An overview of the structural design of mine haulage roads

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Synopsis

The structural design of a pavement relates to the ability of the road to carry the imposed loads without the need for excessive maintenance or rehabilitation. Current techniques for the structural design of haulage roads are empirical and based primarily on the previous experience of personnel assigned to pavement design, both in terms of the strength of the structure and the quality of the wearing course material. This has the potential for unwarranted expenditure on too thick a structure or, conversely, premature deformation leading to the need for excessive expenditure on maintenance. Furthermore, the effect of larger haulage vehicles on the structural performance of a pavement cannot be predicted. Thus, there is a need to develop a portable and practical method of structural design. This paper presents an overview of structural-design methods for mine haulage roads and, through an analysis and quantification of the structural performance of existing pavements, recommends the mechanistic design procedure, together with a revised structural design and associated limiting design criteria. It is concluded that the application of the mechanistic method to a design project can reduce the costs of haulage roads construction and accrue additional benefit in terms of reduced operating and maintenance costs.

Introduction

Large-scale surface mining in South Africa is a relatively recent innovation. At the turn of the century, open-pit mining, almost without exception, was short-lived and quickly replaced by underground mining. Only in the early 1960s did extensive open-pit mining begin, with mines such as Palabora and Sishen. A decade later, the crisis in the oil industry provided the impetus for the large-scale development of South Africa's coal reserves. Production rose from 66 Mt of run-of-mine coal in 1974 to 260 Mt in 1994. Of this total amount, some 40 per cent, or 106 Mt, was produced by open-cast methods, which require, *inter alia,* the transportation of raw coal from the pit to the loading or transfer point.

In addition to the mechanical-engineering challenges involved in the design and construction of large dump trucks, specific mining-engineering problems arise, primarily as a result of the gross vehicle mass (GVM) and the resultant loading applied to the pavement. Taking the Caterpillar 789 as a typical example of a 170t capacity rear dump truck, the GVM of 317.4 t results in a maximum dual-wheel axle load of 2086 kN, as illustrated in Figure 1. In comparison, public road authorities permit a legal maximum dual-wheel axle loading of 80 kN, which is similar in magnitude to that associated with a 25 t truck with tandem rear axles.

Large mine haulage trucks impose axle loads ranging from 110 to 170 t, which are applied to haulage roads that have been, at best, designed empirically on the premise of 'satisfactory' or 'failed'. This design method served its purpose in an era when off-highway trucks were lighter and less financial outlay was required in terms of the initial costs of pavement construction, the ongoing costs of road maintenance, and the costs of vehicle maintenance. Currently, the costs of truck haulage can account for between 20 and 40 per cent of the total costs incurred by a strip mine and, as the trend in increasing truck size continues, the current pavement systems will prove inadequate. Not only will the maintenance costs of the existing roads of inadequate thickness increase, but vehicle operating and maintenance costs will also increase prohibitively.

The operating performance of a pavement or road structure system can be subdivided into the following three distinct design categories.

- *Structural design.* This concerns the ability of a haulage road to carry the imposed loads without excessive deformation of the pavement and, consequently, the need for excessive maintenance.
- *Functional design.* This refers to the ability of a haulage road to perform its

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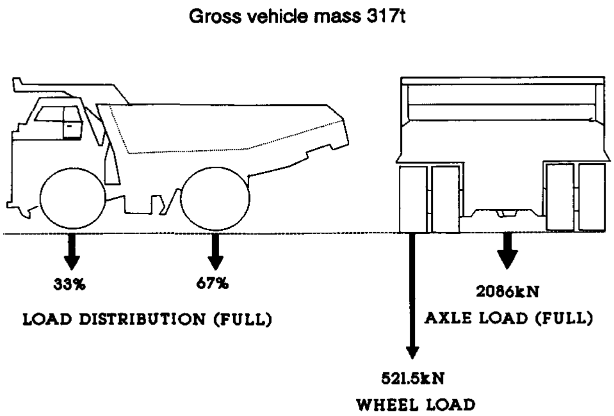

Figure 1—Magnitude of pavement loading associated with a large haulage truck

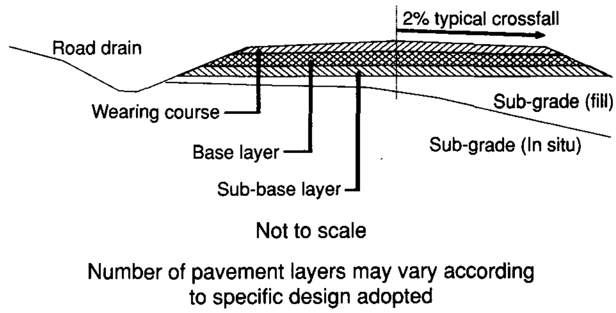

Figure 2—Terminology used to describe the structure of haulage roads

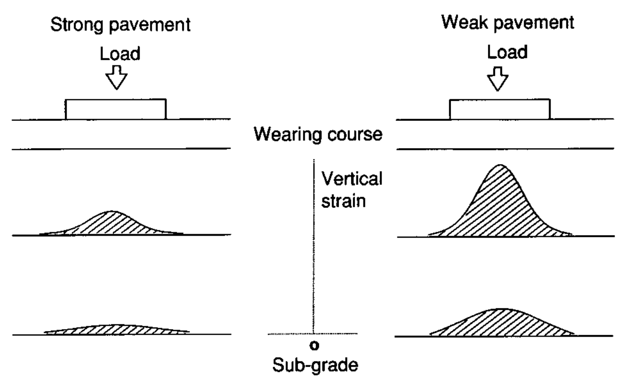

Figure 3—Load-distribution characteristics of a strong versus a weak pavement

function, i.e to provide an economic, safe, and vehicle-friendly ride. The selection of wearing-course materials primarily controls the functional performance.

- *Maintenance design.* The maintenance aspect of haulage-road design cannot be considered separately from the structural and functional design aspects since the two are mutually inclusive. An optimal functional design will include a certain amount and frequency of maintenance (watering, grading, etc.), and thus maintenance can be planned and scheduled within the limits of the expected road performance. The major problem encountered in the analysis of maintenance requirements for haulage roads is the subjective nature of the problem; the levels of acceptability or serviceability for the road are user-specific.

When applied to the design of mine haulage roads, each of these components is addressed singularly, and then combined to produce specific and individual haulage-road designs based on a highly portable, comprehensive, general design strategy applicable to most surface-mining operations. The aim of this paper is to present an overview of structural-design methods for mine haulage roads and, through an analysis and quantification of the structural performance of existing pavements, to recommend a mechanistic design procedure in conjunction with specific design criteria. Through a comparison of the mechanistic design with existing structural designs, it is shown how the mechanistic design can reduce the cost of haulage-road construction and accrue additional benefits in terms of reduced operating and maintenance costs.

Structural design of pavements

The terminology applied in the description of the various structural layers of a pavement is illustrated in Figure 2. The structural design of a pavement concerns the ability of the road to carry the imposed loads without the need for excessive maintenance or rehabilitation.

Pavements deteriorate with time owing to the interactive effects of the traffic load and specific sub-grade material strengths and structural thicknesses. Vertical compressive strains induced in a pavement by heavy wheel loads decrease with increasing depth, as illustrated in Figure 3. This permits the use of a gradation of materials and preparation techniques, stronger materials being used in the upper regions of the pavement. The pavement as a whole must limit the strains in the sub-grade to an acceptable level, and the upper layers must, in a similar manner, protect the layers below. Based on this premise, the road structure should theoretically provide adequate service over its design life.

In an attempt to obtain satisfactory service over the design life of a road, pavement design models can be used to predict performance over a wide range of traffic loads and road structural designs. Pavement structural design is the process of developing the most economical combination of pavement layers (in relation to both the thickness and the type of materials available) that is commensurate with the *in situ* material and traffic to be carried over the design life.

Current state of structural design

The structural design of public (mainly paved) roads has been the focus of considerable attention from as early as the 1920s. The structural design of unpaved roads in the public domain has received less attention, design guidelines having been developed only recently[1]. Similarly, structural-design techniques for haulage roads that promote safer, more efficient hauling have received little attention until recently.

Early haulage road design techniques consisted of placing several layers of granular material over the *in situ* material and, as excessive deterioration occurred, more layers were added to provide adequate strength. In 1977, a research study carried out on behalf of the United States Bureau of Mines[2] (USBM) considered the structural-design aspects of mine haulage roads. It was recognized that a stable road base is a fundamental consideration in road design. The placement of a road surface over any material that cannot adequately support the weight of traffic using it will hamper vehicular mobility and controllability. The findings of the USBM report were that the structural-design techniques for haulage roads were entirely empirical, mine operators often electing to forego the use of sub-base materials and accepting infringements on mobility in the interest of economics. The USBM work was one of the first annotated applications of the California bearing ratio (CBR) cover-thickness design technique for mine haulage roads.

CBR structural-design technique

The load-bearing capacity of a soil is directly related to its shear strength, given by the Mohr–Coulomb equation. Tyre loadings for large haulage trucks generally exceed the bearing capacity of most soils, and thus anything less consolidated than soft rock will not provide a stable base for a haulage road, and other materials will need to be placed over the sub-grade to protect it and adequately support the road structure and traffic.

A survey conducted in 1928–1929 by the California Roads Department to determine the extent and cause of pavement failures concluded that failure was due to inadequate compaction of materials forming the road layers and insufficient cover over weak *in situ* material. These conclusions indicated the importance of material-compaction and shear-strength considerations in road building, both in terms of a suitable design procedure and an associated method of materials testing. The notion of the CBR value for a specific material was thus developed from a laboratory penetration test of a soaked sample of pavement material from which its shear strength could be inferred.

The first indications of cover requirements over *in situ* materials of specific CBR (percentage) values were reported by Porter[3], who enumerated the concept of cover thickness. Later modifications included a consideration of traffic volumes, single wheel loads, and increased wheel loads based on an estimated maximum allowable shear stress for specific materials. The problem of dual-wheel assemblies was addressed by Boyd and Foster[4] through consideration of the equivalent single-wheel load (ESWL), by which a load is calculated that generates the same tyre contact area and maximum deflection as would a group of wheels. The concept of equivalent deflection was used to equate an equivalent single wheel to the multiple-wheel group.

Despite the empirical origins of the technique, Turnbull and Ahlvin[5] derived a mathematical approach to the calculation of cover requirements using the CBR method. This approach is adopted for the calculation of cover requirements over *in situ* material as predicted by the CBR design method for ultra-heavy axles. For the complete mathematical treatise, readers are referred to Turnbull and Ahlvin[5] and Ahlvin *et al.*[6]. A typical CBR cover thickness curve is illustrated in Figure 4 for the case of a Haulpak 630E fully laden dual-wheel rear axle (53 t per wheel). In addition, the actual CBR values for the *in situ* pavement layers are also shown. The CBR cover thickness curve represents the minimum cover thickness required to eliminate over-stressing (and consequential deformation) of the pavement. The line representing the CBR values for the *in situ* pavement layer should then lie to the right of the predicted cover curve if the pavement is adequately designed; to the left if the pavement is under-designed. In this case, layers two and three exhibit strengths below the CBR-predicted minimum cover requirements and the possibility of over-stressing and deformation exists.

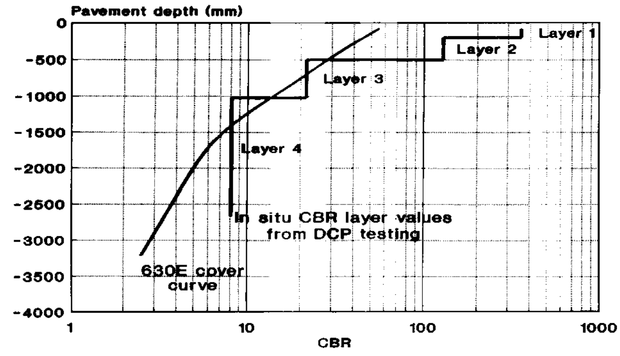

Figure 4—Typical CBR cover curve design for a Haulpak 603E truck (fully laden dual-wheel rear axle) in comparison with in situ pavement CBR derived from analysis by use of the dynamic cone penetrometer (DCP)

Although the CBR approach is an elementary and straightforward empirical structural design technique, based on and improved by considerable design experience, there are numerous disadvantages in the application of the method to the structural design of haulage roads.

- ➤ The method has its base in Boussinesq's semi-infinite single-layer theory, which assumes a constant elastic modulus for the material. Mine haulage road structure consists of numerous layers of differing materials, each with its own specific elastic and other properties.
- ➤ More specifically, the CBR method is based on empirical results from public roads subjected to a maximum axle load of 80 kN. Mine haulage roads are subjected to axle loads that are 25 times as high. Simple extrapolation of these empirical design criteria to accommodate higher axle loads can lead to serious errors of under- or over-design.

The method is thus recommended exclusively to haulage road structural design cases that incorporate single layers only. However, 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 remains to be quantified. Where cemented or stabilized layers are included in the design, or where the optimal structural design is sought, use should be made of other design techniques that can account for the different pavement layer material properties and more accurately predict their performance under the action of ultra-heavy axle loads.

One of the tenets of the CBR cover-thickness design technique is the determination of the bearing capacity of the *in situ* pavement layers. This can be estimated by use of the dynamic cone penetrometer (DCP).

DCP pavement design and analysis

The extensive use of the DCP in the determination of the *in situ* shear resistance of a material has enabled predictive models of pavement performance to be developed for thin-surfaced, unbound-gravel, flexible road pavements, together with the correlation of the DCP results with the CBR[7,8], as well as with the 7-day soaked unconfined compressive strength (UCS) of lightly cemented materials (UCS < 3000 kPa), as discussed by Kleyn[9] and De Beer[10].

Although the DCP instrument is ideally suited to the evaluation of existing pavements, the original research[7] was used to establish a design method for new pavements. This design approach is, in principle, similar to the CBR approach in that over-stressing of the lower layers is prevented through a balanced increase in layer strength. The DCP instrument can be used in the investigation of haulage-road structural design for the analysis of

- the location of various pavement interfaces
- the CBR values of these various layers
- the overall balance of the structural design.

A first attempt at the recognition of pavement layers can be made from a DCP-generated layer strength diagram. This relates the depth of each layer (vertical axis) to the CBR on the horizontal axis. The CBR values are derived from the DCP penetration, as described by Kleyn and Van Heerden[11]. The typical *in situ* pavement layer CBR profile shown in Figure 4 was derived accordingly.

Although the DCP data afford an insight into 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 be determined only from an analysis of the response of each layer to the applied loads. When the deficiencies inherent in the CBR cover-curve design technique and the DCP characterization are considered from the point of view of the structural design of mine haulage roads, it would appear that a more formal technique is required in which pavement-layer material is assessed more rigorously in both single- and multi-layered structures.

Mechanistic structural design

The mechanistic approach to pavement engineering involves the calculation of stresses, strains, and deflections in the pavement based on the extension of Boussinesq's single-layer theory to multiple layers. The approach adopted for a mechanistic analysis and design embraces the prediction of material behaviour prior to construction through appropriate laboratory and field tests. The response of a pavement to an applied load is simulated, and the stresses and strains generated in each pavement layer are compared with limiting design criteria. This contrasts with the CBR method, in which empirical designs are based on data obtained from actual pavement behaviour in response to an applied load.

Empirical design criteria are to some extent a requirement of all structural-design techniques. While the CBR-based approach is entirely empirical and therefore subject to limitations imposed by the characteristics of the data, the mechanistic approach, although including an empirical component, relies on mechanistically derived data to which empirical procedures are applied, therefore extending the applicability of the technique. Typical benefits of the mechanistic–empirical approach are as follows.

- It can accommodate changing loads and their impact on the structural performance of a pavement.
- It can utilize available construction materials in a more efficient manner.
- It can accommodate new materials.
- The performance predictions are more reliable.
- The material properties used in the design process are more closely related to the field performance of the structure.
- The definition of existing pavement-layer properties is improved.

A simple and convenient method to assess the structural properties of pavements involves the application of a load and measurement of the resulting depth-deflection profile. This is most readily achieved through the use of a multi-depth deflectometer (MDD), which is described by De Beer *et al.*[12] and Basson *et al.*[13]. In essence, an array of six linear voltage-differential transducers is used to determine individual pavement layer deflections resulting from an applied load. These deflections are compared with those generated iteratively from the ELSYM5A[14] multi-layer analysis program under various assumed values for the effective elastic modulus of pavement layers until the observed and calculated deflections agree to within pre-determined ranges. Once the moduli of the individual layers have been resolved, the stresses and strains can be determined and compared with established design criteria to verify whether critical stresses or strains have been exceeded.

As little published data exists concerning established design criteria for haulage roads, the most tractable approach is to identify the damage parameters applied in the design of roads subject to standard axle loadings and, by categorization of the structural performance of haulage-road test sections, deduce acceptable limiting design criteria for the structural design of haulage roads. The development of empirical limiting fatigue or distress criteria applicable to the structural design of mine haulage roads can then be used to evaluate the structural performance of a pavement and, if necessary, the efficacy of corrective measures or new structural designs.

Since much of the structural deterioration of a pavement is attributable to the stresses or strains developed in individual pavement layers, these parameters are important in a consideration of limiting design criteria. Vertical strains in the top of the sub-base and sub-grade layers are associated with rutting and deformation, while horizontal strains in the upper, stabilized layers are associated with cracking.

According to this strategy, two design criteria can be identified from conventional road design.

Vertical (compressive) strain

Limitations are usually placed on the permissible compressive vertical strains at the top of sub-grade layers to prevent rutting and subsequent deformation of the road. Three pavement characteristics influence the magnitude of sub-grade strains under the application of a constant wheel load:

- resilient modulus of the wearing-course material
- thickness of the wearing-course layer
- resilient modulus of the sub-grade.

The design criterion for the layers below the wearing course is that of horizontal tensile strain or vertical compressive strain, depending on whether the layers have been stabilized or not. These relate to the failure criteria of fatigue cracking in the stabilized layers and rut initiation in the sub-grade respectively. There are no published data relating the limiting values for strains in a haulage road associated with adequate structural performance. Recourse must be made to categorization of the performance from which limiting values of vertical strain can be deduced, taking cognizance of the characteristics listed.

Factor of safety (FOS)

Granular materials exhibit distress through cumulative permanent deformation or inadequate stability. Both forms of distress are related to the available shear strength of the material and, to prohibit shear failure or excessive gradual shear deformation in the layer, the shear stresses generated must be limited.

While the FOS at any point in a layer can be deduced from consideration of the applied load and shear-strength characteristics of the material[15], in the structural design of haulage roads, extrapolation of established FOS values is unreliable owing to the uncertainty surrounding the damage attributable to ultra-heavy axle loads. Thus, in the deduction of limiting safety factors, recourse must be made to the categorization of actual haulage-road performance.

Sensitivity of the materials to stress

In addition to the characterization of the pavement-layer response in terms of limiting design criteria, it is important that the stress-sensitivity to of the material comprising these layers should be assessed. Departures from the expected behaviour (especially the predicted stress-hardening in granular materials)[16] may lead to under-design. The stress dependency of unbound gravel layers comprising the structure of haulage roads needs to be assessed at the load levels encountered with large haulage trucks so that the structural integrity of a particular road or design can be predicted.

The vertical compressive strain, FOS, and stress sensitivity of the materials comprising each pavement layer at a test site were determined from the results of the ELSYM5A analysis for the various loads applied. The effective modulus of elasticity (E_{eff}) and Poisson's ratio (μ) define the material properties required for the computation of the deviator and sum of the principal stresses and strains (vertical ε_v and horizontal ε_h) in a pavement structure. In addition to the material properties, the layer thickness is specified, in this case with reference to the DCP-derived data for the re-defined structural thickness of the layers. Figure 5 summarizes the layered elastic model, the data requirements, and the design criteria adopted in the analysis.

Comparison of various design methods

In a determination of the suitability of the previously mentioned techniques of structural design as they apply to mine haulage roads, existing mine pavements were assessed in terms of a number of independent variables (factors) that were recognized as predominantly controlling the structural performance of a haulage road. These factors are applied load, strength of the sub-grade, and structural thickness and strength of the layers.

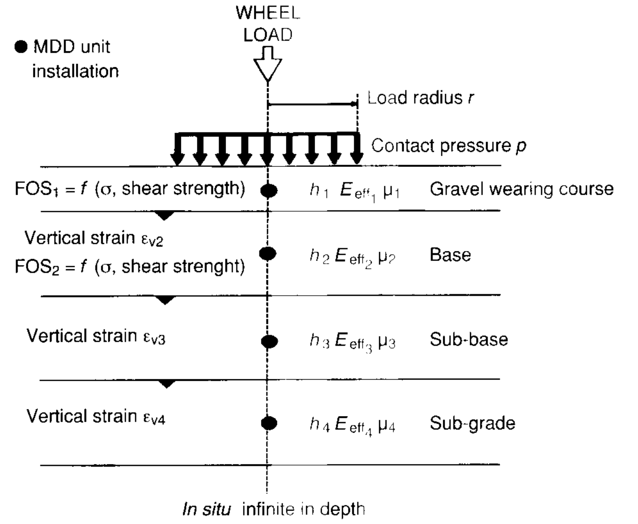

Figure 5—Model of a layered elastic pavement for mechanistic structural design and analysis

The structural performance of existing haulage-road designs were fully characterized through the analysis of each combination of factors at various levels by use of a designed factorial experiment. Nine test sites were identified at three mines, which enabled 27 factor combinations to be assessed. For each of the independent variables, actual field values were recorded, together with the resilient deformations in each of the test-site pavement layers and sub-grade. By this approach, the utility of each design method was assessed over a range of factor levels, enabling a comparative analysis to be completed for all combinations of haulage-truck loads, construction materials, structural thicknesses, and layer strengths.

As a precursor to the analysis of the structural performance of haulage roads and the derivation of limiting design criteria, a classification was drawn up of the structural performance of haulage roads to indicate in broad terms the adequacy of the various designs encountered at each mine test site. This was achieved by the assignment of an index to each site representing poor to excellent structural performance, together with a short summary of the structural defects observed or reported by mine personnel. In addition, the maximum deflection recorded by the MDD in the structure was depicted for each site as an aid to classification.

DCP analysis

Nine mine haulage-road test sites were evaluated in terms of the layer profile, layer CBR, and balance of the design. A range of pavement designs were encountered. In general, the test sites in which most of the pavement strength lies in the upper layers were found to be more sensitive to increased wheel loads and consequential failure of the upper layers. In contrast, a test site where the supporting layers were strong was less sensitive to any increase in wheel loads, but excessive deformation in the weaker upper layers could occur. However, the extent to which these effects occur in haulage roads and the degree to which each type of design fulfils the structural performance requirements could be confirmed only by correlation with the results of the mechanistic analysis.

CBR analysis

The CBR method has been widely applied to the design of surface haulage roads in which untreated materials are used. In essence, the method relates the cover thickness required to the *in situ* bearing capacity, thereby eliminating over-stressing and consequent deformation of the sub-grade due to axle loading.

The results relating the required cover thickness and CBR value for a particular vehicle and the actual (as constructed) cover were compiled for each test site, using the particular vehicle for which the road was constructed and the largest vehicle currently operated. The results ranged from potential under-design of the road (inadequate cover) to probable over-design (excessive cover). In the case of the indicated under-design, there was a correlation between poor structural performance as determined from the performance classification and inadequate CBR values for the pavement layers. Recourse to mechanistic analysis is necessary to quantify the extent of any over- or under-design recognized from the CBR approach, since each layer cannot be assessed independently in terms of its load-bearing capability by use of the latter technique. The technique can, however, be used to generate reliable estimates of the total cover over the *in situ* material, subject to the limiting assumption of a single layer. Where multi-layer structures are involved and the optimal design is sought, the mechanistic approach is more appropriate.

Mechanistic analysis

Two design criteria were proposed for the assessment of the structural performance of mine haulage roads: the vertical compressive strain in each layer below the top layer, and the FOS for the two uppermost layers. Figure 6 relates the vertical strains in each layer for three typical test sites; the other sites exhibited similar responses. A comparison of these data with the performance classification showed that the vertical strain criterion correlates well with the structural performance of the road; those mine sites exhibiting poor performance and an associated excessive deformation or maximum deflection were associated with large values of vertical compressive strain in one or more layers. From an analysis of all the data, it was found that the vertical strain values should not exceed 2000 microstrains. Higher strain values were found to be associated with unacceptable structural performance.

With regard to the FOS for the upper layers, it was found that this criterion is not applicable to the design of haulage roads since the FOS is a function of the failure load carried by each layer, which is not normally attained. In the absence of any definitive criterion, a 200 mm layer of compacted (95 to 98 per cent Mod. AASHTO) good-quality gravel is recommended for the wearing course. This recommendation is derived from the observation of wearing-course layers at mine sites that exhibited adequate structural performance.

Regarding the propensity of the various pavement layers to stress-harden or -soften, some localized evidence of stress-hardening and -softening was seen. However, this is more a function of the specific construction material used at each site rather than a universal phenomenon.

If the CBR cover-curve design (Figure 4) is compared with the vertical-strain results for the same site (site 1 in Figure 6), it can be seen that the outcome of the CBR technique is under-design of the pavement at site 1, specifically in terms of the excessive vertical strains in layers 3 and 4. This is evidenced by the approach of the top of layers 3 and 4 to less than the minimum cover requirements. In the case of site 2, under-design was also apparent. This is due in part to the very different CBR profile from that of the mechanistically generated profile of effective elastic moduli. The pavement design at this site included a layer of dump rock (layer 3) at

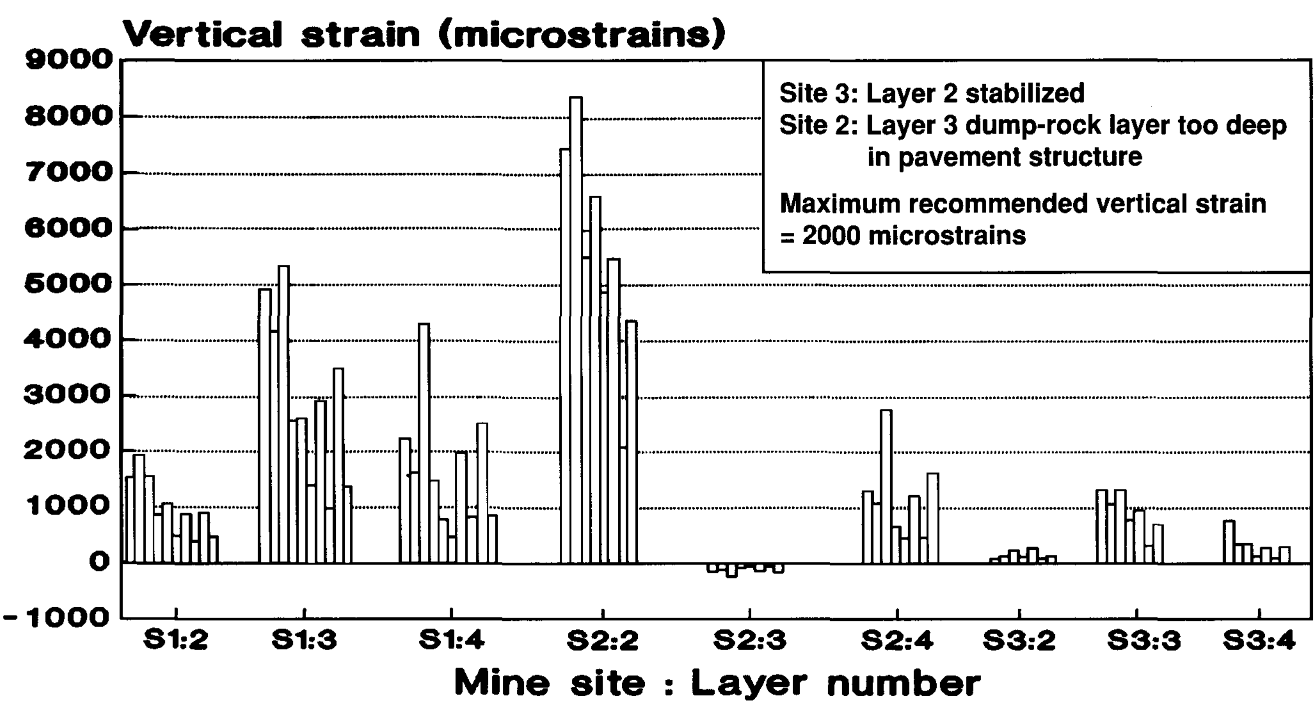

Figure 6—Vertical strain recordings for various test sites and layers under a range of wheel loads

depth and, although vertical strains are much reduced, the deep rock layer does not appear to improve the performance of the road, as indicated by the CBR-predicted over-design. At site 3, it was seen that, despite the fact that most of the pavement strength lies in the upper layers, the road performs well and is not susceptible to the effects of high axle loads in the upper layers, primarily because of the load-carrying capacity of the stabilized layer (layer 2). This result has important implications in terms of the optimal structural design of a road.

The proposed structural design for pavements is based on the findings from the mechanistic analysis of existing haulage roads. Of particular importance in this respect is a road that incorporates a stabilized layer immediately below the wearing course. Although stabilization techniques are expensive and the layers themselves are subject to cracking if not adequately designed, the most tractable option is the use of mine spoil rock in place of a stabilized layer. This provides increased resilience to the applied loads without the need for excessive structural thickness.

Summary of comparative analyses

From the foregoing, it is evident that both the DCP and the CBR techniques of structural design have only limited applicability in the design of mine haulage roads. The DCP technique can be employed in the determination of the location of various pavement layers and their associated CBR values. In general terms, the pavement strength profiles to be avoided are those incorporating strong or stabilized layers deep in the structure, which are associated with excessive vertical strains in the pavement. Although the DCP data afford 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 be determined only from an analysis of the response of each layer to the applied loads.

As regards the CBR structural-design technique, under-design can be associated with poor structural performance, but the extent of any potential under- or over-design cannot be quantified. When the DCP re-defined layer strengths were analysed in conjunction with the CBR cover curves generated, it was found that the DCP method, when applied judiciously, can be used in the determination of safe (total) cover over *in situ* materials. The method is thus exclusively recommended for single layer design cases. Where cemented or stabilized layers are included in a design, or where the optimal structural design is sought, owing to the very different properties of the layer from those of normal road-building gravels, use should be made of design techniques that can account for the different material properties and more accurately predict their performance.

Based on the experimental work completed, the mechanistic method appears to provide the most tractable and reliable approach to the structural design of haulage roads in which the limiting vertical strain in each layer is used as the design criterion. In addition, as shown by the analysis of the various structural designs encountered, the inclusion of a rock layer immediately below the wearing course confers additional benefits in terms of reduced structural thickness for similar load-bearing capacities. The mechanistic-design procedure, together with the design criteria and optimum design thus established, was applied to a typical structural design case study, and the results of which are discussed in the next section.

Case study of mechanistic design

The optimal mechanistic structural design of a haulage road for a surface mine embodies the selection of target effective elastic modulus values for the construction materials and the placement of those materials so as to optimize their performance both as individual layers and over the entire structure. The performance was analysed in terms of the minimum thickness and compaction of the wearing course and the limiting design criterion 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 afforded the structure increased resilience to the applied loads without the need for excessive structural thickness.

For comparative purposes, two design options were considered: a conventional design based on the CBR cover-curve design methodology, and a mechanistically designed optimal equivalent as discussed previously. It was assumed that the *in situ* and road construction material properties remained the same irrespective of the design technique adopted. For both options, a wearing course with a minimum thickness of 200 mm compacted to a density of 98 per cent Mod. AASHTO was adopted. A Euclid R170 truck was used to assess the response of the structure to applied loads generated by a fully laden rear dual-wheel axle, and the assumption was made that no load-induced deflections exist below 3000 mm. The various design options are summarized in Figure 7.

CBR cover-curve design

The cover-curve and layer-strength diagram was developed as discussed previously, based on a CBR value of 17 per cent minimum for the compacted *in situ* material. Structural-design data are given in Table I. To determine the likely structural performance of the road in the light of the critical design factors previously identified, a mechanistic analysis was conducted by use of the ELSYM5A program and the assignment of target values of effective elastic modulus for each layer. These values were determined from a classification of the materials comprising the pavement layers in terms of grading, Atterberg limits, CBR, swelling, and field compaction[17].

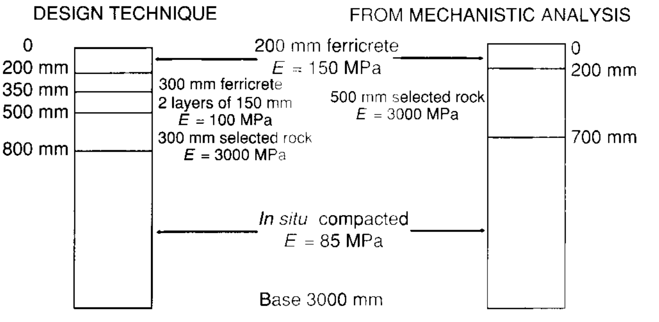

Figure 7—Details of the structural-design options

Table I

CBR structural-design data

Layer	Layer thickness mm	Mod. AASHTO compaction %	CBR achieved %	Target effective elastic modulus MPa	Material description
1	200	98	90	150	Selected ferricrete
2	150	95	50	100	Selected ferricrete
3	150	93	35	100	Selected ferricrete
4	300		25	3 000	Selected sandstone ex-pit <300 mm block size
5	*In situ*		17	85	*In situ* compacted

Figure 8 presents the results of the mechanistic analysis of the CBR-derived cover-curve design. It is evident that excessive vertical compressive strains were generated in the tops of layers 2 and 3. The strains in excess of 2000 microstrains were associated with an unacceptable amount of rutting and pavement deformation. The surface deflections generated by the applied load of 3,65 mm did not appear to be excessive but, when accompanied by severe load-induced strains, will eventually initiate structural failure. The comments made regarding the inapplicability and under-design apparent when the CBR design technique is used are borne out by these results, specifically the large vertical strains developed in the pavement as the design strengths of the layers approached the cover-curve line.

Optimal haulage-road design

The design adopted is depicted in Figure 7 and described in Table II. The design was analysed mechanistically to determine the likely structural performance of the road in the light of the critical design factors previously identified.

Figure 8 also shows 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 owing to the support generated by the shallow dump-rock layer. The maximum values of vertical strain do not exceed the limiting design value of 2000 microstrains, and the maximum surface deflections are approximately 2 mm. The proposed optimal design thus provides a better 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.

Table II

Optimal structural-design data

Layer	Layer thickness mm	Mod. AASHTO compaction %	CBR achieved %	Target effective elastic modulus MPa	Material description
1	200	98	90	150	Selected ferricrete
2	500		>200	3 000	Selected sandstone ex-pit <300 mm block size
3	*In situ*		17	85	*In situ* compacted

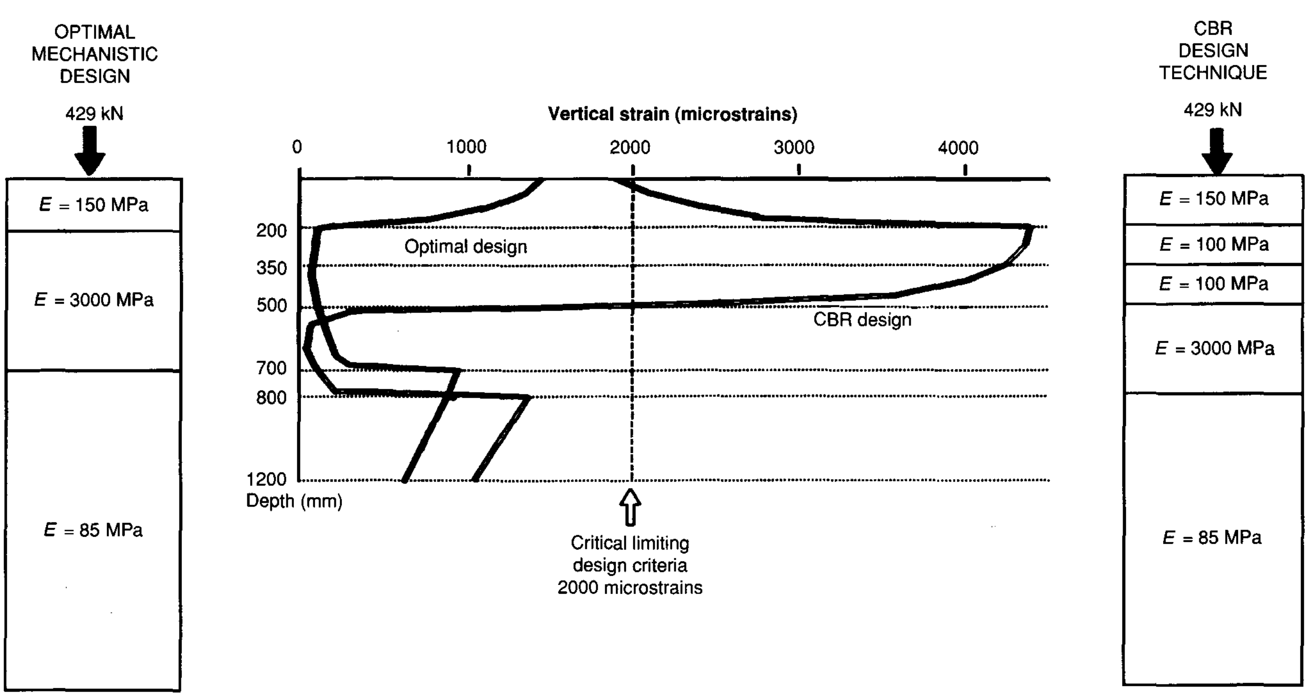

Figure 8—Results in terms of design criteria for vertical strain as determined for the CBR and mechanistic optimal designs

Cost implications of optimal design

A cost comparison was compiled, based on contractor tender unit costs, for the construction of a road designed according to the CBR cover-curve technique and one constructed according to the mechanistically derived optimal design. Included in the comparison were contractor's preliminary and general costs, which were assumed to remain constant irrespective of the structural design adopted. It was also assumed that rock and borrow-pit materials were within the free-haulage distance of the construction site.

The variable costs taken into account were those of the volume and area of materials required, and the associated costs of placement and compaction. The equivalent cost of the optimal mechanistic design was calculated from the actual construction costs of the conventional design. It was found that there was a 28.5 per cent saving in variable costs realised, by virtue of the reduced material-volumetric and -compaction requirements associated with the mechanistic optimal design. In terms of the total construction cost (including the preliminary and general costs), there is a total cost saving of 17,4 per cent. In addition, further benefits should accrue in terms of the reduced operating and maintenance costs arising from the superior structural performance of the road as evidenced from the foregoing analysis.

Summary

Various structural-design methods for pavements were assessed in terms of their applicability to the design of haulage roads. Although the DCP data afford 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 be determined only from an analysis of the response of each layer to the applied loads. As a precursor to the analysis, the CBR design technique was investigated in which data generated from the DCP investigation were compared with the cover requirements predicted from the CBR-design method.

The deficiencies inherent in the development of the CBR-design method, together with the potential for under-design associated with multi-layer structures, limit the utility of the technique when applied to the structural design of mine haulage roads. The method can, when applied judiciously, be used in the determination of a safe (total) cover over *in situ* materials, although the extent of over- or under-design associated with the method cannot be quantified. The method is thus exclusively recommended for the design of single-layer pavements. Where cemented or stabilized layers are to be used, or where the optimal structural design is sought, the mechanistic design technique should be employed.

The derivation of the design criteria for the mechanistic design of surface-mine haulage roads is based on categorization of the structural performance of those roads and, as such, reflects a range of structural designs and performance. Of the two design criteria proposed, that of vertical strain correlates well with the structural performance of a road, and an upper limit of 2000 microstrains is proposed for the layers of a pavement. The FOS criterion is not applicable to haulage-road design since the FOS is a function of the failure load carried by each layer, which is normally not attained. In the absence of any definitive criterion, a 200 mm layer of compacted (95 to 98 per cent Mod. AASHTO) good-quality gravel is recommended for the wearing course.

The recommendations regarding the structural design of surface-mine haulage roads are centred on the inclusion of a layer of dump rock within the structure. The optimal location of this layer is immediately below the wearing-course layer. Using this approach, a reduced structural thickness is realized without the attendant deformation and reduction in structural performance that would otherwise be evident without a rock layer. An analysis of the proposed optimal design in a case study comparing it with the conventional CBR design indicated that the mechanistically derived optimal design provides an improved structural response to the applied loads and, in addition, does not exceed any of the proposed design criteria. As a result of the reduced structural thickness, a saving in construction costs of 17,4 per cent over those for the conventional design is realized, together with further benefits as a result of the reduced operating and maintenance costs arising from the superior structural performance of the road.

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