The functional design of surface mine haul roads

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Synopsis

The functional design of a pavement relates to the selection of appropriate wearing course materials which optimise the trafficability of a pavement. Trafficability is dictated to a large degree by the choice, application and maintenance of locally available wearing course materials. Poor functional performance results in decreased safety and operational efficiency and increasing road and vehicle maintenance requirements. An optimal functional design will include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance itself can be planned, scheduled and optimized within the limits of required road performance and minimum vehicle operating and road maintenance costs. Since no wearing course material selection guidelines, tailored to the specific needs of surface mines, were available, there was the need to identify appropriate selection guidelines for the range of materials commonly encountered for road building on South African mines.

The aim of this paper is to present an overview of the functional design method for mine haul roads and, through an analysis and quantification of existing wearing course material performance, to recommend appropriate wearing course material selection guidelines. The functional design technique has been applied at a number of mines and is illustrated by an application case study which demonstrates the potential reduction in total transportation operating costs associated with the optimal functional design.

Introduction

Surface mining in South Africa accounts for over 70% of copper, 80% of ferrous metals and 95% or 65 million tons of the land's industrial mineral mining. In the coal mining industry in 1997, over 40% or 106 million tons run-of-mine coal which requires *inter alia,* the transport of raw coal from the pit to the loading or transfer point, was produced by opencast methods. In any surface mining operation, the transport of ore, and to a lesser extent waste, is accomplished by large haul trucks running on haul roads that have, at best, been empirically designed with little or no recognition of the consequences of inadequate design on cost per ton hauled, operational efficiency or safety. Considering that truck haulage costs can account for up to 50% of the total costs incurred by a surface mine, it is of paramount importance that these costs are minimized. This becomes all the more critical as tonnage increases and larger haul trucks are deployed. Not only do the maintenance costs of existing roads of inadequate design increase but, vehicle operating and maintenance costs also increase prohibitively.

The operating performance of a pavement can be subdivided into three distinct design categories as defined in Figure 1. The structural design of surface mine haul roads has been addressed previously (Thompson and Visser)[1,2]. Just as important as the structural strength of the design, is the functional trafficability of the pavement. This is dictated to a large degree through the choice, application and maintenance of wearing course materials. The current functional performance analysis methods are subjective and localised in nature and any deterioration in pavement condition is consequently hard to assess. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. The result of these effects is seen as an increase in overall vehicle operating and maintenance costs.

The maintenance aspect of haul road design cannot be considered separately from the structural and functional design aspects since the two are mutually inclusive. Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs. Whilst it is possible to construct a mine haul road that requires no maintenance over its service life, this would be prohibitively expensive—as would the converse, the latter in terms of operating and maintenance costs. An optimal

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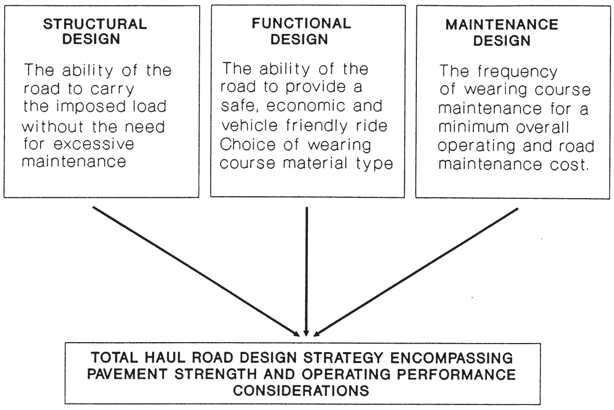

Figure 1—Three components of a total haul road design strategy

functional design will include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance can be planned, scheduled and optimised within the limits of required road performance and minimum vehicle operating and road maintenance costs. The major problem encountered when analysing maintenance requirements for haul roads is the subjective and localised nature of the problem—levels of functionality or serviceability being user- and site-specific. No guidelines exist for maintenance management and scheduling for specific levels of functionality, nor for the cost implications thereof, both in terms of vehicle operating and road maintenance.

Geometric design refers to the layout and alignment of the road, in both the horizontal (curve radius, etc.) and vertical (incline, decline, ramp gradients, cross-fall, super-elevation etc.) plane, stopping distances, sight distances, junction layout, berm walls, provision of shoulders and road width variation, within the limits imposed by structural, functional and maintenance design parameters. The ultimate aim is to produce an optimally efficient and safe geometric design and considerable data already exists pertaining good engineering practice in geometric design. Suffice it to say that an optimally safe and efficient design can only be achieved when sound geometric design principles are applied in conjunction with the optimal structural, functional and maintenance designs (Thompson *et al*)[3].

The aim of this paper is to present an overview of the functional design method for surface mine haul roads, specifically the development of wearing course material selection criteria. The results of a functional performance survey of existing wearing course materials are presented, from which modelling and categorization of material performance and the derivation of optimal selection parameters follows. The functional design technique has been applied at a number of mines and is illustrated by an application case study which demonstrates the potential improvements in wearing course trafficability and the associated reduced maintenance requirements.

Current State of Mine Haul Road Functional Design

Compacted natural gravel and crushed stone and gravel mixtures have been widely used in strip coal mines for haul road construction, especially for base and wearing course layers. The functional design of a haul road is the process of selecting the most appropriate wearing course natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations.

Most mines use cost per ton material moved as an immediate measure of haulage efficiency and in general terms the contribution of haulage costs to total mining working costs may vary between 10-50%. When considering those factors influencing the cost per ton hauled and the truck/road interaction, those with most significant impact on the functional performance of the road are rolling resistance and trafficability. These two factors can have a significant impact on both immediate and long term performance and cost. Recent work by Paige-Green[4] has illustrated that the choice of wearing course material is critical to optimal functional performance, not only in terms of rolling resistance and trafficability, but also in terms of numerous other defects which, in combination, will greatly affect user costs or the cost per ton hauled.

Kaufman and Ault[5] provide an early insight into haul road functionality through a limited consideration of general road performance. They stated that the primary characteristics to be considered were road adhesion and rolling resistance and the most practical construction materials recognised were asphaltic concrete, crushed stone or gravel and stabilized earth. The concept of functionality was not specifically introduced but rather alluded to in terms of some of the defects reported with these various construction materials. Large rocks were seen to lead to excessive tyre replacement costs, whilst excessive fines or poor compaction led to dust problems. The impact of the dust problem on haulage operations was related to excessive vehicle maintenance costs and reduced visibility. Dust control by watering was associated with adhesion problems and erosion of the road surface, especially where poorly compacted or unstabilized earth was employed. In conclusion, they recommended crushed stone or good quality natural gravel as wearing course materials, together with specifications for gradation and Atterberg limits.

Off-highway vehicles were until recently considered 'rugged' and the quality and condition of a mine haul road were not sensitive factors in the application of surface mine transport. Recently, due to the increasing size and variation in the design of haul trucks and the changing economic climate (altering the balance in the trade-off between haul route quality, productivity and haul truck maintenance costs) more attention has been given to these factors. Kondo[6] suggested that haul trucks are more sensitive to haul road conditions when travelling at speed than are standard vehicles with a more responsive suspension. This has been attributed, in part, to the generation of harmonics in the vehicle frame. Combined with high impact stresses produced by irregularities in the road, these vibrations can lead to metal fatigue, often manifest as failure of the goose neck connections on bottom dump trucks. More recent work by Deslandes and Marshall[7] recognised haul road surface quality as being an important factor influencing structural fatigue damage of haul truck frames. Recommendations were made with regard to road maintenance and construction practices generally in geometric terms, but also including reference to the reduction of road surface roughness where laden travel occurs and at bends and intersections.

Wearing Course Materials

Work by Kaufman and Ault[5] concerning the choice of wearing course materials highlighted the most appropriate material characteristic design parameters, namely rolling resistance and adhesion. The most common wearing course material for haul roads remains compacted gravel or gravel and crushed stone mixtures. In addition to their low rolling resistance and high coefficient of adhesion, their greatest advantage over other wearing course materials is that roadway surfaces can be constructed rapidly and at relatively low cost. As with structural designs, if local mine material can be used for construction, the costs are all the more favourable. This cost advantage is, however, not apparent in the long term if the characteristics of the wearing course material result in sub-optimal functional performance.

Wearing course gravel characteristics have been described additionally by Fung[8], McInnes[9], Atkinson and Walton[10] and Taylor and Hurry[11]. These specify, in general, a good quality natural gravel or crushed stone. Whilst these limited characteristics broadly define the suitability of materials used for wearing course construction, they are generally lacking in their ability to predict the functional performance of haul roads. Numerous material selection guidelines for unpaved public roads have been developed, including those of the Committee of State Road Authorities (CSRA) TRH14[12] and TRH20[13], illustrated in Figure 2, which are based on performance or defect-related specifications. The suitability of these guidelines needed to be investigated in terms of the required functionality of the haul road and the performance of existing pavements. As a first step in isolating typical haul road functional performance defects, it is necessary to review ideal wearing course requirements.

Ideal Wearing Course Requirements

Whilst immediate measures are useful to a mine in assessing short-term road functional performance, the definitive economic analysis of haul road functionality is based on the comparison of the benefits and costs of providing other alternatives. Benefits are seen as overall cost savings through increased productivity and reduced fuel, tyre and maintenance costs. Improved functional performance implies a reduction in pavement defects and since functional performance is based almost entirely on qualitative measure, it is useful to review typical unpaved road defects.

McInnes[9] introduced the concept of wearing course trafficability in which a number of ideal requirements were alluded to. Building on and updating this approach, an ideal wearing course for mine haul road construction can also be considered by modifying public unpaved road requirements following Netterberg[14] and Paige-Green[4];

- The ability to provide a safe and vehicle-friendly ride without the need for excessive maintenance.
- Adequate trafficability under wet and dry conditions.
- The ability to shed water without excessive erosion.
- Resistance to the abrasive action of traffic.
- Freedom from excessive dust in dry weather.
- Freedom from excessive slipperiness in wet weather.
- Low cost and ease of maintenance.

The relative importance of the various characteristics comprising overall functional performance needs to be assessed, as they apply to mining operations. The effect of haul road functional performance and maintenance on mine economics and safety is not well defined at present. However, it is clear that a strong relationship exists between road structural and functional performance and safe, economically optimal mining operations.

For existing operations, which may not have optimally designed and maintained systems, the problem of identifying existing deficiencies, quantifying their impact and assigning priorities within the constraints imposed by limited capital and manpower, is problematic. Assessing the impact of various haul road functional deficiencies in order to identify the safety and economic benefits of taking corrective actions such as more frequent maintenance, regravelling or betterment, is hampered by the lack of a problem-solving methodology which can address the complex interactions of various components in a haulage system. This is reflected in the fact that most surface mine operators agree good roads are desirable, but find it difficult to translate this into proposed betterment activities.

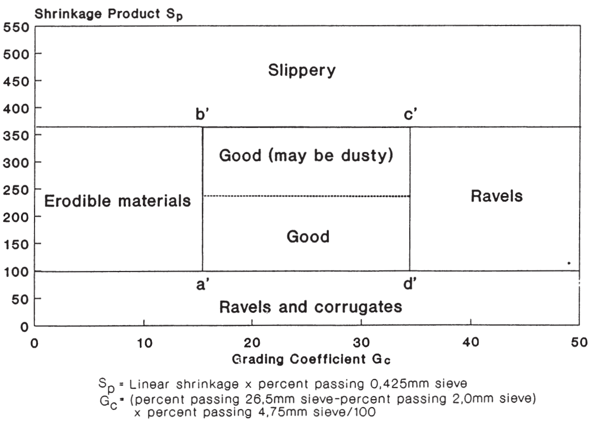

Figure 2—Wearing course gravel material selection guidelines for public roads (after CSRA TRH20[13])

Functional performance survey

A functional performance survey of existing wearing course materials was undertaken to establish the trafficability of existing wearing course materials used for haul road construction and to ascertain the validity and applicability of published (unpaved public road) selection guidelines. The most efficient approach entailed the analysis of a number of in-service mine roads which covered the greatest range of the major factors influencing functional performance. This was achieved through use of a designed factorial experiment where a number of dependent (D) and independent (I) variables (factors) were analysed at various levels. Table 1 summarizes these variables.

Choice of wearing course materials was limited to those weathering products (as defined by Weinert[15]) typically encountered in strip coal mining areas and included pedocretes, argillaceous, arenaceous, basic crystalline and

Table I

Summary of dependent and independent variables and measuring systems

Variable	Measurement System
Traffic volume (D)	Production statistics
Wearing course material (I)	Laboratory classification
Days since last maintenance (D)	Mine records
Moisture conditions of surface layer (D)	Functional assessment methodology
Surface drainage conditions (D)	Functional assessment methodology
Surface erosion (D)	Functional assessment methodology
Functional performance (D)	Functional assessment methodology
Road geometry (I)	Survey plans
Rut depth and corrugation geometry (D)	Straight edge

acid crystalline, together with mixtures of these. Climate was discounted as an independent variable since most strip coal mines were situated within the same physiographical (N-value) region (following Weinert[15]) and thus the weathering products used as levels for the independent variable of wearing course material were unique and limited to that physiographical region (N=2 to N=5). Sixteen test sites which covered the greatest number of factors were established and the functional performance of these sites was monitored over a 12-month period.

Since existing mine haul road functional performance analysis methods were subjective and localized in nature, a new visual assessment methodology was developed, based on recorded defects on unpaved public roads[13,16] and the Standard Visual Assessment Manual for Pavement Management Systems[17], suitably modified to accommodate the requirements of mine haul road operators.

The condition of the pavement was considered from the point of view of the road user and incorporated appraisal in terms of those characteristics that affect the quality of travel. The assessment is entirely qualitative and to reduce the amount of subjectivity involved, distress characteristics are recorded in terms of degree and extent. The degree of a particular type of distress is a measure of its severity. Degree is indicated by a number where Degree 1 indicates the first evidence of a particular type of distress and Degree 5 very severe distress. The extent of distress is a measure of how widespread the distress is over the test section. Extent is indicated by a number where Extent 1 indicates an isolated occurrence and Extent 5 an extensive occurrence of a particular type of distress. The descriptions of extent are not associated with a specific functional defect and the rating of extent was applied only to those defects related to the wearing course material. Defects relating to formation and function (drainage, erosion and skid resistance) are analysed only in terms of degree. The general descriptions of degree and extent are given in Addendum 1.

By summing the product of each wearing course defect degree and extent, formation and function (degree only), a total functional defect score could be found for each surveyed section of road. Figure 3 shows how individual and total functional defect scores were characterised for one mine test site.

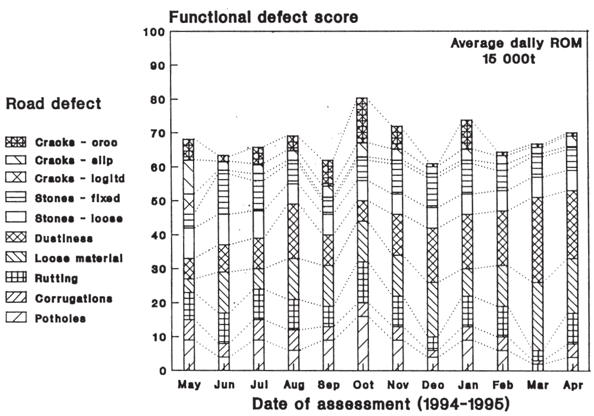

Figure 3—Typical functional performance assessment results over a 12-month monitoring period

Modelling haul road functional performance

A functional performance assessment of the mine test sites in terms of individual defect score variations with time, does not enable predictions to be made regarding the effect of traffic volume, wearing course material type, material properties or maintenance intervals on the functional performance of the haul road; nor can the propensity of a particular material property to contribute to a particular haul road defect be analysed.

The development of a predictive model for defect score progression with time is critical both in terms of the development of a maintenance design model for mine haul roads and as a measure of pavement condition that can be directly associated with vehicle operating costs. The defect score at a particular point in time is a reflection of the type of wearing course material used and its engineering properties, the level of maintenance, season and traffic volumes. Whilst a slight seasonal fluctuation in functionality was observed, the comparatively frequent watering and blading activities on mine haul roads obscured any significant seasonal variations. Thus in the analysis of the effect of maintenance on defect scores which follows, a combination of defect scores and maintenance interval data over both seasons was adopted and seasonality ignored.

A defect score progression model was hypothized as shown in Figure 4, based on four distinct traffic, maintenance and wearing course material interactions;

(A) Immediately following maintenance there will be a traffic induced reduction of loose material and dust defect scores such that the post-maintenance defect scores decrease overall.

(B) A minimum defect score will be acheived where the progression changes from decreasing to increasing.

(C) The increasing traffic volumes and dynamic loadings imposed on the road, together with an increase in abrasion result in an increase in the defect scores until traffic speed slows and wheel paths change to avoid damaged sections.

(D) At this point the defect score would remain essentially constant.

In the selection of a model for defect score progression, a piecewise combination of two exponential curves was chosen to represent the decreasing and increasing rate of change of

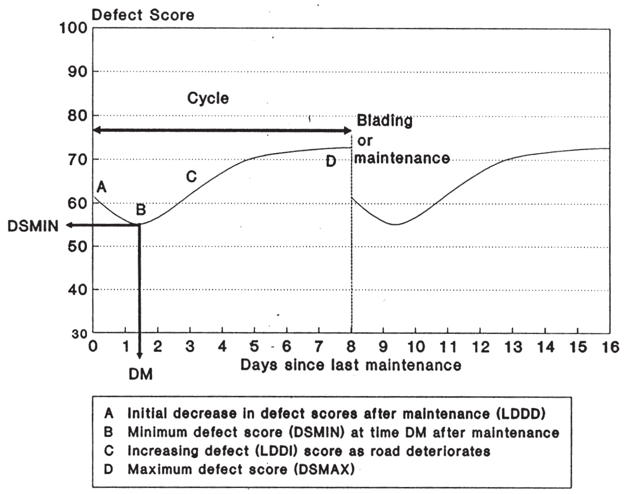

Figure 4—Schematic illustration of the development of functional defects on a haul road

defect score with time (or traffic volume). Using a logarithmic transformation of defect scores, a regression function was developed based on a linear combination of the independent variables for the rate of defect score decrease (LDDD) and increase (LDDI). In addition, an expression for the minimum defect score after maintenance (DSMIN) was sought together with its location in terms of days since maintenance (DM), both assumed to be a linear combination of the independent

Table II

Independent variables used in the Defect Score Progression Model

Independent Variable	Description
KT	Average daily tonnage hauled (kt)
M	Wearing course material type; 0=ferricretes 1=mixtures of materials
P075	Percentage of material passing 0,075mm sieve
DR	Dust ratio, defined as; $\frac{P075}{P425}$ where P425=percentage of material passing the 0,425mm sieve
PI	Plasticity index
CBR	100% Mod. California Bearing Ratio of wearing course material
GC	Grading coefficient, defined as; $\frac{(P265 - P2)xP475}{100}$ where P265=percentage of material passing the 26,5mm sieve P2 =percentage of material passing the 2,0mm sieve P475=percentage of material passing the 4,75mm sieve
SP	Shrinkage product, defined as; $LSxP425$ where LS= Bar linear shrinkage
PL	Plasticity limit
D	Days since last maintenance
DM	Days between last maintenance and minimum cycle defect score
DSMIN	Minimum defect score in cycle

variables, as illustrated in Figure 4. The rate of change in defect scores was calculated over a maintenance cycle and these values used as the dependent variables in a multiple correlation analysis in order to identify the significant factors affecting defect progression. The independent variables listed in Table 2 were evaluated.

The following models were proposed to describe the defect score progression18;

$$LDD = 1,261 + DM(0,000121.CBR.KT-0,02954.GC + 0.009824.SP.DR) \quad [1]$$

$$LDDI = 1,7929 + D(0,002276.KT + GC(0,01029.DR - 0,010887)) \quad [2]$$

$$DSMAX = 35,0249 + 26,7827.M - 0,5672.KT + 1,6508.GC + 0,4464.SP - 10,9393.PI \quad [3]$$

Since no statistically reliable model could be derived for DM (days since last maintenance), recourse was made to the modal value of DM=2 days to locate the position of DSMIN. The regression of DSMIN on the independent variables rendered the following model:

$$DSMIN = 37,9146 - 0.15799.KT + 12.7093.M + 1,3836.GC - 0,08752.SP \quad [4]$$

These predictive models, together with the assumption of the modal time since maintenance for the location of the minimum defect score, enable the functional response of a mine haul road to be modelled in terms of rates of decrease and, more importantly, rates of increase in defect score with time and traffic volumes. Figure 5 compares the prediction model with typical mine site defect score progression data, using Equations [1] and [2] bounded by Equations [3] and [4], whilst Figure 6 illustrates the effect of traffic volume (kt per day) variation on defect score progression for one particular set of material property and minimum defect score values. As can be seen, if an intervention level (or maximum acceptable defect score) of 70 is used, given a monthly production of 230 000t a maintenance interval of 13 days is advocated. When the monthly tonnage hauled increases to 1 150 000t a maximum maintenance interval of seven days is implicated for the given wearing course material parameters used in the model.

Whilst a model of defect score progression is useful to predict and compare the functional performance of a particular wearing course material (in terms of its

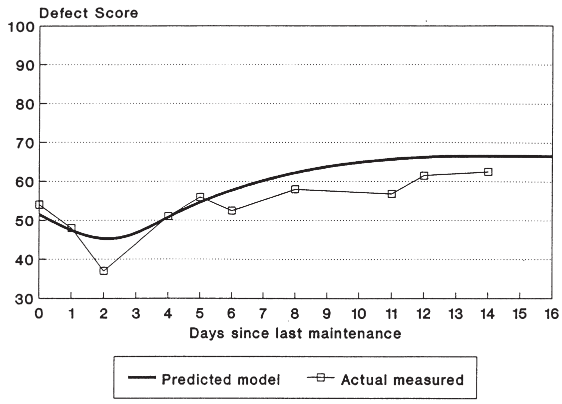

Figure 5—Estimation characteristics of prediction model for rate of increase in functionality defect score

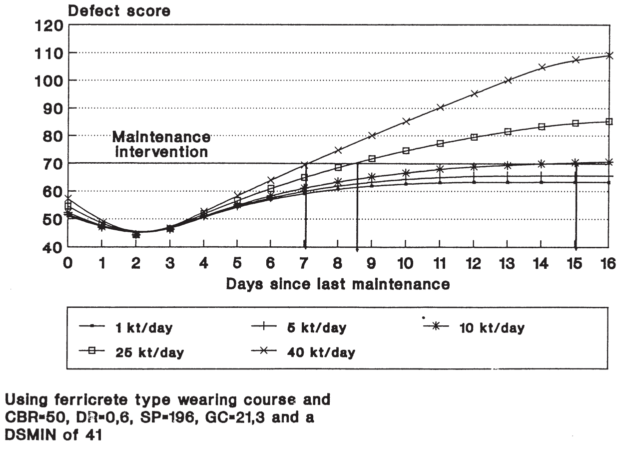

Figure 6—Effect of increasing traffic volume on defect score progression rates and associated maintenance interval

engineering properties and the effect of traffic volume on the road) with the acceptability requirements of the road-user, it is also useful to determine the propensity of a particular material to form specific functional defects, through consideration of the material's engineering properties. One of the major objectives of defect score prediction was to compare the proclivity of various types of materials to deteriorate over time. Results of the study are presented by Thompson[18], from which it is seen that, in keeping with other such analyses, such deterioration models showed low R-squared values with statistically significant correlations by virtue of the large sample size, with the exception of material properties which were defined over a much smaller inference space than the previous studies, which may limit the applicability of the models where materials significantly different from those encountered during testwork are to be assessed.

Despite these limitations it may be concluded that wearing course geotechnical properties, especially the particle size distribution and plasticity, together with traffic volume, are the most important material parameters with regard to the prediction of deterioration progression.

Acceptability criteria for haul road functional performance

Functional defect progression models and wearing course parameter properties cannot be used to assess the applicability of current material selection guidelines for unpaved road construction without some measure of acceptability limits for the various material, formation and functional defects previously analysed. In this assessment of acceptability the following areas were assessed;

1. Road-user assessment of desirable, undesirable and unacceptable limits of performance for each functional defect previously identified
2. The impact of these defects on the safety and economics of a mining operation.

The first area was assessed by using the standard descriptions of degree and extent for each wearing course, formation and function defect referred to in Addendum 1. Respondents classified the lower limit of desirability and the upper limit of unacceptability for each defect.

The second area was quantified using an approach developed by the United States Bureau of Mines Minerals Health and Safety Technology Division (USBM)[19], suitably modified to accommodate those conditions or characteristics previously identified as important in the functional performance of wearing course materials. Respondents were asked initially to decide if a given condition or characteristic can affect either the truck, the tyres or the operation's productivity and the degree to which this occurs was scored. The safety impact was estimated by scoring the accident potential of each condition and characteristic. Respondents were asked to consider each item in a broad sense, ie. scoring in terms of its impact on average or typical daily operating conditions on the haul road. Full details are presented elsewhere[18].

In order to quantify these parameters various mines were invited to complete a functionality rating questionnaire in which both production and engineering personnel had inputs. To further quantify the limits of acceptability respondents were also invited to categorize each defect in terms of its impact on the components of the hauling system, namely the truck, tyres or operation. In addition, haul truck manufacturers were also invited to respond so as to qualify mine operators' functionality requirements with those of the manufacturers. The results of the questionnaires represented over 169 years of operating experience with mine haul roads. In addition, the data was representative of nearly 70% of the total coal tonnage transported on mine haul roads in South Africa.

Road-user Assessment of Functional Performance Limits

Figure 7 presents a summary of the responses in terms of the average acceptability limits for each functional defect, upon which is superimposed results from one mine test site showing the average range of defect score variation. From the figure it is evident that potholes, corrugations, loose material, dustiness, loose stones and wet and dry skid resistance are considered undesirable when the defect score exceeds 3-4 (for skid resistance wet and dry, the assumed extent of 5, representing conditions affecting the whole road, artificially exaggerates the lower limit of desirability). It is

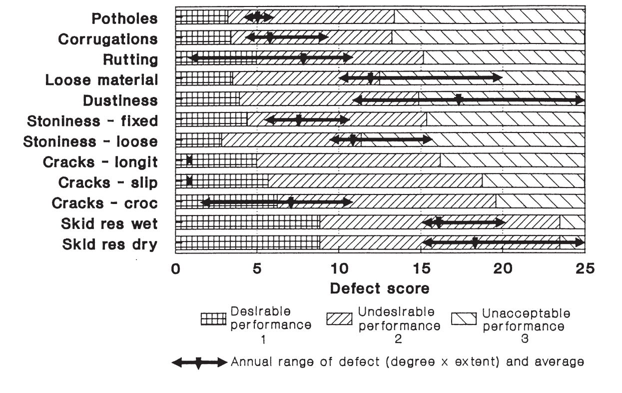

Figure 7—Range and annual average values for mine test site functional performance in relation to established performance limits

also seen that the defects of loose material, dustiness and stoniness (fixed and loose) seldom exhibit desirable performance, demonstrating the need for improved wearing course material selection parameters.

Whilst establishing the acceptability limits for each functional defect provides an insight into the ideal levels of performance expected for a wearing course material, an appraisal of the impact of these defects on the hauling operation is necessary to qualify the extent to which defects may affect economics and safety.

Road User Assessment of Defect Impact and Accident Potential

The impact of a particular functional defect was quantified on the questionnaire using the impact ranking scale which reflects that common functional defects, resulting from a less than optimal wearing course material (or maintenance program) are not catastrophic. Results were compiled for average annual functionality of a mine's road. The results echoed the road user assessment of functionality, with dustiness and wet skid resistance perceived as being primary defects affecting the operation, each accounting for an 11-15% reduction in productivity. Impacts on the truck centred on the defects of potholes, corrugations and skid resistance, accounting for downtimes of less than one shift. Impacts on the tyre were similar, including, in addition, loose material and stoniness, which account for a 5-10% decrease in tyre life. Cracks were considered almost irrelevant in terms of their impact on the hauling components.

The accident potential was determined in a similar fashion, in this case irrespective of which component of the hauling it affected. The accident-potential scale assigned probabilities that the impact will occur, following USBM guidelines. The average accident potential scores are given in Figure 8, from which it is seen that the defects of dust and skid resistance are the functional factors most likely to cause accidents. The formational defect associated with drainage on the side of the road was recognised as having a high accident potential, which also implicates the functional defect of loose material or in more general terms, wearing course material erodibility, in accidents.

The acceptability criteria were derived by combining defect impact and accident potential, thus identifying and

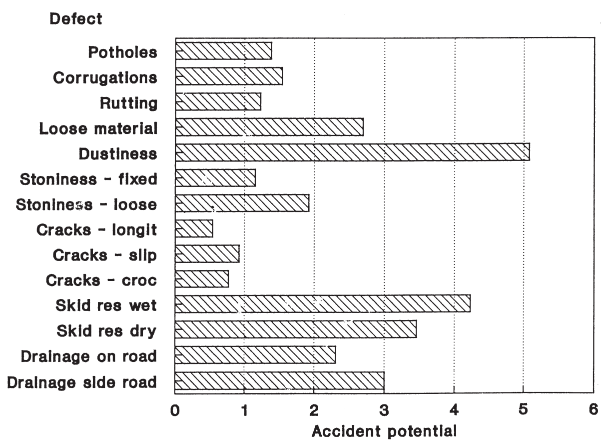

Figure 8—Accident potential of haul road functional defects

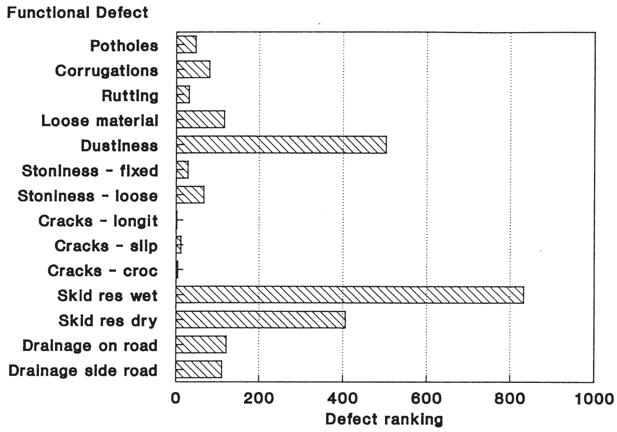

Figure 9—Ranking of haul road functional defects from the combined accident potential and impact scores

ranking aspects of functional performance that should enjoy priority when considering opposing selection criteria. The methodology for ranking defects involved summing the product of impact and accident potential for each defect to give a cumulative score for each defect. The product of cumulative impact score, cumulative defect score and accident potential then gave the overall ranking of the defect. Figure 9 shows the actual ranking scores from which it is evident that wet skid resistance has the greatest impact and accident potential, followed by dustiness, dry skid resistance and loose material. The formational aspects of drainage, both on and off the road, are also significant in the ranking of functional defects.

Derivation of wearing course material specifications

The derivation of wearing course material selection guidelines was based on the identification, characterization and ranking of haul road functional defects, as previously discussed. Prior to the development of the specifications, a reference framework was developed within which suitable specifications should fall.

Two approaches were adopted in deriving suitable specifications. Initially, the important material property parameters controlling both functional performance and individual defect score progression rates, were assessed in relation to the overall haul road functional performance classification in order to identify likely trends and limits for individual parameter values. Secondly, the suitability of the wearing course material selection guidelines proposed in TRH20[13] as a source for mine haul road material specification were analysed. This enabled specifications to be developed which, whilst stipulating individual parameter limits, also have predictive capabilities which contribute to an understanding of the consequences when materials outside the specified ranges are used as wearing course materials.

Haul Road Wearing Course Specification Requirements

The development of suitable specifications for wearing course materials should ideally encompass both individual wearing course material parameter specifications and a broader indication of likely functional defects associated with departure from the established guidelines. Ideal specification requirements following Paige-Green[4] are described below, modified for mine haul road operation and design;

(i) They should be simple with as few requirements or test methods as possible.
(ii) They should be inexpensive, reproducible, necessitate the minimum of sophisticated equipment and operator training.
(iii) The limits should not be restricted to a narrow range of a significant property, but must also be adequately comprehensive in order to recognise and reject unsuitable materials.
(iv) The specifications should not be unduly restrictive and accommodate mine haul road construction cost and material volume considerations. An indication of the likely consequences of employing local mine material which falls outside the recommended parameter range is useful.

Material selection guidelines must thus take cognisance of the road-user functional performance requirements and the limitations imposed by material availability, cost and volume considerations. Since some defect/material property trade-off is inevitable when local mine construction materials are used, it is important to establish a performance ranking system in which material properties associated with critical defects enjoy priority over less significant defects, especially where opposing material selection parameters are encountered.

In the road-user assessment of defect acceptability criteria, a number of defects which critically affect functionality were identified and considered to represent the critical defects which should be addressed in the derivation of material specifications. Limits of acceptability were also determined in terms of desirable, undesirable and unacceptable levels of defect score. These acceptability limits are categorized in Table 3. Since those mine sites exhibiting a reasonable level of functional performance were not adequately differentiated from noticeably poorer sites, a further sub-division of performance classification was developed in order to adequately differentiate between these sites and defects (upper B1 and C1) and lower (B2 and C2) sub-groups.

Using these acceptability levels (A-C2) it was possible to investigate material property and performance relationships, both in terms of overall test site performance and the individual defect contribution to overall performance. In addition, the utility of existing guidelines was assessed in terms of the extent to which such guidelines accommodate and reflect the various overall and individual defect rankings.

Table III

Acceptability limits for critical functional defects

Acceptability level	Acceptability limits of defect score		Description of acceptability limits	Operability limits
	• Corrugation • Loose material • Dustiness • Loose stoniness	• Wet skid resistance • Dry skid resistance		
A	<5	<5	Desirable	Operable
B1	5 - 7	5 - 10	Undesirable (upper)	Operable
B2	8 - 10	11 - 15	Undesirable (lower)	Marginal
C1	11 - 17	16 - 20	Unacceptable (upper)	Inoperable
C2	>17	>20	Unacceptable (lower)	Inoperable

Assessment of Material Property and Performance Relationships

From the statistical analysis and modelling of overall road and individual defect functional performance, the material parameters of plasticity and grading were identified as primarily controlling the functional performance of a haul road. Specifically, the grading coefficient (GC), dust ratio (DR), shrinkage product (SP), plasticity index (PI) and liquid (LL) and plastic (PL) limits were found to contribute to the rate of defect score increase or decrease. Accordingly, these wearing course material property values were classified according to the overall road or individual defect acceptability levels (between A-C2) in an attempt to determine wearing course material property limits.

The relative significance of each critical defect analysed is important when an overall classification of performance and associated material properties is attempted. Greater importance should be attached to those material properties associated with the more critical functional defects. This was achieved by incorporating the defect weighting factors derived from the assessment of acceptability criteria and defect accident potential. In this manner, overall performance was related to the criticality of a defect, those with high-ranking scores contributing proportionally more to the overall ranking.

Derivation of Selection Guidelines

The TRH20[13] wearing course material selection guidelines were developed from functional performance considerations of unpaved public roads as described by Paige-Green[4] in his development of the guidelines, and thus were selected as the most suitable basis for mine haul road wearing course material selection. Figure 10 illustrates the location of each mine test site in terms of shrinkage product (SP) and grading coefficient (GC) values and the overall functional performance ranking (A-C2). From the figure it is clear that the majority of the mine sites lie within the recommended material selection limits (a'b'c'd' in Figure 2). Of those sites lying outside the recommended limits (R1, R3, N1 and N3), only sites R1 and N3 exhibited the predicted excessive ravelling and corrugation defects.

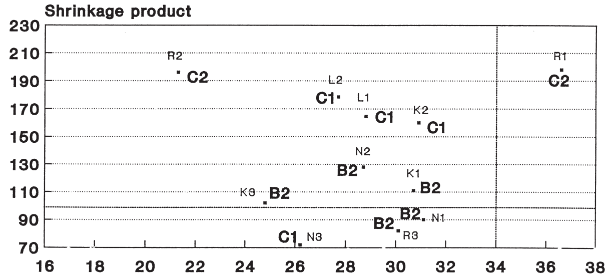

Figure 10—Overall mine site functional performance classification in relation to TRH20 specifications

The overall functional classification shown in Figure 10 reveals that most of the test sites exhibited undesirable (lower B2) to unacceptable (upper C1) performance, albeit operable. Of those sites lying outside the recommended limits (R1, R3, N1 and N3), only sites R1 and N3 exhibited unacceptable performance (upper C1) and were excluded from the modified recommended selection range for mine haul road wearing course materials. Since all the mine test sites lie within or close to the recommended material selection limits, points outside this area are ideally required to confirm the selection parameters. It is apparent that the TRH20 specifications provide a suitable base for material specification and in addition, reflect the typical defect associated with departure from the specifications. If the three most critical defects are considered in the light of the TRH20 specifications, it appears that road-user preference is for much reduced wet skid resistance, dust and dry skid resistance defects, at the expense of an increase in the other defect scores. This alters the focus point of the specifications to an area bounded by a grading coefficient of 25-32 and a shrinkage product of 95-130 in which the overall and individual defect performance is optimised (Area 1). Extending this region to encompass poorer (but nevertheless operable) performance enables an additional area (Area 2) to be defined as given in Table 4 and Figure 11.

The suitability of the modified TRH20 technique of wearing course material selection based on grading coefficient and shrinkage product parameters has been established, together with a range over which optimal performance is assured. This approach should be tempered through the consideration of the other material properties identified as important in functional performance, but not directly assessed in the TRH20 technique. Table 4 presents a summary of these property limits, derived from the statistical analysis of wearing course material defect progression rates.

Wearing course material specifications associated with the structural design of mine haul roads have been proposed[1,2] in terms of TRH14[12]. In addition, haul road design work often specifies material requirements in terms of TRH14 and it is thus useful to consider the equivalence of the latter to the modified specifications established in Table 4. Material available on South African surface coal mines for the construction of the wearing course, is derived from borrow pits comprising, generally, ferricrete or similar materials and is classified (following TRH14) as G4-G7. Using G4 material specifications, a location range can be determined for the equivalent TRH20 specification. The range of grading coefficient lies between 12 and 52 and that of shrinkage product between 30 and 90 (for the full allowable grading variability specified in TRH14). Whilst the grading coefficient parameter encompasses materials liable to erode and to ravel, the shrinkage product lies in the range of material types associated with ravelling and corrugation only. If poorer quality materials are considered (G5-G7), although no specific grading requirements are given in TRH14, the increase in allowable linear shrinkage should improve the location range of these materials in terms of the optimum haul road material selection parameter ranges given in Table 4. It is clear that TRH14 alone does not provide sufficient differentiation between material parameters and haul road defects to enable it to be used as a specification for mine haul road wearing course material selection.

Table IV

Recommended parameter ranges for mine haul road wearing course material selection

Material Parameter	Range Min	Range Max	Impact on Functionality
Shrinkage Product	85	200	Reduce slipperiness but prone to ravelling and corrugation
Grading Coefficient	20	35	Reduce erodibility of fine materials, but induces tendency to ravel
Dust Ratio	0,4	0,6	Reduce dust generation but induces ravelling
Liquid Limit (%)	17	24	Reduce slipperiness but prone to dustiness
Plastic Limit (%)	12	17	Reduce slipperiness but prone to dustiness
Plasticity Index	4	8	Reduce slipperiness but prone to dustiness and ravelling
CBR at 98% Mod AASHTO	80		Resistance to ersosion, rutting and improved trafficability
Maximum Particle size (mm)		40	Ease of maintenance, vehicle-friendly ride and no tyre damage

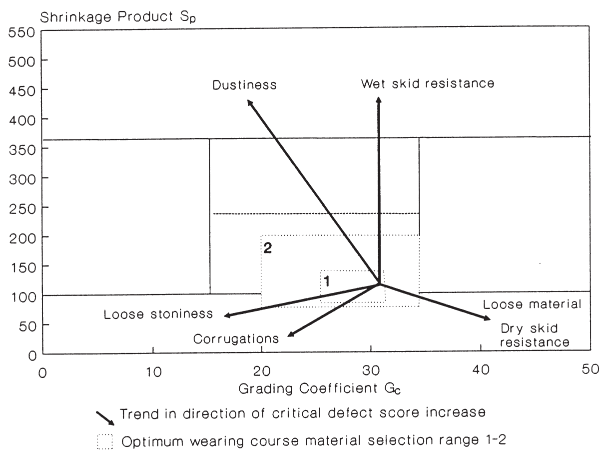

Figure 11—Optimum mine haul road wearing course material selection ranges (1, 2) and general trends of increasing functional defect scores

Wearing course material selection case study

The wearing course material as presently used at a mining operation (M1) is depicted in Figure 12 in terms of the proposed selection guidelines, together with two other materials that could be used for blending with the current wearing course (BS and ASH). When the wearing course material is considered in relation to the recommended optimal material selection ranges, besides being prone to dustiness when dry, it may also present a skid resistance hazard when wet (typically a slippery surface after rain or watering).

If the wearing course material is modelled in terms of how its functional defect score progression varies with the interval between maintaining the road, the unsuitability of the wearing course material is evident from the high defect score and rate of deterioration, as shown in Figure 13. These defect scores and optimum maintenance intervals may change, depending on the specific model parameters adopted.

In this case a daily production of 15kt was used; as tonnage hauled increases, the rate of defect score increase also increases, as illustrated in Figure 6.

In order to improve the functional performance of the wearing course at the mine, some blending of materials was necessary. Using the recommended material specifications, in conjunction with the defect score progression model, it was possible to determine the optimal mix associated with the best functional performance. In this case, 40% BS and 30% ASH was added to the original wearing course, to achieve a mix within the specified selection range. Figure 13 shows the much reduced predicted functional defect progression rate for the new wearing course when subjected to the same traffic volumes as previously. If maintenance is delayed, the defect score eventually stabilises at a much lower value than for the original wearing courses. In terms of the optimal maintenance interval required for the roads, it may be seen that the materials are not as sensitive to over- or under-maintenance as the original materials.

For the new wearing course material mix, a maximum maintenance interval of two days is recommended, this maintenance interval giving the lowest average defect score,

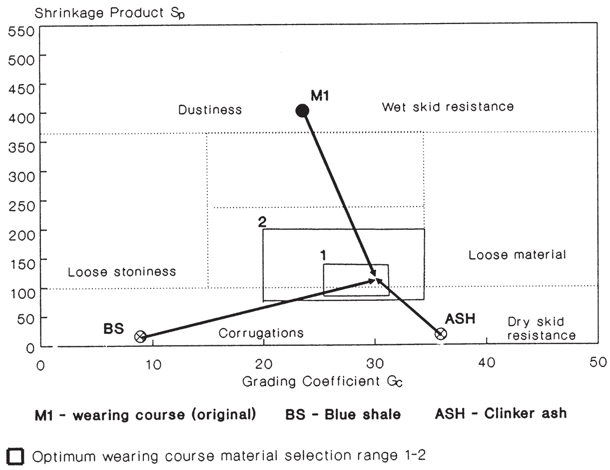

Figure 12—Location of case-study mine 1 wearing course material in comparison to recommended selection range

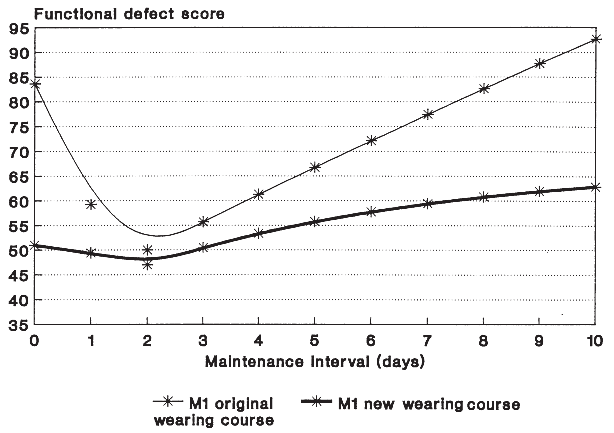

Figure 13—Predicted variation of functionality for original and optimised wearing course materials

commensurate with maximized safety and productivity. A maintenance interval of 4 days would give the same minimum defect score as the unimproved wearing course when a 2-day maintenance regime is applied. When considering total haulage costs, the cost components associated with operating the haul truck (fuel, tyres, maintenance parts and labour) and maintaining the road (grader and water-car operating costs) need to be analysed systematically in conjunction with the wearing course materials.

Conclusions

Functional design aspects refer to the ability of the haul road to perform its function, i.e. to provide an economic, safe and vehicle-friendly ride. This is dictated to a large degree through the choice, application and maintenance of wearing course materials. The commonality between typical defects reported for unpaved public roads and the functionality requirements for mine haul roads, indicated that existing specifications for unpaved public road wearing course construction materials would form a suitable base for the development of specifications for mine haul roads. A qualitative functional performance assessment methodology was developed, based on typical haul road wearing course, formation and function defects, in order to assess the utility of established performance-related wearing course selection guidelines and as a basis for revised functional performance parameter specifications.

From the functionality assessment exercise it was found that the major haul road functional defects encountered were dustiness, loose material and fixed and loose stoniness. A statistical analysis of deterioration and maintenance effects associated with these key defects revealed that wearing course material properties, especially grading and plasticity parameters, together with traffic volume, could be used to adequately model the functional performance of these key defects. However, the applicability of the model was limited by the relatively small inference space of the data and where materials are encountered which differ significantly from those assessed during the test work, judgement and care should be exercised when applying the predicted results. In determining suitable wearing course material selection guidelines, this work confirmed qualitative observations that grading and plasticity parameters would adequately anticipate the functional performance of a wearing course material.

The development of acceptability criteria for haul road functionality fulfilled a requirement for a structured approach to the assessment of mine haul road functionality. In addition to assigning acceptability ranges to each type of defect, the impact and accident potential of each defect was categorized and ranked according to the total impact and accident potential on the components of hauling, namely operation, truck and tyre. It was concluded from the ranking exercise that wet skid resistance, dustiness, erodibility and ravelling and corrugating are critical defects which control the functionality of mine haul roads and that the consequences, in terms of the possible generation of these defects, should therefore be incorporated into any suitable selection criteria established for mine haul road wearing course materials.

Addendum 1 Classification of haul road functionl defects

Characteristic	Description				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Potholes total	Surface is pock-marked <50mm diameter.	Potholes 50-100mm diameter.	Potholes 100-400mm diameter and influence riding quality.	Potholes 400-800mm diameter, influence riding quality and obviously avoided by most vehicles.	Potholes >800mm diameter, influence riding quality and require speed reduction or avoidance.
Corrugations	Slight corrugations, difficult to feel in light vehicle.	Corrugations present and noticeable in light vehicles.	Corrugations very visible and reduce riding qual;ity noticeably.	Corrugations noticeable in haul truck and causing driver to reduce speed.	Corrugations noticeable in haul ruck and causing driver to reduce speed significantly.
Rutting	Difficult to discern unaided, <20mm.	Just discernible with eye 20-50mm.	Discernible, 50-80mm.	Obvious from moving vehicle, >80mm.	Severe, affects direction stability of vehicle.
Loose material	Very little loose material on road, <5mm depth.	Small amount of loose material on road to a depth of 5-10mm.	Loose material present on road to a depth of 10-20mm.	Significant loose material on road to a depth of 20-40mm.	Considerable loose material, depth >40mm.
Dustiness	Dust just visible behind vehicle.	Dust visible, no oncoming vehicle driver discomfort, good visibility.	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking difficult.	Significant amount of dust, windows closed in oncoming vehicle, visibility poor.	Very dusty, surroundings obscured to a dangerous level.
Stoniness - fixed in wearing course	Some protruding stones, but barely felt or heard when travelling in light vehicle.	Protruding stones felt and heard in light vehicle.	Protruding stones influence riding quality in light vehicle but still acceptable.	Protruding stones occasionally require evasive action of light vehicle.	Protruding stones require evasive action of haul truck.
Stoniness - loose on road	Occasional loose stone (>75mm diameter), <2/m^2	Some loose stone, 2-4/m^2	Loose stone 4-6/m^2, occasional discomfort felt.	Considerable loose stone on surface, >6/m^2, reduce riding quality.	Large amounts of loose stone causing significant reduction in riding quality.
Cracks - longitudinal	Faint cracks discernible when surface cleaned.	Distinct, mostly closed, easily discernible when walking.	Distinct, mostly open, discernible from vehicle.	Open cracks, >3mm separation or wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks or extensive wide open cracks >10mm separation, in travelling lanes.
Cracks - slip	Faint cracks discernible when surface cleaned.	Distinct, mostly closed, easily discernible when walking.	Distinct, mostly open, discernible from vehicle.	Open cracks, >3mm separation or wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks or extensive wide open cracks >10mm separation, in travelling lanes.
Cracks - crocodile	Very faint cracks in wheel path.	Faint cracks discernible when walking, closed.	Distinct cracks upto 2mm wide, no apparent deformation.	Open cracks (>2mm) with some deformation and/or spalling of cracked areas.	Open cracks with severe deformation and/or spalling of edges.
Skid resistance - wet	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, water standing on surface when raining, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, road very slippery when wet, loose material reduces skid resistance unacceptably.
Skid resistance - dry	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, loose material reduces skid resistance unacceptably.
Drainage on road	Very little water accumulates on road, no surface erosion is evident.	Shallow depressions may retain water for a limited time, most water drains away rapidly.	Water may be retained in ruts and potholes, some surface erosion evident.	Water retained over a significant portion of the road, surface erosion <50mm deep in channels.	Water ponding on road to depths >50mm and erosion channels deeper than 50mm.
Drainage at roadside	Side drains very effective, well shaped with no obstructions.	Slightly irregular, some loose debris or occasional erosion, road well above side drain level.	Drains irregular in shape, blocked or eroded, road above side drain level.	Drains irregular or eroded and blocked over >25% road length, road and side drain at same elevation.	Side drains deeply eroded or non existent along 75% of road length or road surface below side drain.

The derivation of wearing course material selection guidelines was based on the identification, characterization and ranking of haul road functional defects. A reference framework was developed within which suitable specifications should fall, based on an assessment of the requirements of good specifications in the light of functional defect ranking and acceptability limits. The TRH20 wearing course material selection guidelines were found to be a suitable source for the specification of mine haul road wearing course material parameter requirements. A revised range of parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects. The specification included the parameters of shrinkage product and grading coefficient and limits of 85-200 and 20-35 respectively, were proposed. In addition, from analysis of the range of material property parameters assessed and their association with the functional defects analysed, parameter ranges were additionally specified for density, dust ratio, Atterberg limits, CBR and maximum particle size. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the variation in functional defects which would arise when departures are made from recommended parameter limits.

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