cost saving per kilometre is realised. In addition, further benefits should accrue in terms of reduced operating and maintenance costs arising from the superior structural performance of the road as evidenced from the foregoing analysis.

7.6 Summary

The design criteria derived from the mechanistic analysis of existing haul roads was used in this section to complete a comparative structural design costing exercise for a road recently constructed at Kleinkopje Colliery. Two design options were considered; the AMCOAL CBR cover curve design methodology and the mechanistically designed optimal equivalent, based on the design catalogue presented in Chapter 6 and the particular in-situ material strength and load characteristics prevalent in the 2A area at Kleinkopje.

It was assumed that in-situ and road construction material properties remain the same irrespective of the structural design technique adopted. For both options a minimum wearing course thickness of 200mm was used, compacted to 98% Mod AASHTO. The in-situ material was ascribed a CBR of 17 and a modulus of 85MPa. The CBR cover curve design incorporated 4 layers, including a rock-fill layer above the in-situ material. In contrast, the optimal mechanistic equivalent for this road consisted of 2 layers above insitu.

From an analysis of vertical compressive strains developed in each layer due to the applied load of a R170 truck, it was found that excessive strains were developed in layers 2 and 3 of the CBR-based design. The optimal design did not evidence any excessive strains, primarily due to the support generated from the shallow rock layer. The proposed optimal design thus provided a better structural response to the applied loads than did the thicker CBR based design and, in addition, did not exceed any of the proposed design criteria for the particular performance index and traffic volume used in the analysis.

A cost comparison of the two designs was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. The variable costs taken into account were those of the volume and area of materials required and the associated costs of placing and compaction. By virtue of the reduced material volumetric and compaction requirements associated with the optimal design, a cost saving of R155 060, or 25% was realised. In terms of total construction cost (including preliminary and general costs), a 15% cost saving was realised over the CBR-based design.

The optimal mechanistic design derived in the analysis is based on the particular in-situ material strength, applied load and required road performance (at a particular traffic volume) characteristics. From Equation [6.1] it may be seen that if traffic volume from the 2A pit were to increase, the structural performance of road, based on the CBR design, would further deteriorate. However, even with a 25% increase in traffic volume, the strains generated in the various layers of the mechanistically designed pavement remain below the design criteria. When departures are made from the 85MPa in-situ material, Table 6.10 can be used to down-grade the applicable material modulus according to the particular CBR value of the material. If the type of truck changes, or the required performance index or tonnage hauled on the road, these can be modified in the analysis itself, following Equation [6.1]. In this respect the mechanistic design methodology and catalogue of values is transferable between sites.

CHAPTER 8
SUMMARY OF STRUCTURAL DESIGN RESEARCH

8.1 DCP Analysis of Pavements

Regarding the empirical analysis and quantification of existing pavement structural designs, the use of the Dynamic Cone Penetrometer in the context of haul road structural design investigations was employed to determine the location of various pavement layers, the California Bearing Ratio (CBR) values of these various layers and the overall balance of the structural design. The results generated in the first instance confirm the classification of test sites proposed in the experimental design for the site location matrix. In general, those sites showing a shallow structure, in which the majority of the pavement strength lies in the upper layers may be more sensitive to increased wheel loads and consequential failure of the upper layers. A deep structure, in contrast, would be less sensitive to any increase in wheel loads, but may well show signs of excessive permanent deformation in the weaker upper layers. The extent to which these effects are seen in haul roads can only be reliably determined from in-situ deflection measurements.

It has been shown that the balance profile approach has limited application in the design of mine haul roads since one of the most efficient and structurally sound designs incorporates a rock layer at a shallow depth resulting in a poorly balanced shallow strength profile. In addition, the pavement strength-balance concept focuses on the upper 1,8m of material, which, for most mine sites generally includes a portion of sub-grade. The strength-balance concept does not address whether the pavement as a whole is suited to the sub-grade strength. In general terms the strength balances to be avoided are those of inverted structures and, to a lesser extent, poorly balanced deep. Both are associated with excessive elastic vertical compressive strains in the pavement.

8.2 California Bearing Ratio (CBR) Design Procedure

Although the DCP data affords an insight into the actual road structure as opposed to the design structure and the strength of each layer actually achieved in the field, the extent to which each type of design fulfils the structural performance requirements can only be determined from analysis of the response of each layer to the applied loads. As a precursor to the analysis, the California Bearing Ratio design technique was investigated in which CBR data generated from the DCP investigation is compared to actual cover requirements predicted from the CBR design method. Although the CBR method is a simple and straight forward design method based on and improved by considerable practical experience, numerous disadvantages were found when applying the method to mine haul road design problems. Mine haul road structures consist of various layers of differing material each with its own specific elastic and other properties. More specifically, the CBR method was based on empirical results relating to the design of asphalt-surfaced airfield pavements for wheel-gear loads up to 4 400kN. When aggregate-surfaced mine haul roads are considered in conjunction with stabilised bases, albeit at similar load levels, the same approach is of questionable validity. The graphical relationship proposed by Ahlvin in conjunction with the modified CBR design technique would therefore also not appear to be applicable to haul road structural design. Simple extrapolation of these empirical design criteria to accommodate higher axle loads and different pavement layer materials can lead to serious errors of under- or over-design.

The deficiencies inherent in the development of the CBR design method militate against using the techniques for the structural design of mine haul roads. When the results of the DCP redefined layer strengths are analysed in conjunction with the CBR cover curves generated, it would appear that the method, when applied judiciously, can be used to determine safe (total) cover over in-situ materials, although the extent of over or under design associated with the method cannot be qualified. The method is thus exclusively recommended to design cases where no surface layers exist above standard gravel bases. Where cemented or stabilised layers are included in the design, or where the optimal structural design is sought, due to the very different properties of the layer in comparison to normal roadbuilding gravels, a mechanistic design techniques should be employed which can account for the different material properties and more accurately predict their performance.

8.3 Derivation of Mechanistic Structural Design

The derivation of the design criteria for the mechanistic design of surface mine haul roads was based on the structural performance categorisation of mine haul roads. Stresses and strains generated from the multi-layer elastic solution for the particular road test section were then compared with the structural performance and traffic volume categorisation to established suitable design criteria. Construction material elastic moduli were assessed in terms of both the TRH14 and TRH20 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction were derived.

Two design criteria were proposed with which to assess the structural performance of mine haul roads, namely factor of safety (FOS) for the two uppermost layers and vertical compressive strain for each layer below the top layer. It was found that the vertical strain criterion correlates well with structural performance/traffic volume of the road; those mine sites exhibiting poor performance and an associated excessive deformation/maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. From analysis of the data it was found that when using a performance index of 7 and 300kt coal production per month, an upper limit of 2000 microstrain should be placed on layer strain values. Strain values exceeding this value have been shown to be associated with unacceptable structural performance in both public road and airfield design. The depth of influence at which load induced stresses are no longer felt was identified at approximately 3000mm pavement depth.

With regard to the FOS design criteria for the upper layers, it is concluded that this criteria is not applicable to haul road design since the applied stresses were much lower than the ultimate strength of pavement layer material, which was normally not mobilised. In addition, the location of the point in the wearing course layer at which the FOS is calculated is very much dependant on layer thickness, stress reversals being seen in relatively thin, poorly supported layers. In the absence of any definitive criterion, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality gravel is recommended. This recommendation is derived from the observation of mine site wearing course layers which exhibited adequate structural performance.

The optimal mechanistic structural design of a surface mine haul road embodies the selection of target effective elastic modulus values for the construction materials available and the placement of those materials such as to optimise their performance both as individual layers and over the entire structure. Performance has been analysed in terms of minimum wearing course thickness and compaction and the limiting design criteria of vertical strain in the base, sub-base and sub-grade layers. In addition, of the various design options analysed at each mine test site, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness.

8.4 Selection of Effective Elastic Modulus Values

Materials available on site for the construction of roads is derived from borrow pits or the pit itself. Borrow pit material comprises generally ferricrete and may be classified (following TRH14) as G4-G6. Selection criteria for these materials were analysed in terms of material grading, Atterberg limits, CBR, swelling and field compaction characteristics in order to assign target effective elastic modulus values to these materials. It was found that the modal material classification (ignoring in-situ material) is that of a G5-G6 gravel or low quality gravel where local mine ferricrete is used. To reduce the requirements for testing materials and to enhance the practical application of the mechanistic design method, it is prudent to adopt blanket modulus values where these, or other essentially similar material types are encountered. A modulus range of 150-200MPa is proposed for G4-G6 gravels when used as a wearing course and 75-100MPa for the same material when used as a base or sub-base layer. These values are slightly lower than typical published values, thereby accommodating local deviations from the standard material classification. Values for the modulus of the in-situ sub-grade material are very much site and material specific and range from 17MPa to 388MPa and often exhibit stress softening. Dump rock material, consisting of selected sandstone or parting should be assigned a target effective elastic modulus value of 3000 MPa.

Whilst the empirical relationship proposed for determining the seed value for the effective elastic modulus for the mechanistic model could be advanced as a means of determining modulus values for insitu material, although some trend is evident, the confidence limits calculated for the relationship are large and a solution within 80% confidence extends over two decades. The associated standard error of estimate is 0,487 and R^2=68%. It is concluded that it is difficult to motivate for the existence of a direct relationship between effective elastic modulus and DCP penetration rate due to the very different testing techniques employed to derive different characteristic parameters for the same material. Where a modulus value is required for pavement layer modelling, the use of DCP probe derived CBR values in conjunction with published data provide the most tractable approach to ascertaining suitable modulus values for this material.

8.5 Recommended Mechanistic Design Procedure

Recommendations regarding the structural design of surface mine haul roads are centred on the inclusion of a dumprock layer within the structure. The optimal location of this layer was found to be immediately below the wearing course layer, thereby reducing deflections (and consequent deformation) in the lower layers to a minimum. Using this approach, a reduced structural thickness was realised without the attendant deformation and reduction in structural performance that would otherwise be evident without a rock layer.

The design criteria derived from the mechanistic analysis of existing haul roads was used to complete a comparative structural design for a road recently constructed at Kleinkopje Colliery. For comparative purposes, two design options were considered; the AMCOAL design based on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed optimal equivalent. Finally, the cost implications of the optimal design were analysed.

The optimal design incorporated a 200mm ferricrete wearing course layer with an effective elastic modulus of 150MPa and a 500mm layer of selected rock with an effective elastic modulus of 3000MPa constructed upon in-situ material with an effective elastic modulus of

85MPa. The structure was subjected to a 429kN dual rear wheel load and a 630kPa contact stress. It was seen that no excessive vertical compressive strains were generated in the structure, primarily due to the support generated by the shallow rock layer. Maximum surface deflections were approximately 2mm, reducing to 1,52mm in the in-situ material at a depth of 700mm. Deflections at a similar depth for the CBR based design in the in-situ material (800mm) were reduced to 1,43mm (compared with 2,02mm). The proposed optimal design thus provides an improved structural response to the applied loads than does the thicker CBR based design and, in addition, does not contravene any of the proposed design criteria for the particular performance index and traffic volume used in the analysis. .

A cost comparison of the two designs was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. The variable costs taken into account were those of the volume and area of materials required and the associated costs of placing and compaction. By virtue of the reduced material volumetric and compaction requirements associated with the optimal design, a cost saving of R155 060, or 25% was realised. In terms of total construction cost (including preliminary and general costs), a 15% cost saving per kilometre was realised over the CBR-based design.

The optimal mechanistic design derived in the analysis was based on the particular in-situ material strength, applied load and required road performance (at a particular traffic volume) characteristics. If the type of truck changes, or the required performance index or tonnage hauled on the road, these can be modified in the analysis itself according to the proposed relationship between maximum strain and traffic volume/performance. In this respect the mechanistic design methodology and catalogue of values is transferable between sites which exhibit construction materials or traffic volumes within the inference space of the data analysed.