SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

FINAL PROJECT REPORT COL467

The reduction of the safety and health risk associated with the generation of dust on strip coal mine haul roads.

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THE REDUCTION OF THE SAFETY AND HEALTH RISK ASSOCIATED WITH THE GENERATION OF DUST ON STRIP COAL MINE HAUL ROADS.

EXECUTIVE SUMMARY

This report presents the findings of the SIMRAC (SIMCOL) research project COL467 which examines techniques to reduce the safety and health risk associated with the generation of dust on strip coal mine haul roads. The objective of this report was to develop a set of guidelines for the appropriate surface treatment selection, application and maintenance to provide a cost-effective means of reducing the safety and health hazard associated with dust on strip coal mine haul roads. This would be used to identify suitable spray-on or mix-in surface treatments to reduce the generation of dust, within the constraints of cost effectiveness and maintainability, through consideration of wearing course material type, traffic volumes and current road maintenance activities.

The mining industry, specifically surface strip coal mine operators can use the guidelines to optimise the safety and health of surface strip coal mine transport operations, specifically through the reduction of transport related accidents and the structured recognition, evaluation and solution of dust generation problems on mine haul roads, leading to safer mining operations. The objectives were addressed through an assessment of the following enabling activities;

1. A literature study encompassing current state of the art regarding dust suppression techniques, products and measurement and assessment methodologies.
2. The identification of an appropriate experimental design and the establishment and/or characterisation of sites and test sections on participating mines
3. The identification of suitable surface treatments products
4. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites without treatment
5. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites with treatment, over a full climatic cycle where possible
6. A report offering recommendations and conclusions regarding the optimal wearing course surface treatment and management strategy

The following primary outputs were provided:

- Guidelines to enable mine operators to cost-effectively reduce the safety and health risk of dust generated on strip coal mine haul roads through the optimal selection, application, evaluation, and maintenance of spray-on or mix-in dust palliation treatments.
- A qualitative methodology for evaluating haul road dust hazards and intervention levels adapted from a quantitative measuring system.
- The modelling and prediction of haul road dust hazards from consideration of wearing course material type, traffic volume, climate, maintenance and surface treatment applied to the road.
- The development of acceptability criteria for the haul road dust defect hazard and the dust health risk.

The following conclusions and recommendations are made in the light of the findings of the research contained in this report;

1. From a mining perspective, the following parameters define an acceptable dust palliative;
    - Mix-in establishment applications with minimal site preparation (rip, mix-in and recompact) and spray-on maintenance re-applications, or (less preferable), spray-on establishment applications with deep penetration into the compacted wearing course, followed by spray-on maintenance re-applications.
    - Straight-forward applications requiring minimal supervision, not sensitive nor requiring excessive maintenance or closely controlled re-applications.
    - Trafficable within a maximum of 24 hours (short product curing period).
    - Availability in sufficient quantity at reasonable prices.
    - Adequate proven or guaranteed durability, efficiency and resistance to deterioration by leaching, evaporation, ultra-violet light and chemical reaction with wearing course or spillage on road, to provide a high degree of dust palliation over a period commensurate with the functional deterioration profile of the road.
    - Effective over both wet and dry seasons.
    - Safe to handle, non-inflammable, non-corrosive, non-toxic, neither in its pre- nor post application (leached constituents) state and environmentally acceptable. Evaluated against local and international standards.
2. The management strategy recommended for water-spray based dust suppression should be based on user defined levels of dust defect acceptability and an average degree of palliation which can be maintained over a specified period. In general, the consensus of road-users was that a dust defect score of two represented a practical dust defect

intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

3 Since the evaluation of haul truck driver exposure to haul road respirable dust concluded that it is unlikely that such dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are used, it is recommended that where low capacity open cab trucks are used in conjunction with inherently dusty wearing course materials with high (>5%) respirable alpha-quartz fractions, palliation should be considered to improve AQI's, especially if the benefits of palliation were extended to better dust control at the loading and tipping points.

4 Whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources and the associated safety benefits. Coupled with the need to reduce dust from a safety perspective, the use of palliatives can still be motivated where water-spray tankers are re-deployed to reduce dust emissions, especially at loading or tipping areas.

5 Under typical summer conditions, for a water-based spray suppression system with a large rear-dump truck running on a well built and maintained haul road, re-watering is required at approximately 30 minute intervals to maintain a dust defect that at no time exceeds a score of two. Under winter conditions, the re-application interval extends to approximately 50 minutes.

6 The watering model should be used to determine individual mine watering frequencies for the characteristic site parameter combinations. Further refinement of the model is recommended to enable a greater range of variables to be reliably analysed and thereby improve the predictive capability.

7 The average degree of palliation achieved using chemical palliatives can significantly reduce dust emissions from mine haul road, and the primary impact of these reductions would be improved visibility and safety, and in the case of open-cab trucks, an improvement in the air quality index. It is recommended that palliatives be considered as a dust suppression system, subject to the limitations described.

8 A mix-in establishment is recommended for a mine haul road, irrespective of palliative

type, followed by spray-on maintenance re-applications. A poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative and it is recommended that the haul road wearing course material should at least satisfy the minimum material selection specifications. If not, the inherent functional deficiencies of the material will negate any benefit of gained from using dust palliatives.

9 A spray-on treatment is recommended to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions generated from truck induced turbulence.

10 All palliatives (with infrequent watering) share one common failing as compared with frequent water-spray systems. Material spillage on roadways was extremely common at all sites and spilled material was subject to re-entrainment. In mines where spillage cannot be effectively controlled, watering, or failing that, the use of a road sweeper/vacuum in combination with a dust palliative may prove to be more effective for dust control.

11 The use of a palliative in dumping and tipping areas is not recommended due to the high lateral shear forces generated by slow speed manoeuvring. In permanent tip areas, the solution may lie in the provision of a concrete cast in-situ pavement which can be swept clean.

12 Road functionality can be significantly improved by through the use of dust palliatives. A palliative application frequency is recommended which matches road blading intervals; the palliative degenerating over time at a similar rate to functionality, thus when the road is bladed, the maximum economic life has been extracted from the treatment.

13 The model developed for the analysis of palliative comparative cost-effectiveness should be used as a basis for the identification and costing of the key components that affect the overall cost of dust control. Care should be taken when specifying the modelled or alternate establishment and re-application strategies and it is important that the data used closely reflects the anticipated palliative performance. Since the testwork conducted did not allow for the build-up of palliative in the road it is possible that the model under-estimates the average degree of palliation achieved over a specified time

period, especially where multiple re-applications are envisaged.

14 For a maximum allowable dust defect score between two and three, several classes of product rendered a cheaper overall cost per square meter of treated road than did dust control by water-based spraying. When the allowable dust defect score reached four, due to associated lower average degree of dust palliation required, water-based spraying was the cheaper option. Current mine operating practice is typically represented by a dust defect value of between three and four which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, using a road-user defined maximum dust defect score of two, some form of chemical palliation would be beneficial in the long term, subject to the individual mine cost constraints and assumed palliative performance models.

15 Additional blading of the road (typically at intervals not dissimilar from the blading frequency associated with water-based dust suppression) should be avoided since this resulted in a significant increase in costs, making watering the cheapest suppression option. Improvements in road functionality significantly impact costs per square meter and any palliative applied should ideally contribute to improved functionality.

16 Where the road is required to handle traffic over short period of time per day, typically below 14-16 hours, watering will invariably represent the cheapest suppression option under these circumstances, subject to individual mine cost and road performance constraints.

17 The assumption that water used for dust allaying purposes is a no cost item is incorrect and should be re-evaluated by mines since there is a cost associated with the provision and maintenance of the water filling points and reticulation system. Subject to the actual cost of water being determined, this could significantly enhance the viability (in terms of cost-effectiveness) of using dust palliatives and may even warrant the assessment of flexible bitumen-rubber bound chip seals.

CONTENTS

4 EVALUATION OF HAUL ROAD WATER-SPRAY BASED DUST SUPPRESSION STRATEGIES

5 EVALUATION OF TEST SITE PALLIATIVE SUPPRESSION PERFORMANCE

Page

6 EVALUATION OF HAUL TRUCK DRIVER EXPOSURE TO HAUL ROAD RESPIRABLE DUST

7 ANALYSIS OF DUST PALLIATIVE COST EFFECTIVENESS

Page

8 CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 1

INTRODUCTION AND INVESTIGATION DEVELOPMENT

1.1 Introduction

The SIMRAC report (OTH202) by Simpson et al (1996) investigating the causes of transport and tramming accidents highlighted the fact that 74% of these accidents on surface mines were associated with ore transfer by haul truck and service vehicle operation. Dust generation was identified as a significant contributory factor in a number of these incidents. Further work by Thompson (1996) and Fourie et al (OTH308, 1997) confirmed the significance of dust as a contributory factor in attributable reportable accidents and incidents associated with free-steered vehicles operating on unpaved mine haul roads.

The design and management of mine haul roads encompasses the following individual components;

- Structural
- Functional
- Geometric
- Maintenance

The use of dust palliatives to reduce the safety and health risks on mine haul roads primarily impacts on the functional design or performance of the road. Functional design is defined as;

> "the ability of the haul road to perform its function, i.e to provide a safe, economic and vehicle friendly ride. The selection and management of wearing course materials (or surfacing) primarily controls the functional performance".

Functional performance specifications for mine haul road wearing course materials developed in stage II of the AMCOAL/University of Pretoria haul roads research project (Thompson and Visser, 1995) enabled the performance of a specific wearing course material type to be predicted in terms of the likely functional defects it would generate. Further, from an analysis of road-user acceptability criteria, incorporating over 280 years of operating experience on mine haul roads, it was found that the dust defect was critical in terms of overall road safety hazards and accident potential.

Most locally available untreated wearing course materials exhibit excessive dust defects and thus there is the need to reduce the dust defect through an analysis of the available palliatives in conjunction with current haul road maintenance activities, traffic volumes and wearing course material types. Dust is currently controlled by the regular application of water to mine haul roads. This approach is problematic where long road networks are operated and the rate of evaporation of dust-allaying water is high: On evaporation of the water applied to the road, no residual dust binding or palliation is evident and frequent re-watering is thus necessary. Where water is a strategic issue, or where the cost of water is high (bearing in mind the proposed legislation encompassing the cost of water used by mines), water may prove to be the most expensive and least effective dust palliative.

Two approaches to the use of additives to mine haul road wearing courses for dust palliation purposes predominate; those of mix-in or spray-on treatments. Whilst the mix-in treatment approach is more appropriate for mine haul roads, it is not ideally applicable (requiring considerable road preparation). The spray-on approach is workable and may represent a viable option once the application and maintenance strategies are determined in conjunction with the efficacy of the various treatments in reducing safety and health risks. This can be most readily achieved through semi-quantitative measurements (in one-dimension) of the dust plume generated by a haul truck on a section of road, in terms of a dust concentration of the respirable (minus 10 m fraction) of the total suspended fugitive dust.

In comparison to reportable accident and incident data, little data exists with which to quantify the health risk associated with the respirable fractions of haul road dust (especially where a quartz-rich wearing course material is used). It is thus necessary to determine likely reductions in respirable dust levels through analysis of quantitative sampling data before and after palliation treatments and where possible, isolate the specific emission sources and their contribution to the overall air quality and exposure risk for the particular statistical population.

Combining these approaches will then enable guidelines for the appropriate surface treatment selection, application and maintenance to be developed, thereby providing an indication of a cost-effective means to reduce the safety and health hazard associated with dust on strip coal mine haul roads.

1.2 Investigation Objective

The scope of the investigation was originally presented in the COL467 (revised) project proposal and is summarised on the following pages in terms of objective and application criteria.

1.2.1 Objective Statement

The reduction of the safety and health risk associated with the generation of dust on strip coal mine haul roads through the development of guidelines for the selection of appropriate surface treatments, their application and maintenance to provide a cost-effective means of reducing the safety and health hazard associated with dust on strip coal mine haul roads.

1.2.2 Application Criteria

For use by the mining industry; specifically surface strip coal mine operators to optimise the safety and health of surface strip coal mine transport operations. The potential impact is a reduction of transport related accidents and the structured recognition, evaluation and solution of dust generation problems on mine haul roads, leading to safer mining operations. It is applied through consideration of wearing course material type, traffic volumes and current road maintenance activities, to determine suitable spray-on or mix-in surface treatments which, within the constraints of cost effectiveness and maintainability, reduce the generation of fugitive dust.

1.3 Primary outputs

The following primary outputs were identified:

1. A set of guidelines which enable mine operators to cost-effectively reduce the safety and health risk of dust generated on strip coal mine haul roads through the optimal selection, application, evaluation, and maintenance of spray-on or mix-in dust palliation treatments
2. A qualitative methodology for evaluating haul road dust hazards and intervention levels adapted from a quantitative measuring system.

3. The modelling and prediction of haul road dust hazards from consideration of wearing course material type, traffic volume, climate, maintenance and surface treatment applied to the road.

4. The development of acceptability criteria for the haul road dust defect hazard and the dust health risk.

1.3.1 Enabling Outputs

To achieve these outputs the following broadly defined enabling activities were identified;

1. Literature study
2. Experimental design and the establishment and/or characterisation of sites and test sections on participating mines
3. Identification of suitable surface treatments products
4. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites without treatment
5. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites with treatment, over a full climatic cycle where possible
6. A report offering recommendations and conclusions regarding the optimal wearing course surface treatment and management strategy

1.4 Structure and Scope of Report

Chapter two presents the historical background to mine haul road dust suppression, following which the current state is reviewed, both locally and internationally, and inherent deficiencies identified. A summary of research pertaining to the techniques and products available in the public domain is presented where this work has the potential for application in mine haul road dust suppression. Through the identification of the deficiencies that exist in current dust suppression analysis and practices on haul roads and the recommendation of appropriate assessment and monitoring strategies, the basis for the experimental design is established. The experimental design adopted as a basis for the analysis of dust generation and palliation on mine haul roads is addressed in Chapter three. The experimental design is outlined in terms of the measurement of site variables from which the safety and health hazards associated with dust generation and the efficacy of various dust treatments, can be determined. The test methodology is then outlined prior to a review of the various mine test sites available and the extent to which each site fulfils the data requirements envisaged in the experimental design.

Water-spray based dust suppression is the most common means of reducing dustiness on mine haul roads and Chapter four presents a study of the base-case scenario. The combination of a water-car and regular spray applications of water providing a relatively inexpensive, but not necessarily efficient, means of dust suppression. To determine the base-case scenario, the degree of dust palliation achieved with watering is initially compared to the untreated dustiness of various test sections, to determine the average and instantaneous degree of dust palliation achieved under typical winter operating conditions. Acceptability criteria are introduced, based on mine personnel evaluations of the intervention dust defect levels and averages degree of palliation achieved, from a safety perspective. This data is then used in Chapter five to calculate suppression efficiencies of the various classes of palliatives evaluated. By combining these criteria with dust prediction models based on wearing course and traffic parameters, an estimate of water-spray based suppression re-application rates was determined. The chapter concludes with an example calculation procedure for determining typical re-application frequencies as a precursor to the comparative evaluation of other types of dust palliatives.

The experimental design described in Chapter three forms the basis of the palliative evaluations described in Chapter five. Nine treated sections of road were evaluated in terms of the untreated (base case) dustiness levels, the degree of palliation achieved and suppression efficiency compared to a single application of water. The results are categorised according to the class of palliative evaluated. The use of palliatives may also lead to improvements in road functionality and to determine the extent of these benefits, results of the functionality and roughness monitoring exercise are also presented for each test site, compared to the untreated wearing course defect progression rates. Additional observations are offered, centred on the performance of the test site following palliation, both in terms of dust suppression and road performance.

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a typical operating cycle. Data pertaining to seven test sites are presented in Chapter six, where typical air quality indices (AQI's) that could be expected for a truck driver during a normal working day were evaluated, linking sources of dust to overall AQI contribution during a typical haul cycle. Using the previously established intervention level and re-application frequencies to generate an average degree of dust palliation, the impact of this reduced dustiness is assessed in the light of expected improvements in the overall AQI.

The development and evaluation of dust control strategies requires an analysis of the relative costs of alternative palliation options, such that the most cost-efficient option can be determined, together with an indication of the sensitivity of the selection in terms of the primary modelling parameters. Chapter seven details the development of the cost-effectiveness model, introducing the primary data classes required prior to specifying the individual model components. The data classes are described and component values ascribed, based on current (1999) data and costs. A comparative analysis is then undertaken for each class of palliative previously monitored, using the water-spray efficiency model and required degree of palliation for a maximum specified dust defect as the starting point. The individual palliative cost-effectiveness, compared to a base-case cost of water-spray application and the associated Rand per square meter cost is then discussed.

Finally, a summary of the main conclusions of the SIMRAC (SIMCOL) research project COL467 which examined techniques to reduce the safety and health risk associated with the generation of dust on strip coal mine haul roads are offered in Chapter eight, following which recommendations are made in respect of the stated research aims and objectives highlighted in this Chapter.

CHAPTER 2

CURRENT STATE OF DUST SUPPRESSION ON MINE HAUL ROADS

2.1 Introduction

The historical background to mine haul road dust suppression is presented following which the current state is reviewed, both locally and internationally, and inherent deficiencies identified. A summary of research pertaining to the techniques and products generally available is presented where this work has the potential for application in mine haul road dust suppression. Through the identification of the deficiencies that exist in current dust suppression analysis and practices on haul roads and the recommendation of appropriate assessment and monitoring strategies, the basis for the experimental design is established.

2.2 Dust Characterisation

2.2.1 Dust Generation

Dust generation may be loosely defined as the process by which particulate matter becomes airborne, to be carried downwind from the point of origin or source. Such generation is termed a fugitive (or open) dust source. The amount of dust that will be emitted is a function of two basic factors (ARRB, 1996);

- the erodibility of the material involved
- the erosivity of the actions to which the material is subjected

In broad terms, the effectiveness of controls applied to reduce dust released from a particular source is thus dependant on changing one or both of these factors. The nature and particle size distribution of a mine haul road wearing course material has a fundamental influence on the tendency to form fugitive dust. Particles that become suspended for a noticeable length of time are generally <30 μm in diameter. The proportion of material in this range is therefore approximately proportional to a material's erodibility. In general, the silt and fine sand content of a material (ie. 2-75 μm) is a good indication of its erodibility.

Erodibility is reduced by cohesion, which increases with clay content and/or the use of additional chemical binders. This forms the basic motivation for the use of some additional agent to reduce a material's inherent erodibility, since the finer fraction, although contributing to cohesiveness, also generates much of the dust, particularly when the material is dry. The presence of larger fractions in the material will help reduce erodibility of the finer fractions, as will the presence of moisture, but only at the interface between the surface and the mechanical/natural eroding action. This forms the basis of the water-based dust suppression techniques used most commonly on mine haul roads, together with the addition of hygroscopic chemical additives to attract more moisture onto the surface of the material. The various classes of palliative will be described in more detail later.

The potential for an activity to generate dust depends on a number of factors, including;

- the mechanical actions involved
- the amount of energy imparted to the material
- the scale and duration (frequency) of the activity.

Mechanical action involves a combination of reducing particle sizes by impaction and friction, followed by ejection into the air. Coppin and Armstrong (1996) suggest that whilst mechanical activity is the most significant process, in the case of (mine haul) roads, vehicle disturbance can lead to significant wind-related emissions from a surface by;

- physically ejecting particles from the surface by the action of the wheels
- creating local turbulent eddies of high velocity.

Thus the amount of dust generated from a pavement surface can depend on;

- Wind speed at the road surface. Addo and Sanders (1995) report that speed appears to be linearly related to the amount of dust generated (for light passenger vehicles), as does the vehicle aerodynamic shape, especially the wind shear (lower vehicles with many wheels tending to cause an increase in dust).
- The traffic volume, or number of vehicles using the road.
- Particle size distribution of the wearing course.
- Restraint of fines. This is related to compaction of the road surface, cohesiveness and bonding of the surface material, durability of the material and the amount of imported fines (spillage) on the road.
- Climate, particularly humidity, number of days with rain, mean daily evaporation rates and the prevailing wind speed and direction.

The adverse effects of dust generated from mine haul roads have been noted by various authors (Thompson and Visser, 1999, Thompson et al, 1997, Amponsah Dacosta, 1997, Jones, 1996, Simpson et al, 1996, USEPA, 1988 and USBM, 1983). In general terms these include;

- Loss and degradation of the road pavement material, the finer particles being lost as dust and the coarser aggregates being swept from the surface or generating a dry skid resistance functional defect.
- Blocking of roadside drainage systems, table drains and culverts.
- Increased health problems - especially for those already suffering from respiratory and allergic disorders.
- Decreased safety and increased accident potential for road-users, due to reduced or obscured vision and reduced local air quality.
- Higher vehicle operating costs, with dust penetrating the engine and other components resulting in increased rates of wear and more frequent maintenance.

The broader environmental effects of dust have also been reviewed, both from the perspective of unpaved public and mine haul roads. Of particular importance is the finding of Amponsah-Dacosta (1997) who conducted an emission inventory for a South African coal strip mining operation. The emission inventory was based on a characterisation of specific dust sources over a specific interval of time, to produce a dispersion model to enable predictions to be made concerning ambient pollution levels and the identification of major control areas. The analysis, conducted according to USEPA (1995) guidelines, found that 93,3% of the total emissions from the mine were attributable to dust generated from the mine haul road (the second highest, at 2,7%, being attributable to top soil removal). Although a high tonnage operation, the extent of the road network on the mine was similar to other such operations and it was concluded that emissions from the road network would be typical of most opencast coal mines, when calculated on a percentage of total emissions basis.

2.2.2 Defining Dust

Dust results from the mechanical disintegration of matter and can be defined as a collection of solid particles which are dispersed in a gaseous medium (air), are able to remain suspended in the medium for a length of time and have a high surface area to volume ratio. It tends to be a heterogenous system of poor stability containing many particles of differing shapes and sizes, although the geometric diameter of airborne dust generally lies between 0,001-100 μm. Dust itself is defined according to its size as given in Table 2.1, from which it may be seen that in the case of dust generated from mine haul roads, both total suspended particulates (TSP) and respirable (or PM_{10}) dust are the critical classes of dust from a safety and health point of view.

Table 2.1 Dust definitions (after Coppin and Armstrong, 1996)

Term	Definition	Typical size range (m)
Dust	Solid particulate matter (mineral, biological) capable of temporary suspension in the air, smaller than grit, larger than smoke.	0,1-75 (up to 100)
Fugitive dust	Dust arising from diffuse sources, not via a stack or duct designed to control their flow (USEPA, 1988), and which disperse some distance from the source.	<30
Total Suspended Particulate (TSP)	The mass of loading of airborne particles, determined gravimetrically (DoE, 1993). Usual units are as a concentration; g/m^3 or mg/m^3 in air.	<100
Deposited dust	Particulate matter that has deposited on a surface by gravitational settlement, impingement or interception, or by wet deposition during rain or mist. Units are mg/m^2 related to a time interval.	<100
Inhalable dust	The fraction of airborne dust that can enter the nose and mouth during breathing and can therefore be deposited in the upper respiratory tract (MDHS14/93).	<100
Respirable dust	The fraction of airborne dust which, when inhaled, enters the alveoli region of the lung (MDHS14/93).	<9
PM_{10}	Particulate matter with an aerodynamic diameter less than 10 microns. Equates approximately to the respirable dust fraction and increasingly used to define health standards.	<10

When a dust cloud or plume, generated from a fugitive source is considered, the primary characteristics are those of plume size and duration; those dust particles of smaller aerodynamic diameter tending to stay longer in suspension and therefore contributing to the opacity of the air, as well as being detrimental to health. These particles tend to be generally less than 30 m in diameter (ARRB, 1996). This is illustrated by considering terminal velocities of dust in air, following Stokes Law with slip correction (Davies, 1947). A 42 m limit is applied to the upper size of the dust (above which turbulent flow applies). At a size of 40 m, terminal velocity is 0,13m/s, reducing to 0,0083m/s at 10 m. This means that if a particle of 10 m is entrained to a height of 4m, it will take 500s or 9 minutes to return to the ground.

A further sub-division of dust may be obtained by considering the health aspects associated with the various types of dust encountered. These sub-classifications of dust (after Gardiner and Schroder, 1982) are derived from the physical, chemical and toxicological properties of the respirable fraction and the resultant innocuous, slight or serious biological disorders that may result.

- Non-fibrogenic dust. Dust which generally cause little or no reaction is referred to as biologically inert dust. More recent work has shown this to be misleading and it is more correct to refer to this type of dust as not causing pulmonary fibrosis, physical impairment or disease since any durable inorganic dust will inevitably provoke some defence mechanism in time.

- Fibrogenic dust. Fibrogenic dust causes the development of fibrogenic tissue in the alveolus of the lungs and other serious secondary effects. Pneumoconiosis is a special condition related to fibrogenic dusts in which an accumulation of such dust causes permanent lesion of the cardio-vascular system. A number of specific pneumoconioses are referred to according to the causative agent involved; alpha quartz dust (SiO_2) generating silicosis and, due to its prevalence in mining, is used widely as a reference for the various air quality indices calculated.

2.2.3 Global and Legal Limits

Burrows (1998) reports that airborne dust fallout with particulate matter less than 10 m but larger than 4 m in diameter may not exceed 650mg/day/m^2 in residential areas or 1300mg/m^2 in industrial areas. The value for fallout in industrial areas equates to approximately 150 g/m^3/day and is currently perceived as a standard and is not legally enforced. For gravimetric or respirable dust, an air quality index (AQI) can be calculated and the maintenance of such is enforced through the Occupational Diseases in Mines and Works Act (78 of 1973). The AQI value takes into account the time weighted average (TWA) of the concentration of the dust in addition to the amount of SiO_2 in the dust. The threshold value for SiO_2 in the respirable fraction is set at 100 g/m^3 when the gravimetric sample contains in excess of 5% SiO_2, or 10mg/m^3 where less than 5% is measured. By using the approach outlined in the Draft Guidelines for the Compilation of a Mandatory Code of Practice for an Occupational Hygene Program (No.1 Personal Exposure to Airborne Pollutants) (Department of Minerals and Energy, draft ammendment 6 of 1999), personal exposure can also be specified according to the bands A to D representing exposures greater than the threshold limit value (or occupational exposure level, OEL) to less than 10% of the OEL.

It is sound occupational hygiene practice to maintain AQI values below 0,5, although typical AQI values for a particular population of workers should conform to the following values;

- AQI<1 Acceptable

- 1<AQI<5 Caution, problem should be addressed
- AQI>5 Unacceptable, no work can be carried out in such and environment

When attempting to relate an acceptable AQI value of less than 1 to a dust concentration value, the USEPA National Ambient Air Quality Standard (USEPA, 1987) can be used as a rough guide. According to this standard, and AQI of 1 or less would account for a dust concentration of 0,3mg/m^3. However, it should be borne in mind that localised (time- and location-wise) concentration measurements cannot be translated directly to AQI values.

The Occupational Diseases in Mines and Works Act (78 of 1973) specifies the sampling areas and statistical populations from which time-weighted average concentrations, threshold limit values from time weighted averages and the calculation of percentage risk of exposure to the measured respirable dust (pollutant) levels as a respirable dust sampling strategy. A haul truck driver would typically represent a member of a statistical population in a defined sampling area and the Act requires that samples be taken gravimetrically during a typical day's operations by a machine attached to the worker such that a typical exposure results. Whilst data is available to quantify the overall risk to the statistical population, it does not adequately differentiate between the various emission sources of the dust. Typically, a haul truck driver would be exposed to dust from driving (including following in another truck's plume, driving through an oncoming vehicle's plume, etc. which is a function of road length, traffic volumes, interactions, etc.), dumping and loading. Other factors also influence the total risk, such as whether the cab is airconditioned, sealed, windows open or closed, etc. Since the established gravimetric sampling methodology does not adequately differentiate these sources, it is necessary to profile typical exposures during a truck cycle to initially estimate the percentage contribution of each source.

2.3 Current Dust Suppression Practices

Apart from sealing a road, there are numerous other methods available to reduce fugitive dust emissions from an unsealed or unpaved mine haul road. These include;

- Providing a tightly bound wearing course material
- Armouring the surface (placing a thin layer of higher quality wearing course on the existing material or tyning this into the top 50mm of material).
- Good maintenance practices
- Regular light watering of the road

- Use of various chemical dust suppressants (palliatives)
- Reducing vehicle speed and/or modifying engine/retarder blower configuration to blow over, not under the vehicle.

An overall appreciation of the degree of dust palliation achieved by some of these techniques was compiled by the ARRB (1996), based on their application to public unpaved roads. No indication is given of whether the degree of palliation is maximum, average, nor over what time and traffic volume it applies and the road wearing course or climate conditions. It nevertheless serves as a useful first attempt at qualifying the various options and is given in Table 2.2.

Table 2.2 Estimates of percentage dust reduction for various treatments (after ARRB, 1996)

Treatment	Degree of dust palliation (%)
Sealing or bound paving[1]	95-100
Oiling (petroleum based)[2]	50-98
Chemical dust suppressants	40-98
Watering	40
Vehicle speed reduction[3]	50-85

Notes

1. Not a viable option for most haul roads due to construction cost constraints
2. Not a legal option in South Africa (due to excessive environmental risk and presence of polychlorinated biphenyls - PCB's)
3. Not a viable option - to maintain tonnage hauled at lower speeds per vehicle - additional vehicles would be required thereby increasing emissions. Based on light passenger vehicle speed reduction from 65km/h to 30km/h.

From the foregoing it is clear that only regular watering, the application of chemical dust suppressants and/or the optimal selection of wearing course materials are the only viable alternatives in controlling mine haul road dust emissions. In terms of the total surface mine haul road network in South Africa, minimal dust control is being exercised other than that provided by watering the road. Many products are available which are claimed to reduce both dust and road maintenance requirements for mine roads. However, minimal specifications of their properties and no comprehensive comparable and controlled performance trials of the various products have been carried out in recognised, published field trials. In South Africa, representatives of the various dust palliative companies tend to oversell their products. Many do not have civil or mining engineering backgrounds and as such incorrect application techniques and construction methods often result. This has led to considerable scepticism about such products and their overall cost-effectiveness. In many instances on public unpaved roads, failures that could have been related to incorrect application or unsuitable wearing course materials were often blamed on the product (Jones, 1999).

From a mining perspective, the following parameters would define an acceptable dust palliative;

- Spray-on application with deep penetration (the ability to penetrate compacted materials), or (less preferable) mix-in applications with minimal site preparation (rip, mix-in and recompact).
- Straight-forward applications requiring minimal supervision, not sensitive nor requiring excessive maintenance or closely controlled re-applications.
- The road should be trafficable within a maximum of 24 hours (short product curing period).
- Availability in sufficient quantity at reasonable prices.
- Adequate proven or guaranteed durability, efficiency and resistance to deterioration by leaching, evaporation, ultra-violet light and chemical reaction with wearing course or spillage on road.
- Effective over both wet and dry seasons.
- Safe to handle, non-inflammable, non-corrosive, non-toxic, neither in its pre- nor post application (leached constituents) state and environmentally acceptable. Evaluated against local and international standards.

The broad classes of products or systems available are listed and the general characteristics of each system are summarised below.

- Water, groundwater containing dissolved salts or wetting agents
- Hygroscopic salts
- Lignosulphonates
- Modified waxes
- Petroleum (or sulphonated petroleum) resins
- Polymer emulsions
- Tar and bitumen products

All the suppressant types listed above will suppress dust for a time, but due to the combined effects of oxidation or leaching, breakdown of the host material exposing fresh untreated surfaces and especially spillage on the road, they will eventually lose effectiveness and re-application or rejuvenation would be required.

2.3.1 Dust Palliative Products

Water

Water is recognised as the cheapest treatment for temporary dust reduction (ARRB, 1996). However, in the case of mine haul roads in South Africa, the frequent re-application rates and capital and operating cost of equipment used, together with legislation entrenched in the new Water Act (36 of 1998), may result in water being the least cost-effective option for mines.

Water acts by surrounding and adhering to adjacent particles, making it more difficult to dislodge them. The period of effectiveness is dependant on weather, wearing course and traffic volumes, and can range from 30 minutes to 12 hours. Regular light watering at approximately 0,3-0,5l/m^2 is more effective than infrequent heavy watering. Heavy watering will generate additional run-off and will produce soft, muddy material in addition to pumping and washing away the finer binding fractions of the wearing course. Excessive watering will reduce functionality of the pavement, cause short term slipperiness and may lead to potholing and rutting. This in turn will require more road maintenance with the potential for greater dust emissions.

Sea or groundwater is thought to be slightly more effective than fresh water due to the presence of small amounts of deliquescent salts. However, high concentrations of salts may lead to efflorescence and the salts may only be hygroscopic at relatively high humidities. In addition, some workers report that the roads treated with water containing salts become excessively slippery when wet. However, such reports often fail to specify the wearing course material to which the water was applied, hence the difficulty in identifying the real causes of such slipperiness.

Surfactants or wetting agents are substances that reduce the surface tension of water to air, thereby allowing water to permeate easier, wetting a greater number of soil particles and preventing them from becoming dislodged. Common surfactants are in the form of soap and have not been analysed as a separate group since they are often a component of other chemical suppressants.

Hygroscopic salts

Hygroscopic salts are typically chloride salts, produced as a by-product of the salt industry. Salts suppress dust by attracting moisture from the air, keeping the road surface moist and are generally applied as surface sprays or mixed-in at approximately 2,0l/m^2 (three passes of 0,5l/m^2

38% solution) followed by a final 0,5l/m^2 wash (rates vary according to material type, preparation and traffic). When the atmospheric moisture falls below 70% relative humidity, the hygroscopic (sodium) chlorides cease to function, whereas the deliquescent (magnesium and calcium) chlorides cease to function at about 30-40% relative humidity (Jones, 1984). The products are thus climate sensitive and Jones (1998) reports their limitation to a climate region bounded by Weinert's N-value (Weinert, 1980) of N<5. This encompasses Gauteng, most of the North West and Free State Provinces as well as Mpumulanga (Highveld). Where applications are required in other climatic regions, recharge water sprays may be required.

Salts such as calcium chloride are able to have their water-attracting functions recharged with a few hours of adequate moisture and humidity. This can be achieved where low-humidity and high temperatures exist through early morning dew recharge.

Lignosulphonates

Lignosulphonates are an organic, non-bituminous binder, the source of this type of suppressant is the waste products of the sulphite pulping industry, their composition being variable depending on the feed and pulping process used. Their action in the road is to adhere to and glue together the wearing course material particles. They also act as a clay dispersant, making the clay more plastic and, after compaction, leading to a denser pavement. Molasses, a residue of the sugar making process also acts in a similar manner on the wearing course material's finer fraction.

They are more generally applied as a mix-in product at approximately 1,0l/m^2 50% solution or 0,8kg/m^2 (3,5l/m^2) depending on the specific product, with spray-on maintenance applications thereafter at approximately 0,6l/m^2 50% or 0,4kg/m^2 per annum solution (rates vary according to material type, preparation and traffic). They are susceptible to leaching from the road and are thus more effective over the dry winter months.

Modified waxes

Modified waxes are manufactured as part of the oil from coal process. They are a relatively new innovation in the field of dust control and have shown potential, as a spray-on application in field trials. This class of palliative has not been extensively researched (Jones, 1997) and no data pertaining to their use on mine haul roads could be found.

Petroleum (or emulsified petroleum) resins

Petroleum (or emulsified petroleum) resins are derived as a by-product of the oil refining industry, emulsified petroleum resins are formulated as dust suppressants and stabilisers. Binding agents added to the emulsified petroleum resin (derived from paraffinic crude oil) formulation which penetrate the wearing course and bind the material, preventing them from becoming airborne. In addition, wetting agents, emulsifiers and dispersants are added to increase the penetration and spreading of the product. This class of products generally do not contain asphalts and are non-corrosive, non-inflammable, non-toxic and non-carcinogenic.

The application methodology is dependant on the wearing course material characteristics, usually an initial mix-in application would be required at approximately 1,12l/m^2 (4:1) followed by maintenance spray-on applications at 0,5l/m^2 (8:1) to give a total treatment of typically 1,3l/m^2 (rates vary according to product, material type, preparation and traffic).

Polymer emulsions

Polymer dispersions are suspensions of synthetic polymers in which the monomers are polymerised in an aquatic medium. Various formulations are available and the product has been widely used for stabilisation, and more recently for dust suppression (Bishop, 1999). Polymer (PVA and PVC) emulsions are used extensively to form thin layers in waterproofing paints for roofs and walls. They no not suffer embrittlement, leaching nor UV degradation and have good adhesive properties, making them potentially successful as dust suppressants by binding wearing course material. Depending on the specific product, they can be mixed-in to the upper 100mm wearing course at rates varying from 0,2-1,0l/m^2 (rates vary according to product, material type, preparation and traffic). The ARRB (1996) report that the product is very effective on sandy soils in dry climates, however, little published information is available regarding its use on mine haul roads.

Tar and bitumen products

Tar and bitumen products are offered by most petrochemical and bitumen suppliers, the tar based products being derived from coal tar distillates to which solvents are added to improve penetration. Bituminous based products are based on 80/100 penetration grade bitumens with solvents added. Emulsifiers and wetting agents may be added to enable the product to be mixed with water and applied as a mix-in product, typically at approximately 3l/m^2, followed by maintenance applications totalling approximately 3l/m^2 over the following 12 months, at an application frequency and dilution dependant on the product itself, material type, preparation and traffic types and volumes. The palliative works by binding the wearing course material, but is sensitive to the quality of the base material and drainage; deformation and cracking result in rapid breakdown of the surface produced.

A summary of the suppressant class climatic, wearing course material and traffic limitations, together with general observations has been published by the ARRB (1996) from results of an application questionnaire and data presented by UMA Engineering (1987) and is presented in Table 2.3. The data relates to applications on unpaved public roads and, in terms of traffic and some of the general comments, may not be directly applicable to mine haul roads.

2.3.2 Selection of Appropriate Wearing Course Materials

As noted in section 2.3.1, the degree of dust palliation achieved and the effective life of a particular product is dependant on the type of wearing course material used on the road; an inherently deficient wearing course material will not perform well, even with the addition and management of the best palliative. It is therefore important to select the optimal wearing course material or mix of materials that reduces the fugitive dust creation potential. The material characteristics which influence the generation of dust on unpaved roads are well understood (Paige-Green, 1989 and Committee of State Road Authorities (CSRA), 1990). For mine haul roads, similar specifications have been developed, tailored to suit the unique requirements of mines. A revised range of parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects (Thompson and Visser, 1999). Table 2.4 and Figure 2.1 illustrate these selection parameters.

Table 2.3 A summary of suppressant class climatic, wearing course material and traffic limitations (after ARRB,1996 and UMA Engineering, 1987)

Suppressant Class	**Climatic Limitations**	**Wearing Course Material Limitations**	**Traffic[1]**	**Comments**
Hygroscopic	Salts loose effectiveness in continual dry periods with low relative humidity. Selection dependant on relative humidity and potential to water road surface.	Recommended for use with moderate surface fines (max 10-20%<0,075mm). Not suitable for low fines materials or high shrinkage product/PI[2] low CBR[3] or slippery materials.	Good for HGVs[4]. Low shrinkage product materials may shear and corrugate with fast moving HGVs. Shear can self-repair.	Leaches down or out of pavement. A high fines content may become slippery when wet. Reblade under moist conditions. $CaCl_2$ is more amenable to spray-on application. Corrosion problems may result. Can be maintained with light watering. Repeated applications accumulate.
Lignosulphonates	Retains effectiveness during long dry periods with low humidity.	Recommended for use where high (<30%<0,075mm) fines exist in a dense graded gravel with no loose material.	As above. Tendency to shear in dry weather - not self-repairing.	Generally ineffective if wearing course contains little fine material or there is excessive loose gravel on the road. Leaches in rain if not sufficiently cured. Best applied as an initial mix-in and quality of construction important. Gradually oxidise and leach out. Repeated applications accumulate. Can be maintained.
Petroleum-based products	Generally effective, regardless of climate but will pothole (small diameter) in wet weather.	Performs best with low fines content (<10%<0,075mm). Use low viscosity products on dense fine grained material, more viscous products on looser, open-textured material.	HGVs turning will cause shearing - not self repairing.	Difficult to maintain - rework. Repeated application accumulate. Does not leach. Long lasting - mor effective in dry climates. Requires sound base and attention to compaction moisture content.
Others (Sulphonated petroleum, Ionic products and Enzymes)	Generally effective, regardless of climate.	PI range 8-35 Fines limit 15-55%,0,075mm. Minimum density ration 98% MDD (Mod). Performance may be dependant on clay mineralogy (enzymes).	Generally no problem once cured.	Generally ineffective if material is low in fines content or where loose gravel exists on surface. Efficacy depends on the cation exchange capacity of the host material. Curing period required. Difficult to maintain - rework. Mix-in application - sensitive to construction quality. Repeated applications accumulate.

Notes

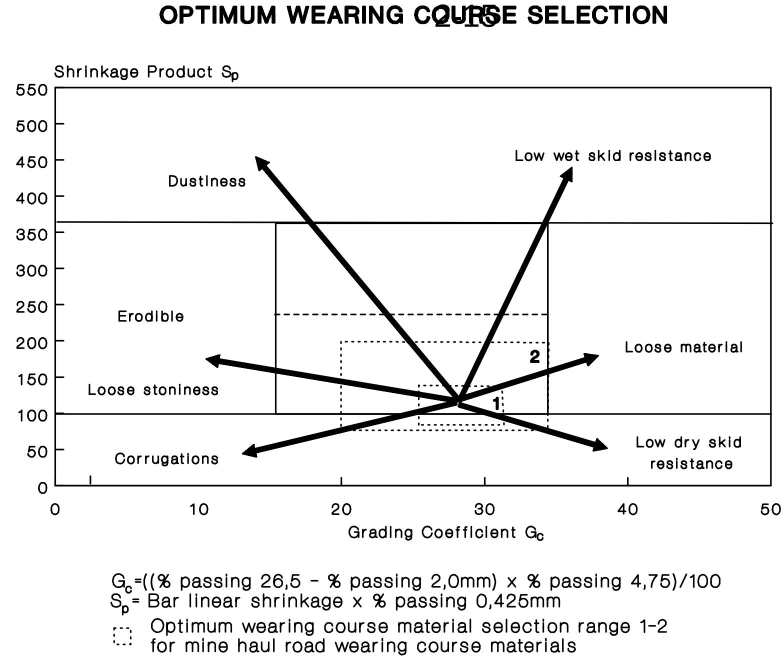
1 Based mostly on public unpaved roads.
2 Plasticity Index
3 California Bearing Ratio (%)
4 Heavy goods vehicles operating on public unpaved roads

Table 2.4 Recommended Parameter Ranges for Wearing Course Material Selection (Thompson and Visser, 1999)

WEARING COURSE MATERIAL SELECTION PARAMETERS			
Material Parameter	**Range** **Min**	 **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 erosion, rutting and improved trafficability
Maximum Particle Size (mm)		40	Ease of maintenance and vehicle friendly ride

From the point of view of dust generation, the following deficiencies (as shown on Figure 2.1) are considered;

- Loose stoniness - finely graded material prone to erosion - should be avoided on grade sections or sections with super-elevation and steep crossfalls.
- Corrugating material - generally lacking in cohesion and likely to generate loose material.
- Loose material - comprises gap-graded gravels with little cohesion. This usually results in ravelling and the production of loose material and dry skid resistance problems.
- Wet skid resistance - an excess of fine plastic material adversely effects wet trafficability and is typically dusty .



By combining the data contained in Tables 2.3 with the revised wearing course parameters for mine haul roads, a product selection matrix can be estimated, based on the work of Jones (1999) as shown in Table 2.5. This selection matrix is based on information and data derived mostly from applications on public unpaved roads and, due to the different traffic types and volumes, maintenance regimes and philosophy of provision, should not be taken as directly applicable in all cases to mine haul roads. Whether a product is more suited to long or short term applications would generate significantly different results in the case of mine haul roads, since the application term may be profoundly different from that of public unpaved roads. The concept of cost effectiveness needs to be considered from the point of view of mine haul road operators - an efficient palliative would be of little use if it was perceived as not being cost effective in reducing fugitive dust emissions.

2.4 Economic Evaluation of Dust Suppressants

The correct application of a rigorous economic assessment model to dust control of unpaved mine haul roads is essential in order to identify and implement the most cost-effective solutions.

Table 2.5 Provisional palliative product selection matrix (after Jones, 1999)

	High PI (>10	Medium PI	Sand	Wet trafficabil	Steep grad	Heavy traffi	Short term	Long term	Spray-on	Mix-in	Maintainable

	)	(>10)		ity	es	c					
Wetting Agents		✓			✓		✓		✓		✓
Hygroscopic Salts		✓				✓	✓		✓	✓	✓
Ligno-sulphonates	✓	✓	✓				✓			✓	✓
Modified Waxes		✓					✓		✓		✓
Petroleum Emulsions	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Polymer emulsions	✓	✓		✓	✓	✓		✓		✓	
Tars and Bitumen		✓		✓				✓	✓		
Sulphonated Oils	✓			✓	✓	✓		✓		✓	✓

The benefits to a mine operator using a dust suppressant include the following;

- Air quality is improved, reducing the health risk to workers, less time lost due to sickness and a cleaner environment.
- Total road-user costs (vehicle and road maintenance) are reduced.
- Improved hauler cycle times.

These three benefits must be completely characterised to fully determine the benefits of dust suppressants. Portions of the last two can be costed, but the primary benefit - that of improved air quality is problematic. In the first instance it needs to be established to what extent anyone using the haul road is exposed to the dust produced, and for how long, thereby determining an AQI for the characteristic dust involved.

Comparison with water-based suppression techniques is valid since most mines have dust control programs in which water is applied at interval to the road to reduce dust. Many of the analysis problems can be eliminated if the comparison is based on the cost to achieve a specified level of control efficiency. In this manner, many of the costs associated with chemical palliatives and watering become equal or do not apply, for example, the comparative benefits from reduced dustiness would become equal. Total road user costs can most readily be assessed by adopting the functional performance assessment methodology described by

Thompson and Visser (1999) to assess the reduction in road maintenanmce frequency realised through the use of dust palliatives. These cost savings can then be incorporated in the evaluation.

A USBM study (USBM, 1983) adopted an across the board 50% control efficiency for the various products tested in its economic evaluation and included establishment, material cost and application costs based on a typical frequency estimated to maintain 50% control efficiency. A spray-on hygroscopic salt was found to be the most cost effective, followed by conventional watering. The USBM note that other economic evaluations suffer from three general failings - data gathered over too short a time period (to fully evaluate the performance of the product), site specific costing, and evaluations based on the manufacturers estimated control efficiencies at certain (optimistic) application rates. The USMB study was based on a single application of the suppressant and "steady-state" conditions were not achieved. This effectively overestimated the cost of the various treatments since the majority of those applied exhibit some residual effect which can be rejuvenated by using lower dilution maintenance applications. Work by Amponsah-Dacosta (1996) echoed the findings of the USBM work, using local mine data and manufacturers estimates of control efficiencies and reduced maintenance frequencies. The approach used in evaluating the economic benefits, if supplemented with establishment and maintenance costs over a longer period, together with actual dust control efficiencies and maintenance interval measured in the field, would provide a sound basis for the economic evaluation. The results of the economic modelling exercise, whether in the form of a ranking, cost per square meter or payback period also need to be evaluated by the user in terms of the cost and tractability of reducing the safety and health risk associated with the generation of fugitive dust emissions on mine haul roads.

2.5 Dust Prediction and Management

Addo and Sanders (1985) report that for a pavement tested in the dry season in Colorado, USA, material was lost from the road at a rate of 1,64t/km for an annual daily traffic (ADT) of 538 vehicles per day, for a pavement 10m wide constructed with material of density 2,11t/m^3. This value was reported to be halved by the use of a dust suppressant on the road. In general the authors reported an annual aggregate saving of between 660kg/km/vehicle to 960kg/km/vehicle. The USDA Forest Service (1983) estimated that 1t of dust (less than 100 m in size) is deposited in a 330m wide corridor centred on an unpaved road per vehicle per year. This equates to approximately 500kg/km/vehicle which correlates well with Addo and Sanders data.

A variety of factors will influence dust generation (aggregate loss) from unpaved roads, especially traffic volumes, road width, climate (wind and rain erosion), material types, etc. The OECD working group (Reichert, 1987) found that in African countries (Nigeria, Kenya and Cameroon), wear was between 10mm-30mm per year for an ADT of 164vpd. Gravel loss has been expressed as a function of these factors and road gradient by Jones (1984) and also by Paige-Green (1989) additionally as a function of the percentage material passing the 26mm sieve size and the product of plastic limit and the percent material passing the 0,075mm sieve size.

Whilst these models predict wearing course material loss, they do not necessarily reflect the levels of dustiness associated with the various parameters modelled. The USEPA (1996) has developed a model to predict the fugitive dust emission capacity for dust with a drift potential of greater than 8m. This incorporates silt fraction, vehicle speed and weight, number of wheels and mean annual days with rainfall grater than 0,25mm. Although based on data gathered from public unpaved roads, it was adopted by Amponsah-Dacosta (1997) to benchmark a local mine in terms of dust generation from mine haul roads. This work revealed that 91% of the total dust generated by the mine was derived from mine haul roads and that an average control efficiency of 70% was achieved by watering. The work was based on a direct application of the USEPA formula and no direct measurements with which to corroborate the data were taken.

Because many of the concerns related to dust involve the issue of safety and health, the need to predict dust levels in terms of visibility and acceptability has been identified for both public (Jones, 1999) and mine roads (Thompson and Visser, 1999). Jones presented a formula based on dust measurements using the CSIR phase II dust monitor (Jones, 1996) in which the percentage of material smaller than 0,006mm was used to predict the level of dustiness in measurement device-related dust units from 0 (no dust) to 100 (total opacity). These dust units were then related to rating system in which 5 control or acceptability levels were identified. Mulholland (1972) used a subjective scale of 0 to 10 whilst Boyd and von Caauwenberghe (1980) used a similar 5-point scale shown in Table 2.6. The 0-5 scale appears easier to use in terms of distinguishing the conditions described, but ideally this should be correlated with a quantifiable measurement and the scale reversed so that the higher numbers represent a greater, or worse, dust defect. A similar approach, using the existing functional defect descriptions of dustiness (Thompson, 1996) could be applied in relating measured dustiness (as dust reading in mg/m^3) to acceptability limits, in this case defined by mine personnel and described from the point of view of the safety risks and avoidance actions such dustiness typically induces (such as closing vehicle windows, overtaking not safely possible, etc.).

Table 2.6 Dust condition rating (After Boyd and von Caauwenberghe, 1980)

Rating	Description of Dust Defect
5	Dust free, no dust rises from passing vehicle
4	Thin dust, rises a few feet when vehicle passes
3	Thin dust cloud, rises a few feet when vehicle passes but vision not restricted
2	Thin dust cloud, visibility fair to poor, cloud drifts away from road
1	Thick dust cloud, driver uncertainty when following, heavy dust drifting
0	Extreme dust conditions, takes 1-5s for visibility to improve, visibility greatly restricted

2.6 Dust Measurement

Fugitive dust emission rates and particle size distributions are difficult to quantify because of the diffuse and variable nature of such sources and the wide range of particle sizes, including particles which deposit immediately adjacent to the source. Standard source testing methods, which are designed for application to steady-state confined forced-flow conditions, are not suitable for the measurement of fugitive emissions unless the plume can be drawn into a forced-flow system.

For the field measurement of fugitive mass emissions from mechanical entrainment (such as vehicles on a mine haul road), four basic techniques are available (following Cowherd, 1986);

1. The quasi-stack method involves capturing the entire particulate emissions stream with enclosures or hoods and applying conventional source-testing techniques to the flow.
2. Roof monitoring techniques for calculating the mass fluxes entering and leaving an enclosed area, such as a haul truck cab
3. Upwind and downwind source samplers applied under known meteorological conditions, followed by a calculation of the source strength (mass emission rate) with atmospheric dispersion models.
4. Exposure profiling in which simultaneous multi-point measurements of particulate concentration and wind speed over the effective cross-section of the dust plume

are made, followed by a calculation of the net particulate mass flux through integration of the plume profiles.

Because it is impractical to enclose the source or capture entire plume emissions, the most feasible approach generally recognised (Cowherd, 1986) as that of exposure profiling for fugitive or open dust source monitoring. The USBM study (USBM, 1983) adopted a plume profiling approach using an array of dustfall samplers, profiler heads, RAM-1 monitors and quartz crystal cascade analyzers to fully characterise the dust plume created by a haul truck in three dimensions at three test points contiguously, using the total suspended particulate. The testing array incorporated 33 separate instruments and each instrument was read after a certain period or traffic volume. During testing, although meteorological conditions varied, the researchers felt that by interrogating data on a time basis, any significant variation in wind speed and resultant plume could be accounted for.

Such an extensive testing array would be inappropriate for the research considered here. Ideally, a single set- up which provided a quantitative assessment of dustiness at a certain position on the road would fulfil most of the data needs. Since the concept of degree (or percentage) of dust palliation was used, although peak values are liable to misinterpretation (if measured at various positions within a plume), the overall percentage reductions, if the method is repeatable, would nevertheless be valid. With the aim of comparing the performance of different palliatives, although plume and total suspended particulate matter would provide equally useful data, the extensive instrumentation required would limit its applicability. A direct reading instrument, mounted in a similar position at each test location, together with the recording of dependant and independent variables encountered at each site was therefore adopted.

A Hund Tydalometer (TM digital P) was used to measure the dust generation profiles in 2 dimensions (time and dust reading) of vehicles passing the measuring point. The instrument operates on the principle of light scattering and is commonly used for routine checking of dust levels associated with mining operations. To measure the dust concentrations, the infra-red beam of a GaAs diode source passes through a measuring chamber in which dust particles exist. The consequent scattering of the light is measured at 70° to the primary beam which corresponds to a maximum measured particle size of approximately 8 m. The result of the measurement is the scattered light intensity I_{tm} which is directly proportional to the dust concentration and, depending on the type of dust measured, can be calibrated to an equivalent mg/m^3 dust concentration if required. It is assumed that the dust particle-size profile generated by a vehicle passing the machine remains similar before and after palliation and thus using the

8 m fraction should thus faithfully reflect the change in dust levels recorded. The US Environmental Protection Agency (USEPA) recently updated the national PM-10 (particulate matter no greater than 10 microns in aerodynamic diameter) in which it was recognised that the respirable pollutant fraction (PM-10) from both industrial (mine) and public unpaved roads contribute most to the PM-10 emission total and, from a health point of view, the reduction of this respirable fraction is of particular importance (USEPA, 1996).

2.7 Summary of the Current State

Scant attention has been paid to aspects of dust and dust control on mine haul roads and what data exists is generally uncoordinated and not comparable from site to site. No work addresses specifically the health aspects of dust generation, although they are alluded to in a number of studies where environmental and safety factors are considered. In the public domain, dust control and the assessment of dust palliatives have received more attention and can form the background to this study, especially in terms of the identification of general factors governing the emission of fugitive dust. Many of the studies undertaken by product manufacturers or road authorities were both uncoordinated and poorly monitored, with minimal information being recorded or published with which to objectively evaluate a product's performance. Many such experiments have failed, both on public roads and mine roads, due to a combination of poor marketing, sub-standard roads or application and construction techniques and no or inappropriate follow-on maintenance. This has resulted in palliatives being viewed with considerable scepticism by the industry.

Seven classes of palliative product have been identified and their key performance limitations identified. The selection matrix needs to be extended to mine haul road applications to confirm their applicability under these significantly different operating conditions. Road wearing course material parameters were reviewed in the light of recommended selection parameters and as a precursor to identifying the likely application range of each palliative.

Economic evaluation forms an integral part of the assessment of dust palliative safety and health related performance issues on mine haul roads. A review of previous studies has identified the key deficiencies in those analyses and provides the basis for the experimental design and test methodology. When coupled with the current state of dust measurement and dust prediction, it is clear that existing prediction models do not provide data required to assess the impact of haul road dust palliatives on safety and health: Control efficiencies over a longer term are required, coupled with as large a variation in the key performance factors previously identified. In addition, an estimate is required of the exposure to fugitive dust by persons on a mine haul road under the various traffic volume, wearing course and palliative types, using water-based suppression as the base case.

The review of the current state has enabled an appropriate and comprehensive qualitative methodology for evaluating haul road dust hazards and intervention levels, adapted from a quantitative measuring system, to be identified. The modelling and prediction of haul road dust hazards from consideration of wearing course material type, traffic volume and type, maintenance and surface treatment applied to the road will thus satisfy the study objectives to produce a set of guidelines which enable mine operators to cost-effectively reduce the safety and health risk of dust generated on strip coal mine haul roads through the optimal selection, application, evaluation, and maintenance of spray-on or mix-in dust palliation treatments.

CHAPTER 3

EXPERIMENTAL DESIGN AND TEST METHODOLOGY

3.1 Introduction

This chapter addresses the experimental design adopted as a basis for the analysis of dust generation and palliation on mine haul roads. The experimental design is outlined in terms of the measurement of site variables from which the safety and health hazards associated with dust generation and the efficacy of various dust treatments, can be determined. The test methodology is then outlined prior to a review of the various mine test sites available and the extent to which each site fulfils the data requirements envisaged in the experimental design.

3.2 Experimental Design for Evaluation of Haul Road Surface Treatments

The primary objective of the study was to determine the most suitable haul road surface treatments which lead to a reduction in the generation of traffic-induced dust, within the constraints of cost effectiveness and maintainability. The extent to which a particular hauling operation may be affected by dust generation is attributable to wearing course material type, traffic volumes, road geometrics, climate and haul road maintenance factors, including the application of palliatives (Visser, 1981, Paige-Green, 1989 and Thompson, 1996). The most efficient approach ideally entails the analysis of a number of in-service mine roads which cover a full range of these factors that influence dust generation.

In respect of palliative selection as a factor in the experimental design, the ideal experimental approach would have been to assess each class of palliative (as outlined in Chapter 2) in conjunction with a range of wearing course material types. However, this approach would have entailed the simultaneous monitoring and assessment of 35 sites covering some 210 000m^2 of road and the suppliers of the various products were unwilling to provide palliatives to cover such an extensive trial, and the project was unable to finance such an experiment. Therefore palliative selection was based primarily on those products already purchased and applied at the various participating mines, together with the purchase of an additional class of palliative to complete the assessment of the most widely used products.

The choice of wearing course materials as a factor is problematic in terms of its sub-division into a number of characteristic properties, the extensive testing required being impractical. A more rational approach has been outlined by Weinert (1980) in which rock types are grouped by their weathering products and geotechnical behaviour, irrespective of their genesis. The following nine material groups are recognised by Wienert;

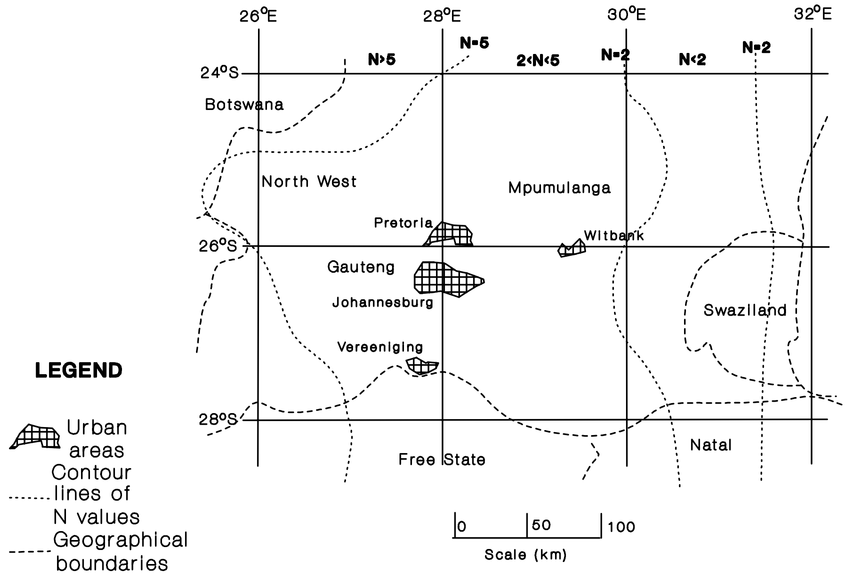
(i) Basic crystalline rocks, eg. basalt, amphibolite, dolerite
(ii) Acid crystalline rocks, eg. felsite, gneiss, granite
(iii) High silica rocks, eg. chert, quartzite, hornfels
(iv) Arenaceous rocks, eg. Arkose, sandstone, mica-schist
(v) Argillaceous rocks, eg. shale, mudstone, phyllite
(vi) Carbonate rocks, eg. dolomite, limestone , marble
(vii) Diamictites, eg. tillite
(viii) Metalliferous rocks, eg. magnesite, magnetite, ironstone
(ix) Pedocretes, eg, calcrete, ferricrete, laterite

Several of these groups may be disregarded for the purposes of this study due in most part to their limited occurrence or unsuitability for mine haul road wearing course construction. In addition, although not a weathering product, mixtures of materials must also be considered as a factor level together with coal discards.

The choice of climate as a factor was based on Weinert's N-value (Weinert, 1980). Weinert's N-value describes the durability of road-building material, based on the relationship between calculated evaporation rates (for the warmest months of the year) and the averaged monthly rainfall. This choice is advantageous since the weathering products used as levels for the independent variable of wearing course material are unique for the particular N-value contour chosen, although as will be shown later, this and the physical location of the mines limits the range of materials available for analysis. In addition, the N-values of 2, 5 and 10 are distinct physiographical boundaries and most Highveld strip coal mines are situated within the physiographical region where N=2 to N=5 as shown in Figure 3.1. This effectively discounts climate as an independent variable in the analysis.

Road geometrics are considered in terms of a section of homogenous, straight road, either level or grade, 200m long with no road junctions entering or leaving the section. It was not always possible to satisfy these demands entirely, especially for level sections, but significant deviations from the factor level are noted where applicable. In addition, the following additional dependent variables were recorded for each test section;

WEINERT N-VALUE CLIMATIC REGIONS
AND LOCATION OF MINE TEST SITES



- Days since last blading
- Traffic (t/day), traffic type and speed
- Moisture conditions of surface layer
- Palliative type, days since last application and method of application
- Road surface erosion
- Road surface and roadside drainage

Laboratory tests of the wearing course materials encountered at each test site involved the quantitative analysis of the following material parameters;

- Grading
- Atterberg limits and linear shrinkage
- California Bearing Ratio (CBR) (soaked)
- Classification according to TRH20 (CSRA, 1990) for shrinkage product and grading coefficient

From these results, recommendations can be made relating to the most desirable parameters for the selection, application and efficacy of dust palliatives for haul roads.

3.3 Measurement of Site Variables

The measurement and data collation of quantitative and qualitative site variables is summarised in Table 3.1 for the principal components of dustiness and the attendant road functionality. Details of the variable measurement systems adopted for the functional analysis are discussed in the following sub-sections.

Table 3.1 Summary of Variable Measuring Systems

VARIABLE	MEASUREMENT SYSTEM
Traffic volume	Production statistics
Wearing course material	Laboratory classification
Days since last maintenance	Mine records
Moisture conditions of surface layer	Functional assessment following 5 point scale of degree
Surface drainage conditions	Functional assessment following 5 point scale of degree
Surface erosion	Functional assessment following 5 point scale of degree
Road surface functionality	Functional assessment following 5 point scale of degree and extent
Road geometry	Survey plans
Quantitative dust defect	Hund Tyndalometer
Airborne dust	Gilian Gil air sampling pump and calibrator

3.3.1 Wearing Course Material

Samples of the wearing course material were collected from a number of surface strip coal mining operations with the aim of fulfilling the range of wearing course material types (weathering products). Samples were subsequently split into an approximately 10kg sample for grading tests and indicator tests and 50kg for compaction and strength tests. Laboratory testing followed the Standard Methods for Testing Materials (NITRR,TMH1, 1986).

3.3.2 Road Surface Functionality

A visual evaluation was used for the qualitative determination of surface moisture conditions, roadside and on-road drainage and erosion (longitudinal and cross directions). The variables affecting haul road functional performance were derived from consideration of the properties of the wearing course surface (material type), those related to the road formation and those related to the way the road user experiences the road. The following defects were considered, both in terms of degree (how adverse is the defect) and extent (how much of the road is affected), except for formation and functional defects, which are only considered in terms of extent.

- Wearing course
  - Potholes
  - Corrugations
  - Loose material
  - Dustiness
  - Stoniness - fixed
  - Stoniness - loose
  - Cracks - longitudinal
  - Cracks - slip
  - Cracks - crocodile

- Formation
  - Drainage - on the road
  - Drainage - side of road

- Function
  - Skid resistance - wet
  - Skid resistance - dry
  - Erosion - longitudinal direction
  - Erosion - cross direction

These defects were used to determine the functionality of a particular road, in terms of a total defect score, derived from consideration of the sum of each defect degree and extent product in the analysis. Recordings were made at each mine test site to generate a profile of the variation of defect score with the other dependent variables analysed together with the type of palliative applied, to ascertain the magnitude of improvement in functionality associated with the use of a particular palliative. Although the primary objective of the investigation was to establish the most suitable surface treatment to reduce the generation of dust, it was nevertheless necessary to consider the wider functional impacts of a dust suppressant, rather then its ability to suppress dust alone. Little safety and health benefit will be gained by using suppressants that, whilst reducing the amount of dust generated, cause an increase in other critical road functional defects.

The characteristics adopted for the visual evaluation of mine haul roads have been derived from recorded defects on unpaved public roads (Pienaar and Visser, 1992, CSRA TRH20, 1990) and the Standard Visual Assessment Manual for Pavement Management Systems (CSRA TMH9, 1990), suitably modified to accommodate the requirements of mine haul road operators following Thompson (1996). The condition of the pavement is considered from the point of view of the road user and incorporates appraisal in terms of those characteristics that affect the functionality of the road. 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. Since the degree of distress can vary over a pavement test section, the recorded degree should give the best average assessment of a particular type of distress over the test section. 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 general descriptions of degree are presented in Table 3.2.

Table 3.2 General Description of Degree Classification (following Thompson, 1996 and CSRA TMH9, 1990).

DEGREE	SEVERITY	DESCRIPTION
0	-	No distress visible
1	Slight	Distress difficult to discern and only slight signs visible
2	Between slight and warning	Easily discernible distress but of little immediate consequence
3	Warning	Distress is notable with respect to possible consequences - start of secondary defects
4	Between warning and severe	Distress is serious with respect to possible consequences. Secondary defects have developed and/or primary defect is serious
5	Severe	Distress is extreme with respect to possible consequences. Secondary defects are notable and/or primary defect is extreme

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 general description of extent given in Table 3.3 is applied in assessing the extent of any defect.

Table 3.3 General Description of Extent Classification (modified following Thompson, 1996 and CSRA TMH9, 1990).

EXTENT	DESCRIPTION
1	Isolated occurrence, less than 5% of road affected.
2	Intermittent occurrence, between 5-15% of road affected.
3	Regular occurrence, between 16-30% of road affected.
4	Frequent occurrence, between 31-60% of road affected.
5	Extensive occurrence, more than 60% of the road affected.

The rating of extent is 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 individual ratings for degree of defect based on the general description of degree classification are given in Table 3.4. The recording form adopted for the investigation is shown in Table 3.5.

3.3.2.1 Analytical Methodology

A mine haul road wearing course material can be modelled in terms of the predicted variation in functional defects, following Thompson (1996). Functionality is measured as the sum of various road defects as shown in Table 3.5, measured as the product of degree and extent of those functional defects. The maximum defect score is 250 and corresponds to very poor functionality. Figure 3.2 illustrates the change in functionality that can be anticipated with a particular wearing course and traffic volume. Optimal functionality can be maintained with a maintenance interval of approximately two days which renders the lowest average defect score. Whilst this maintenance interval provides optimum *functionality*, it may not necessarily coincide with the optimal maintenance interval determined from an analysis of road roughness and the associated road-user cost variation.

Table 3.4 Classification of the Degree of Key Haul Road Defects in the Assessment of Dustiness

CHARACTERISTIC	**DESCRIPTION**				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Potholes	Surface is pock marked , holes < 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 total avoidance.
Corrugations	Slight corrugations, difficult to feel in light vehicle.	Corrugations present and noticeable in light vehicle.	Corrugations very visible and reduce riding quality noticeably.	Corrugations noticeable in haul truck and causing driver to reduce speed.	Corrugations noticeable in haul truck and causing driver to reduce speed significantly.
Rutting	Difficult to discern unaided, <20mm.	Just discernable with eye, 20-50mm.	Discernable, 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, window 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, reducing riding quality.	Large amounts of loose stone causing significant reduction in riding quality.

Table 3.4 (contd) Classification of the Degree of Key Haul Road Defects in the Assessment of Dustiness (continued)

CHARACTERISTIC	**DESCRIPTION**				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Cracks - longitudinal	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable 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
Cracks - slip	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable 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 discernable when walking, closed.	Distinct cracks up to 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	Shallow depressions may retain water for a limited time,	water may be retained in ruts and potholes, some surface	Water retained over a significant portion of the road,	Water ponding on road to depths >50mm and erosion

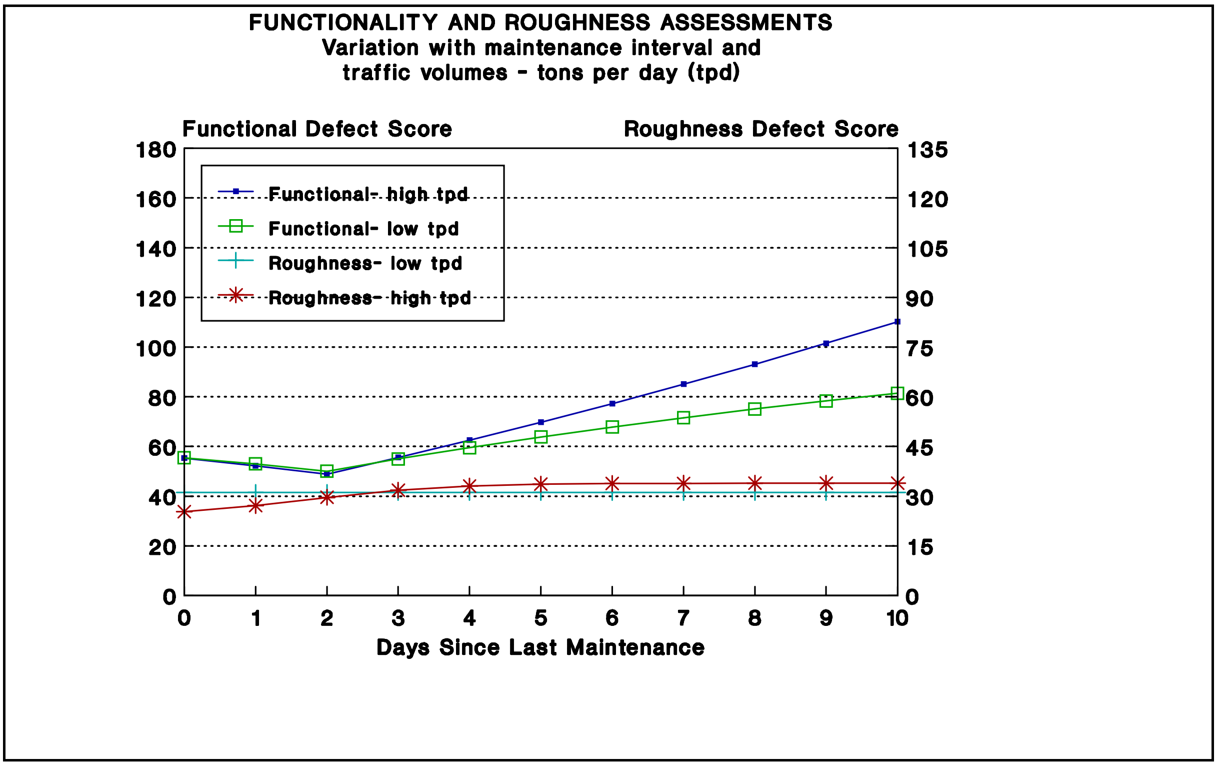
	evident.	most water drains away rapidly.	erosion evident.	surface erosion <50mm deep in channels.	channels deeper than 50mm.
Drainage at roadside	Side drains very effective, well shaped with no obstructions.	Slightly irregular, some loose debris or occasional erosion, road well above side drain level.	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.

Table 3.5 Dust Palliative Functionality Recording Form

UNIVERSITY OF PRETORIA
DUST PALLIATIVE FUNCTIONALITY EVALUATION

DATE		EVALUATOR	
ROAD		SPEED km/hr	
CHAINAGE			
TRAFFIC kt/day			

DEFECT	**FUNCTIONALITY**			
	DEGREE	EXTENT	DEFECT SCORE	NOTES
Potholes				
Corrugations				
Rutting				
Loose material				
Stoniness - fixed				
Dustiness				
Stoniness - loose				
Cracks - longit				
Cracks - slip				
Cracks - croc				
Skid resistance - wet				
Skid resistance - dry				
TOTAL FUNCTIONALITY SCORE				
			Comment	
Drainage	On road			
	Side of road			
Erosion	Longitudinal			
	Cross			



Road roughness comprises the defects of potholes, corrugations, rutting, loose material and fixed stoniness, assessed on the basis of the product of defect degree and extent which gives a maximum roughness defect score of 125. It is these road roughness defects that lead to excessive haulage vehicle operating costs and ideally such defect should be minimised, but not to the extent that excessive slipperiness or skid resistance occurs. From Figure 3.2 it is seen that a daily maintenance is the optimal regime.

The maintenance interval has important implications for the selection and application of dust palliatives to the haul roads. A palliative with a long operational life will not be cost effective if the road is regularly regraded and the palliative must consequently be re-applied. The greatest benefit may accrue from treating both high- and low-volume roads since the latter, due to the lower traffic volumes, will not require such frequent grading and hence the palliative effects will endure over longer periods. These periods will be established in the following Chapters for the various treatments analysed.

3.3.3 Airborne Particulate Matter Qualitative Dust Sampling Methodology

The Hund Tydalometer (TM digital P) was used to measure the dust generation profiles of vehicles passing the measuring point. The instrument operates on the principle of light scattering and is commonly used for routine checking of dust levels associated with mining operations.

The machine is depicted schematically in Figure 3.3. To measure the dust concentrations, the infra-red beam of a GaAs diode source passes through a measuring chamber in which dust particles exist. The consequent scattering of the light is measured at 70° to the primary beam which corresponds to a maximum measured particle size of approximately 8 m. The result of the measurement is the scattered light intensity I_{tm} which is directly proportional to the dust concentration and, depending on the type of dust measured, can be calibrated to an equivalent mg/m^3 dust concentration if required. For rock dust this calibration factor is approximately 0,01 as shown in Figure 3.4. It is assumed that the dust particle-size profile generated by a vehicle passing the machine remains similar before and after palliation and thus using the 8 m fraction should thus faithfully reflect the change in dust levels recorded. The US Environmental Protection Agency (USEPA) recently updated the national PM-10 (particulate matter no greater than 10 microns in aerodynamic diameter) in which it was recognised that the respirable pollutant fraction (PM-10) from both industrial (mine) and public unpaved roads contribute most to the PM-10 emission total and, from a health point of view, the reduction of this respirable fraction is of particular importance (USEPA, 1996).

3.3.3.1 Sampling Procedure

The procedure followed in establishing the dust concentration was based on the following methodology:

(i) Calibration of the instrument prior to sampling.

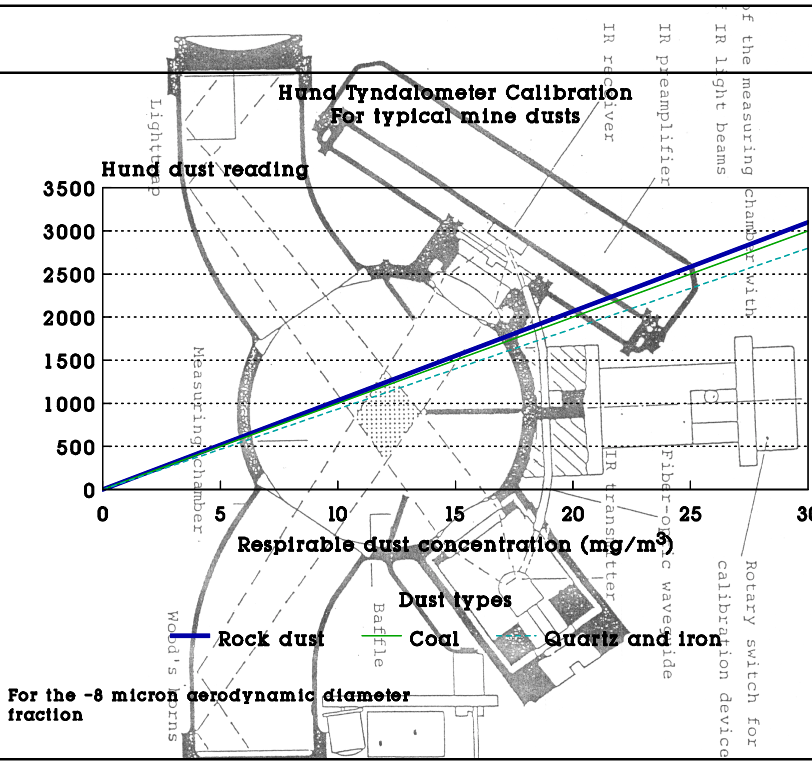
(ii) Set machine up centrally within the test section, approximately 5m from the edge of the road test section on both sides of the road (to cater for wind direction effects and to reduce the effect of carry-over dust from the control or buffer sections). Sampling point set at centre of test section and determine background dust concentration (with no traffic).

(iii) Establish with Abbirko Flowmaster anemometer the wind speeds and directions prior to testing and note any significant changes which would affect emission rates.

(iv) Each vehicle was instructed to pass 1m from the sampling point and vehicle speed was recorded. Exceptions were noted.

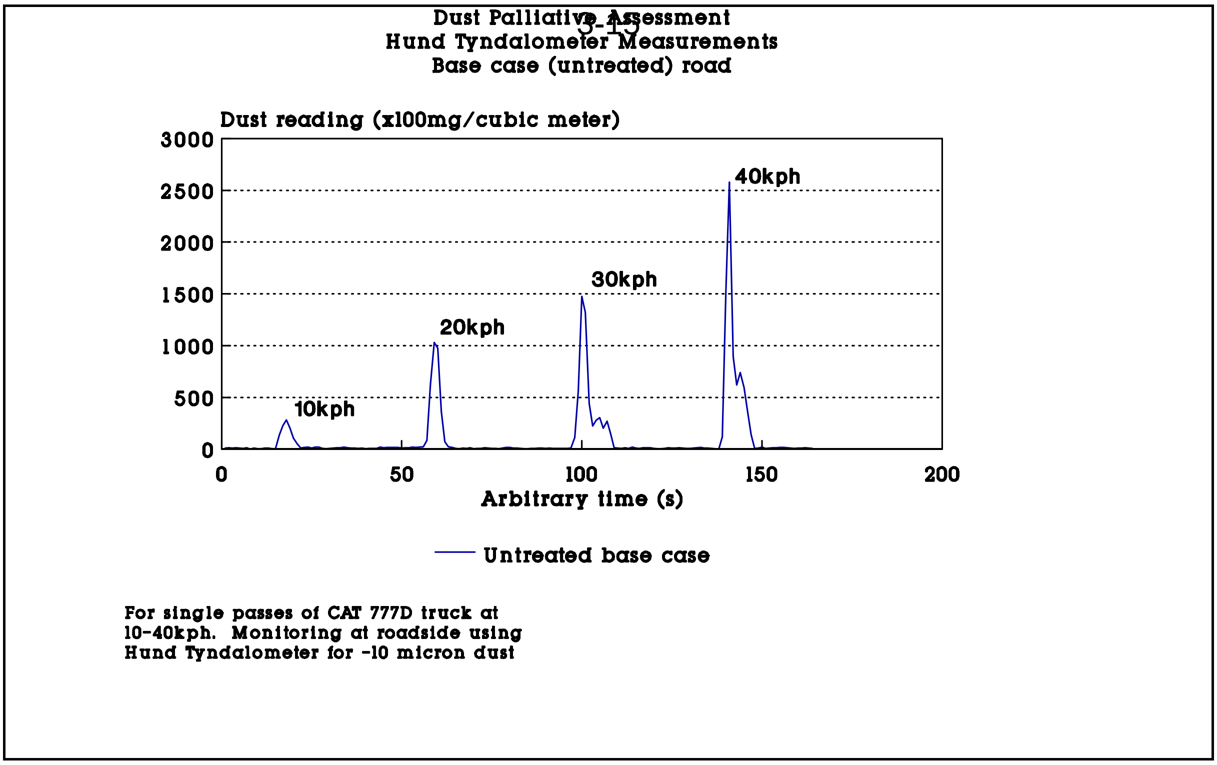
(v) The instrument was set to sample at 1 second intervals and the dust concentration readings recorded until ambient dust levels were re-established following the vehicle pass.

(vi) The instrument zero calibration was checked prior to further deployment.



3.3.3.2 Analysis of Data

Results were analysed in terms of the average dust concentrations measured for a number of vehicle passes, or individual passes where a degeneration profile was required. Conversion factors are normally required with which to correlate the optically measured results with that of the gravimetric method. The conversion factor was determined by conducting comparative measurements at the same time and same location with gravimetric air sampling equipment. Since the sample mass for one vehicle pass is low, the duration of the pass measurement is only 30-40 seconds (compared to the required eight hours gravimetric sampling) and the



For single passes of CAT 777D truck at
10-40kph. Monitoring at roadside using
Hund Tyndalometer for -10 micron dust

character of the dust between and at each test site may change with the application and subsequent degredation of the palliative, no conversion factor was determined. However, with reference to Figure 3.4, it may be assumed that concentrations approximate closely to the control or base case readings taken. In the analysis, results are reported in terms of suppression efficiencies and degree of dust palliation, to overcome the necessity to recalibrate for every type of dust encountered.

Figure 3.5 illustrates a typical set of readings taken with the Hund Tyndalometer for a number of vehicle passes.

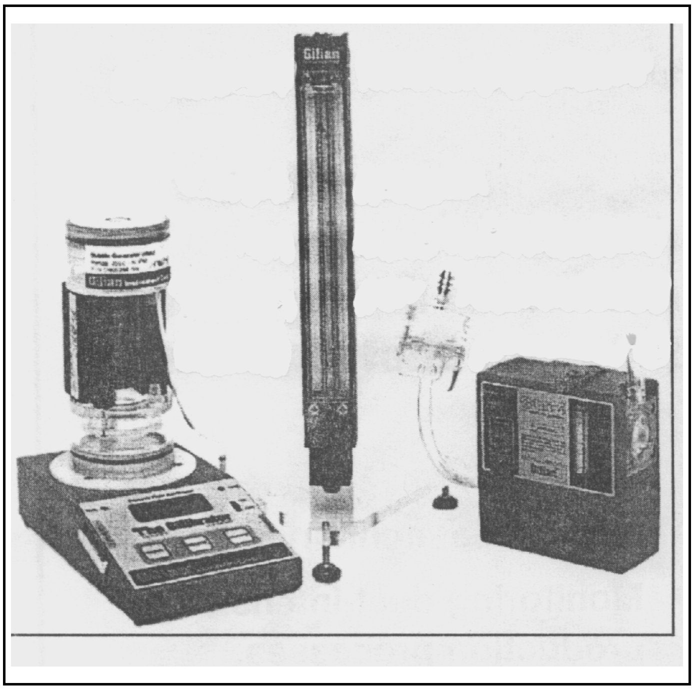
3.3.4 Airborne Particulate Matter Gravimetric Dust Sampling Methodology

The equipment used in this study was a Government Mining Engineer (GME) approved sampling pump and procedure. Sampling pumps were Gilian Gil - Air Sampling Pump (Certificate No. G08 and date 1989/05/18 approved) as shown in Figure 3.6. The Gilian GX-R-25mm Cyclone (Certificate No. G05 and date 1991/04/16 approved) was used in line with the sampling pump to cater for the respirable fraction of the dust sample (<7µm). For calibration purposes before and after use, flow through the instrument was assessed to within 5% of the 1,9 l/min recommended flowrate using the Gilibrator calibrator. A cellulose nitrate filter paper of 25 mm was used as the filter medium in filter cassettes of a design approved by the GME.

3.3.4.1 Sampling Procedure

The procedure followed in establishing total and respirable samples was based on the following methodology:

- (i) All filters weighed before sampling.
- (ii) Calibration of dust sampling instruments in line with sampling train (1,9 l/min).
- (iii) Set sampling train up approximately 5m from the edge of the haulroad test section on either sides of the road (to cater for wind direction effects).
- (iv) At the end of the test period (dayshift) the pumps are removed and the filter samples be transported in the approved carry-box as required by the GME.
- (v) The pumps are recalibrated for flow rate prior to further deployment.



3.3.4.2 Analysis of Results

The samples were weighed and the Time Weighted Average (TWA) calculated to obtain the mass of airborne particulates (mg/m^3). Analysis of the filters included the quartzite (%) content and any other pollutants. An Air Quality Index (AQI) was determined for the samples taken following analysis which may then be used to determine the extent of any reduction in airborne dust associated with the use of a particular palliative.

3.4 Mine Test Site Factor Summary

The experimental design described in section 3.2 forms the basis for the location of suitable test sites. A number of possible test site locations were determined from a preliminary visit to several surface mining operations. For each possible mine test site analysed, the range of independent variables are assessed and summarised in the following sub-sections prior to the selection of specific test sites for dust palliative assessment measurements and/or as a source of data for water-based suppression efficiency and dust defect model generation.

Test Site A

Wearing Course Material

The mine haul road wearing course material at site A consisted of run-of-mine (ROM) discards, including a small amount of carbonaceous shales. Table 3.7 gives the results of the laboratory analysis of the wearing course material sampled at site A1 as shown in Figure 3.7. The discards top size was 150mm, with 16% larger than 37,5mm which makes blader maintenance ineffective. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G5 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibits low shrinkage product (55,5) and grading coefficient (15,8) values which are indicative of excessive ravelling and corrugation which may be compounded by the low CBR of 76% at 98% Mod AASHTO compaction. When a dust ratio for the material is calculated, based on the ratio of material passing the 0,075mm sieve to that passing the 0,425mm sieve, a value of 0,59 is found which can be associated with a tendency to form excessive dust, a fact confirmed by site observation and the generation of fine material as a result of traffic-induced breakdown of the material.

Traffic Volume

The hauling fleet comprised Caterpillar CAT 777 (single rear axle with dual wheels) trucks of 85t capacity. Maximum traffic volumes at the test site can be equated to approximately 3390 truck repetitions per month.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.7.

SITE A1 Ramp 2-3 haul road (approximately level), laden side of road.

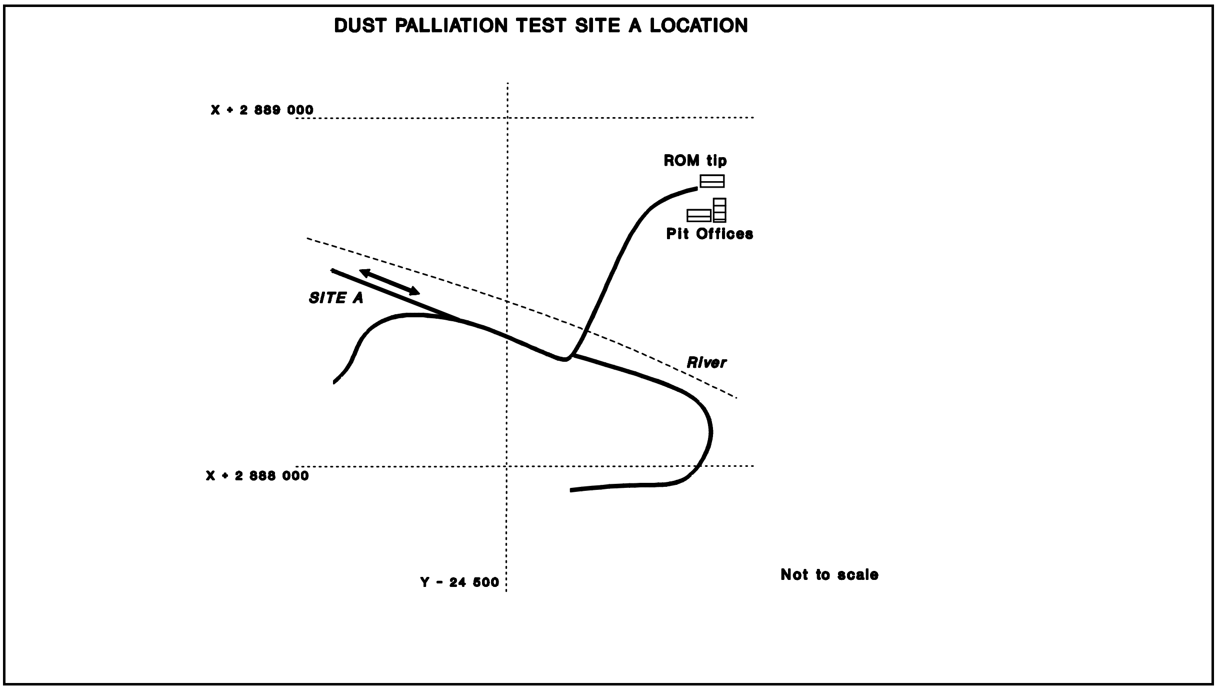
Palliative Treatment

The site was treated with an emulsified tar/bitumen product at an initial establishment rate 3l/m^2 to a depth of approximately 100mm using a mix-in technique, followed by monthly spray-on re-applications of 0,125l/m^2. After 12 months, a total of 6l/m^2 product would have been applied, following which maintenance applications would be required at a frequency dictated by traffic volumes and wearing course dust generation rates. The site was also used as a source of data for water-based suppression efficiency, in its untreated state, prior to the application of the chemical palliative.

Table 3.7 Laboratory Analysis of Wearing Course Material - Site A

SAMPLE SITE: A	**Site 1: Ramp 2-3 road.**
SAMPLE DESCRIPTION	Dark grey coal discards. Fine gravel.
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	93
53.00	92
37.50	84
26.50	79
19.00	74
13.20	72
4.75	63
2.00	54
0.425	37
0.075	22
SOIL MORTAR	
Coarse sand 2.00-0.425mm	32
Coarse fine sand 0.425-0.250mm	9
Medium fine sand 0.250-0.150mm	10
Fine sand 0.150-0.075mm	9
Material <0.075mm	40
CONSTANTS	
Grading modulus	1,87
Liquid limit	22
Plasticity index	4
Linear shrinkage (%)	1.5
Sand equivalent	
Classification - TRB	A-1-b(0)
Classification - TRH14	G5
Classification - TRH20 Shrinkage product	55,5
Classification - TRH20 Grading coefficient	15,75
MOD. AASHTO	
Max dry density (kg/m^3)	1686
OMC (%)	8,0
MMC (%)	7,7
Dry density (kg/m^3)	1693
	100

% Max dry density	100
100% Mod CBR	0,0
% Swell	
NRB	
Dry density (kg/m^3)	1626
% Max dry density	96
100% NRB CBR	63
% Swell	0,1
PROCTOR	
Dry density (kg/m^3)	1563
% Max dry density	93
100% Proctor CBR	32
% Swell	0,1
CBR VALUES	
100% Mod AASHTO	95
98%Mod AASHTO	76
97%Mod AASHTO	67
95%Mod AASHTO	49
93%Mod AASHTO	34
90%Mod AASHTO	20



Test Site B

Wearing Course Material

The mine haul road wearing course material at site B consisted of ferricrete material sourced from local borrow pits. Table 3.8 gives the results of the laboratory analysis of the wearing course material sampled at site B1 as shown in Figure 3.8. The material was seen to be a sand with a top size of 4,75mm. When the laboratory analysis of the material is considered in terms of the TRH14 requirements, the wearing course is classified as comprising a G7 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials, the material exhibits a shrinkage product of 29,5 and grading coefficient of 21,1 which are indicative of excessive ravelling, loose material and corrugation. This may ascribed in part to the absence of fine (clay) binding materials in the wearing course and the associated low plasticity index and shrinkage. The dust ratio for the material of 0,35 is indicative of very little dust problems as would be expected from this type of material. However, traffic-induced breakdown of loose material may lead to greater dust problems than anticipated from the dust ratio alone. Road maintenance involved ad-hoc grading and watering of the road. The roads are ripped and redressed over the winter months.

Table 3.8 Laboratory Analysis of Wearing Course Material - Site B.

SAMPLE SITE: B	**Site B1: Main haul road**
SAMPLE DESCRIPTION	Dark brown ferricrete. Sand.
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	100
26.50	100
19.00	100
13.20	100
4.75	92
2.00	77
0.425	59
0.075	21
SOIL MORTAR	
Coarse sand 2.00-0.425mm	24
Coarse fine sand 0.425-0.250mm	13
Medium fine sand 0.250-0.150mm	16
Fine sand 0.150-0.075mm	20
Material <0.075mm	27
CONSTANTS	
Grading modulus	1,43
Liquid limit	
Plasticity index	SP
Linear shrinkage (%)	0,5
Sand equivalent	
Classification - TRB	A-2-4(0)
Classification - TRH14	G7
Classification - TRH20 Shrinkage product	29.5
Classification - TRH20 Grading coefficient	21.1
MOD. AASHTO	
Max dry density (kg/m^3)	2178
OMC (%)	6,9
MMC (%)	6,9
Dry density (kg/m^3)	2191
% Max dry density	101
100% Mod CBR	111
% Swell	0
NRB	
Dry density (kg/m^3)	2100

% Max dry density	96
100% NRB CBR	46
% Swell	0
PROCTOR	
Dry density (kg/m^3)	2065
% Max dry density	95
100% Proctor CBR	34
% Swell	0
CBR VALUES	
100% Mod AASHTO	98
98%Mod AASHTO	64
97%Mod AASHTO	52
95%Mod AASHTO	35
93%Mod AASHTO	24
90%Mod AASHTO	14

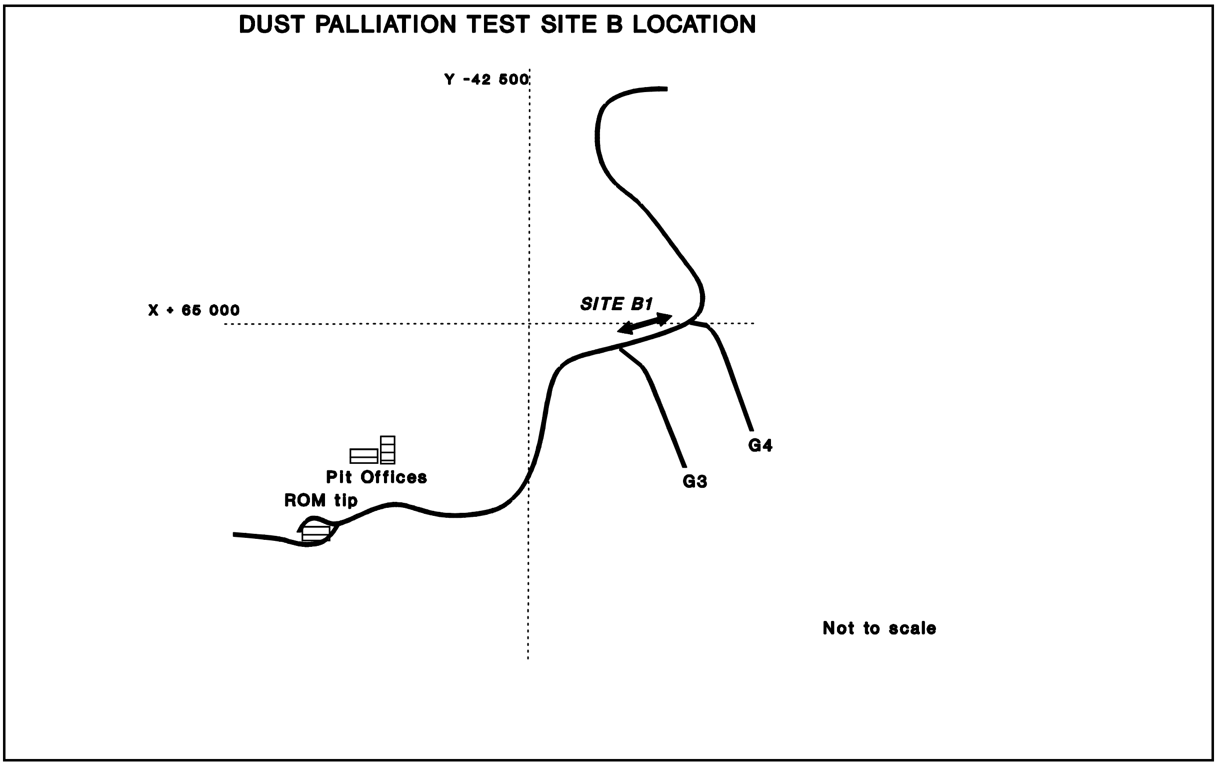
Traffic Volume

The fleet comprised both Caterpillar CAT 785 (single rear axle with dual wheels) trucks of 135t capacity and Caterpillar CAT 776 (horse single rear dual wheel axle and trailer single dual wheel axle) bottom dump trucks of 135t capacity. Traffic volumes at the test site equate to approximately 580 repetitions per month, depending on the production ramps available.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the location given in Figure 3.8.

SITE B Main haul road on approximately level section of road, laden side of road.



DUST PALLIATION TEST SITE B LOCATION

Palliative Treatment

Dust palliation using a lignosulphonate product had been applied and on the roads over the previous season. A spray-on application technique was used, primarily over the dry winter months, to progressively build up product in the road. Product is applied at approximately 16:1 ratio (water:product) every 3-7 weeks depending on traffic volume and dust generation rates, to give approximately 0,2l/m^2 applied.

The site was also used as a source of data for water-based suppression efficiency tests and dust defect model generation, in its untreated state.

Test Site C

Wearing Course Material

The mine haul road wearing course material at site C consisted of ferricrete material (90%) sourced from local borrow pits together with small amounts of bottom ash (10%). Table 3.9 gives the results of the laboratory analysis of the wearing course material sampled at site C1 as shown in Figure 3.9. The material was seen to be a sand with a top size of 4,75mm. When the laboratory analysis of the material is considered in terms of the TRH14 requirements, the wearing course is classified as comprising a G7 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials, the material exhibits a shrinkage product of 157,5 and grading coefficient of 12,6, the latter indicative of excessive loose material and corrugation. This may be ascribed in part to the absence of larger fractions of material in the wearing course and the low plasticity of the material. The dust ratio for the material of 0,49 is within recommended limits for wearing course materials.

Road maintenance involved ad-hoc grading and watering of the road. The roads are ripped and redressed over the winter months.

Traffic Volume

The fleet comprised both Caterpillar CAT 777 (single rear axle with dual wheels) trucks of 85t capacity and nine Caterpillar CAT 785 (single rear dual wheel axle) rear dump trucks of 135t capacity. The location of the test site results in approximately 2050 repetitions per month, depending on the production ramps available.

Road Geometrics

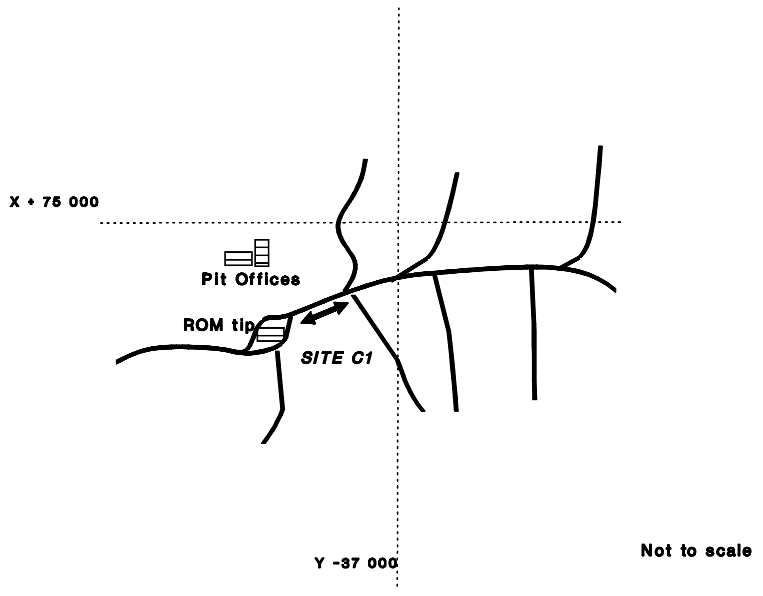
From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. No grade sections were available. The site is summarised overleaf and the location given in Figure 3.9.

Table 3.9 Laboratory Analysis of Wearing Course Material - Site C.

SAMPLE SITE: C	**Site C: Main haul road**
SAMPLE DESCRIPTION	Dark red ferricrete and ash (90/10). Sand.
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	100
26.50	100
19.00	100
13.20	100
4.75	97
2.00	87
0.425	63
0.075	31
SOIL MORTAR	
Coarse sand 2.00-0.425mm	28
Coarse fine sand 0.425-0.250mm	9
Medium fine sand 0.250-0.150mm	13
Fine sand 0.150-0.075mm	15
Material <0.075mm	35
CONSTANTS	
Grading modulus	1,19

Liquid limit	18
Plasticity index	5
Linear shrinkage (%)	2,5
Sand equivalent	
Classification - TRB	A-2-4(0)
Classification - TRH14	G7
Classification - TRH20 Shrinkage product	157,5
Classification - TRH20 Grading coefficient	12,6
MOD. AASHTO	
Max dry density (kg/m^3)	2147
OMC (%)	6,6
MMC (%)	6,5
Dry density (kg/m^3)	2157
% Max dry density	100
100% Mod CBR	102
% Swell	0
NRB	
Dry density (kg/m^3)	2077
% Max dry density	97
100% NRB CBR	61
% Swell	0
PROCTOR	
Dry density (kg/m^3)	1995
% Max dry density	93
100% Proctor CBR	33
% Swell	0,1
CBR VALUES	
100% Mod AASHTO	96
98%Mod AASHTO	73
97%Mod AASHTO	63
95%Mod AASHTO	46
93%Mod AASHTO	33
90%Mod AASHTO	21

DUST PALLIATION TEST SITE C LOCATION



SITE C Main haul road between ramps S4 and S5 on approximately level section of road, laden side of road.

Palliative Treatment

Dust palliation using a lignosulphonate product was applied and is currently used on the roads. A spray-on application technique was used, primarily over the dry winter months, to progressively build up product in the road. Product is applied at approximately 16:1 ratio (water:product) every 3-4 weeks depending on traffic volume and dust generation rates, to give approximately 0,2l/m^2 applied.

The site was also used as a source of data for water-based suppression efficiency tests and dust defect model generation data, in its untreated state.

Test Site D

Wearing Course Material

The mine haul road wearing course material at site D consisted of run-of-mine (ROM) discards, ash and clay-sands, including a small amount of carbonaceous shales. Table 3.10 gives the results of the laboratory analysis of the wearing course material sampled at site D1 as shown in Figure 3.10. The discards top size was 53mm. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G5 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibits a low shrinkage product (25) and high grading coefficient (162) values and some plasticity, which are indicative of a tendency to excessive dustiness. When a dust ratio for the material is calculated, a value of 0,58 is found which is indicative of the potential to generate dustiness. Site observation revealed a tendency to form excessive dust, due to the generation of fine material as a result of traffic-induced breakdown of the coal and shales. Road maintenance involved ad-hoc grading and watering of the road and the roads are ripped and redressed over the winter months.

Traffic Volume

The hauling fleet comprised Euclid R170 (single rear axle with dual wheels) trucks of 130t capacity. Maximum traffic volumes at the test site can be equated to approximately 8000 truck repetitions per month.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.10.

SITE DMain haul road (approximately level), laden side of road.

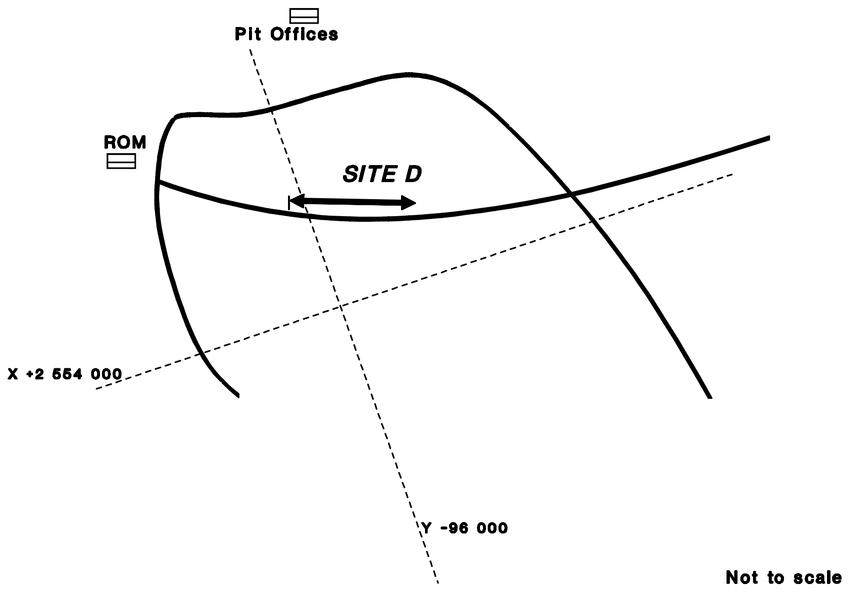
Palliative Treatment

The site was treated with a polymer emulsion product at an initial establishment rate 0,95l/m^2 product to a depth of approximately 100mm using a mix-in technique, followed by monthly spray-on re-applications of 0,005l/m^2 product. After 12 months, a total of 1,01l/m^2 product had been applied, following which maintenance applications would be required at a frequency dictated by traffic volumes and dust generation rates.

Table 3.10 Laboratory Analysis of Wearing Course Material - Site D

SAMPLE SITE: D	Site D1: Main haul road
SAMPLE DESCRIPTION	Soft plinthite, coal and ash
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	97
37.50	94
26.50	90
19.00	86
13.20	82
4.75	66
2.00	51
0.425	36
0.075	21
SOIL MORTAR	
Coarse sand 2.00-0.425mm	31
Coarse fine sand 0.425-0.250mm	9
Medium fine sand 0.250-0.150mm	12
Fine sand 0.150-0.075mm	8
Material <0.075mm	40
CONSTANTS	
Grading modulus	1,92
Liquid limit	27
Plasticity index	9
Linear shrinkage (%)	4,5
Sand equivalent	
Classification - TRB	A-2-4(0)
Classification - TRH14	G5
Classification - TRH20 Shrinkage product	25
Classification - TRH20 Grading coefficient	162
MOD. AASHTO	
Max dry density (kg/m^3)	1975
OMC (%)	8,5
MMC (%)	8,8
Dry density (kg/m^3)	1951
% Max dry density	99
100% Mod CBR	84
% Swell	0
NRB	
Dry density (kg/m^3)	1869
% Max dry density	95
100% NRB CBR	57
% Swell	0
PROCTOR	
Dry density (kg/m^3)	1826
% Max dry density	92
100% Proctor CBR	29
% Swell	0
CBR VALUES	
100% Mod AASHTO	94
98%Mod AASHTO	78
97%Mod AASHTO	71
95%Mod AASHTO	59
93%Mod AASHTO	34
90%Mod AASHTO	24

DUST PALLIATION TEST SITE D LOCATION



Test Site E

Wearing Course Material

The mine haul road wearing course material at site E consisted of plant discards comprising mostly coal and small amount of shale and sandstone. Table 3.11 gives the results of the laboratory analysis of the wearing course material sampled at site E1 as shown in Figure 3.11. The discards top size was 53mm, with 7% larger than 37,5mm which makes blader maintenance difficult. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G5 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibited an acceptable, slightly low shrinkage product (67) and a high grading coefficient (31) value which are indicative of low dry skid resistance and ravelling. When a dust ratio for the material is calculated, a value of 0,39 is found which is indicative of low dustiness. However, site observation revealed a tendency to form excessive dust, due to the generation of fine material as a result of traffic-induced breakdown of the coal and shales. Road maintenance involved ad-hoc grading and watering **Table 3.11** Laboratory Analysis of Wearing Course Material - Site E.

SAMPLE SITE: E	**Site E: New haul road**
SAMPLE DESCRIPTION	Discards
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100

37.50	93
26.50	89
19.00	85
13.20	79
4.75	57
2.00	42
0.425	31
0.075	12
SOIL MORTAR	
Coarse sand 2.00-0.425mm	28
Coarse fine sand 0.425-0.250mm	11
Medium fine sand 0.250-0.150mm	19
Fine sand 0.150-0.075mm	12
Material <0.075mm	30
CONSTANTS	
Grading modulus	2,15
Liquid limit	18
Plasticity index	5
Linear shrinkage (%)	2,0
Sand equivalent	
Classification - TRB	A-1-b(0)
Classification - TRH14	G5
Classification - TRH20 Shrinkage product	67
Classification - TRH20 Grading coefficient	31
MOD. AASHTO	
Max dry density (kg/m^3)	2217
OMC (%)	5,3
MMC (%)	5,1
Dry density (kg/m^3)	2279
% Max dry density	100
100% Mod CBR	124
% Swell	0
NRB	
Dry density (kg/m^3)	2302
% Max dry density	96
100% NRB CBR	29
% Swell	0,1
PROCTOR	
Dry density (kg/m^3)	2233
% Max dry density	98
100% Proctor CBR	94
% Swell	0
CBR VALUES	
100% Mod AASHTO	118
98%Mod AASHTO	88
97%Mod AASHTO	74
95%Mod AASHTO	51
93%Mod AASHTO	35
90%Mod AASHTO	20

of the road and the roads are ripped and redressed over the winter months.

Traffic Volume

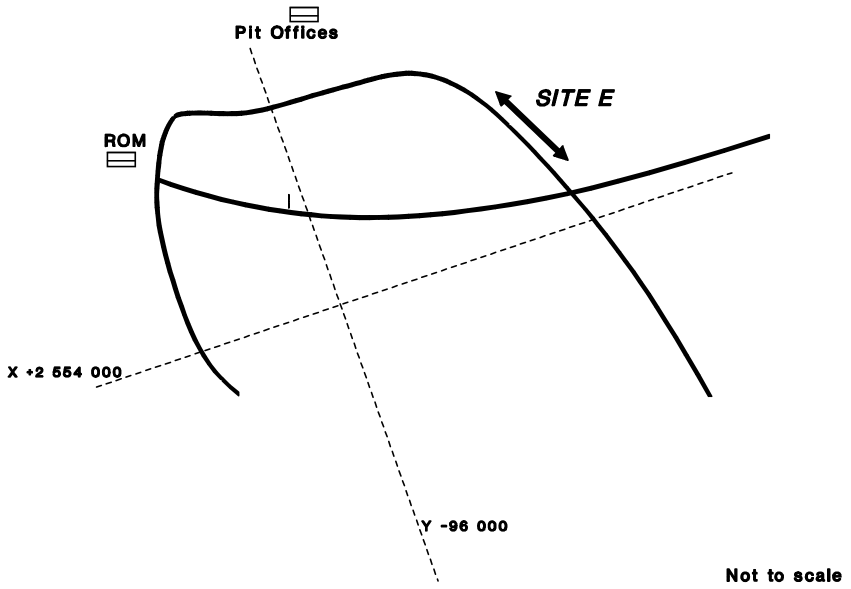
The hauling fleet comprised Euclid R170 (single rear axle with dual wheels) trucks of 130t capacity. Maximum traffic volumes at the test site can be equated to approximately 3600 truck repetitions per month.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.11.

SITE E Main haul road (approximately level), laden side of road.

DUST PALLIATION TEST SITE E LOCATION



Palliative Treatment

The site was treated with an emulsified tar/bitumen product at an initial establishment rate 3l/m^2 to a depth of approximately 100mm using a mix-in technique, followed by monthly spray-on re-applications of 0,25l/m^2. After 12 months, a total of 6l/m^2 product had been applied, following which maintenance applications would be required at a frequency dictated by traffic volumes and wearing course dust generation rates. During the test period, non-delivery of the product resulted in excessive degeneration of the road and, with the removal of the wearing course over specific sections, effectively invalidated the monitoring exercise. The site was used in its untreated state as a source of data for water-based suppression efficiency tests and dust defect model generation data.

Test Site F

Local mine weathered dolerite discard was used for the construction of the wearing course at test Site F. Table 3.12 gives the results of the basic laboratory analysis of the wearing course material at sites F1 and F2. The material exhibited a top size of 63mm. When the laboratory analysis of the material was considered in terms of the TRH14 requirements, the wearing course was classified as comprising a G6 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials, the material exhibits a shrinkage product of 117 and grading coefficient of 26 which are ideal in terms of established wearing course material selection guidelines. The dust ratio for the material is 0,6 which approaches the upper limit of the recommendations.

Traffic Volume

The haulage fleet consisted of Caterpillar 769D (single rear axle with dual wheels) trucks of 35t capacity. This may be equated to between 1600 and 1900 truck repetitions per month using an average laden load factor of 35t per truck.

Road Geometrics

Both grade and approximately level road sections were available, grade sections being all less than 200m in length and incorporating sharp bends. From this data, two test sites were located to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the location given in Figure 3.12.

SITE F1	Haul road 200m on grade, laden (ascending) side of road.
SITE F2	Haul road 200m approximately level, unladen side of road.

Table 3.12 Laboratory Analysis of Wearing Course Material - Site F.

SAMPLE SITE: F	**Sites F1 and F2: Main haul road**
SAMPLE DESCRIPTION	Weathered dolerite
SCREEN ANALYSIS (%) PASSING	
75.00mm	
63.00	98
53.00	95
37.50	83
26.50	71
19.00	61

13.20	53
4.75	37
2.00	23
0.425	15
0.075	9
SOIL MORTAR	
Coarse sand 2.00-0.425mm	
Coarse fine sand 0.425-0.250mm	
Medium fine sand 0.250-0.150mm	
Fine sand 0.150-0.075mm	
Material <0.075mm	
CONSTANTS	
Grading modulus	2.53
Liquid limit	35
Plasticity index	15
Linear shrinkage (%)	6.5
Sand equivalent	
Classification - TRB	
Classification - TRH14	G6
Classification - TRH20 Shrinkage product	117
Classification - TRH20 Grading coefficient	26
MOD. AASHTO	
Max dry density (kg/m^3)	
OMC (%)	
MMC (%)	
Dry density (kg/m^3)	
% Max dry density	
100% Mod CBR	
% Swell	
NRB	
Dry density (kg/m^3)	
% Max dry density	
100% NRB CBR	
% Swell	
PROCTOR	
Dry density (kg/m^3)	
% Max dry density	
100% Proctor CBR	
% Swell	
CBR VALUES	
100% Mod AASHTO	
98%Mod AASHTO	
97%Mod AASHTO	
95%Mod AASHTO	
93%Mod AASHTO	
90%Mod AASHTO	

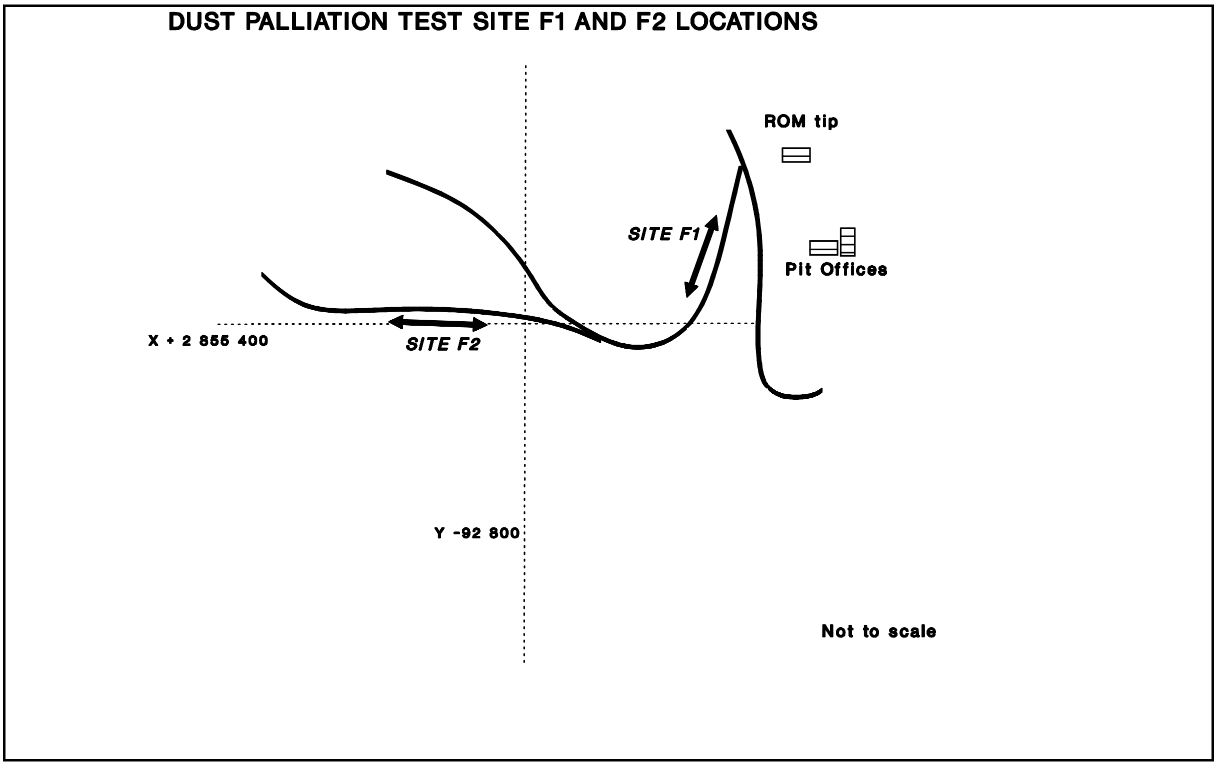
Palliative Treatment

The site was treated with an emulsified petroleum resin product. Two application rates were assessed as follows:

Site F1 An initial establishment 8:1 spray-on mix applied over 4 days to give 0,7l/m^2 product on the road. No maintenance applications.

Site F2 An initial establishment 4:1 spray-on mix applied over 6 days to give 1,12l/m^2 product on the road. Two 8:1 maintenance applications applied as a function of traffic volume and dust generation rates, to give a total of 1.31l/m^2 on the road.

Site F1 was also used as a source of data for water-based suppression efficiency testing and dust defect model generation, in its untreated state.



DUST PALLIATION TEST SITE F1 AND F2 LOCATIONS

Test Site G

Wearing Course Material

The mine haul road wearing course material at site G consisted of weathered sand and calcrete. Table 3.13 gives the results of the laboratory analysis of the wearing course material sampled at site G1 as shown in Figure 3.13. The top size was 4.75mm. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G9/10 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibits no shrinkage product (0) value and a low grading coefficient (1) and no plasticity, which are indicative of excessive erodibility and corrugation, which is further compounded by the low CBR of 13% at 98% Mod AASHTO compaction. When a dust ratio for the material is calculated, a value of 0,22 is found which is indicative of low dustiness. However, site observation revealed a tendency to form excessive dust, due to the generation of loose, fine material as a result of traffic-induced breakdown of the wearing course. Road maintenance involved ad-hoc grading and watering of the road, the latter resulting in considerable longitudinal and cross erosion, even at low (0,2l/m^2) coverage rates. Sand is occasionally placed over the wearing course as a short term solution to reduce dustiness and repair the road.

Traffic Volume

The hauling fleet comprised Caterpillar 789 and Komatsu 730E (single rear axle with dual wheels) trucks of 177t capacity. Maximum traffic volumes at the test site are variable but can be equated to a maximum of approximately 2600 truck repetitions per month.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.13.

SITE G E ramp haul road (on grade), laden (ascending) side of road.

Palliative Treatment

The site was treated with an emulsified tar/bitumen product at an initial establishment rate 3l/m^2 to a depth of approximately 100mm using a mix-in technique, followed by bi-monthly spray-on re-applications of 0,25l/m^2. After 4 months, a total of 4,5l/m^2 product was applied, following

Table 3.13 Laboratory Analysis of Wearing Course Material - Site G

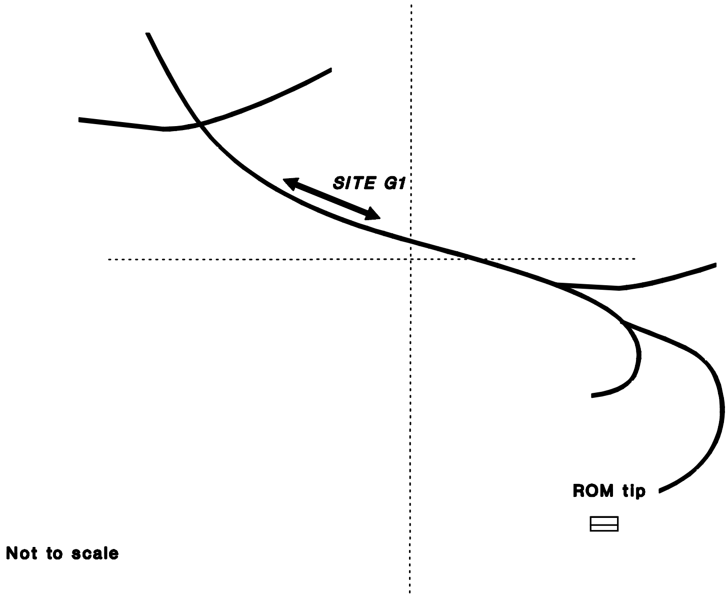
SAMPLE SITE: G	Site G1: E Ramp haul road
SAMPLE DESCRIPTION	Fine sand and calcrete
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	100
26.50	100
19.00	100
13.20	100
4.75	100
2.00	99
0.425	97
0.075	22
SOIL MORTAR	

Coarse sand 2.00-0.425mm	
Coarse fine sand 0.425-0.250mm	
Medium fine sand 0.250-0.150mm	
Fine sand 0.150-0.075mm	
Material <0.075mm	
CONSTANTS	
Grading modulus	0,82
Liquid limit	
Plasticity index	np
Linear shrinkage (%)	-
Sand equivalent	
Classification - TRB	
Classification - TRH14	G9
Classification - TRH20 Shrinkage product	0
Classification - TRH20 Grading coefficient	1
MOD. AASHTO	
Max dry density (kg/m^3)	1921
OMC (%)	6,4
MMC (%)	2,0
Dry density (kg/m^3)	1919
% Max dry density	99.9
100% Mod CBR	14
% Swell	-
NRB	
Dry density (kg/m^3)	
% Max dry density	
100% NRB CBR	
% Swell	
PROCTOR	
Dry density (kg/m^3)	1871
% Max dry density	93,2
100% Proctor CBR	9
% Swell	-
CBR VALUES	
100% Mod AASHTO	
98%Mod AASHTO	12,5
97%Mod AASHTO	
95%Mod AASHTO	9,5
93%Mod AASHTO	7,8
90%Mod AASHTO	5,5

which further maintenance applications would be required at a frequency dictated by traffic volumes and wearing course dust generation rates.

The site was also used as a source of data for water-based suppression efficiency testing and dust defect model generation, in its untreated state.

DUST PALLIATION TEST SITE G LOCATION



Test Site H

Wearing Course Material

The mine haul road wearing course material at site H consisted of a fine dolerite gravel with sand and clay. Table 3.14 gives the results of the laboratory analysis of the wearing course material sampled at site H1 as shown in Figure 3.14. The top size was 53mm, although 98% was finer than 37,5mm. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G5 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibits a shrinkage product of (93) and a slightly low grading coefficient (17). The wearing course is thus liable to ravelling and loose stoniness.

Table 3.14 Laboratory Analysis of Wearing Course Material - Site H

SAMPLE SITE: H	Site H1 and H2: Bench 2 and 5 ramp haul road
SAMPLE DESCRIPTION	Fine dolerite and sand
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100

37.50	98
26.50	96
19.00	93
13.20	89
4.75	77
2.00	65
0.425	41
0.075	21
SOIL MORTAR	
Coarse sand 2.00-0.425mm	37
Coarse fine sand 0.425-0.250mm	11
Medium fine sand 0.250-0.150mm	11
Fine sand 0.150-0.075mm	9
Material <0.075mm	32
CONSTANTS	
Grading modulus	1,73
Liquid limit	21
Plasticity index	9
Linear shrinkage (%)	2,7
Sand equivalent	
Classification - TRB	A-2-b(0)
Classification - TRH14	G5
Classification - TRH20 Shrinkage product	93
Classification - TRH20 Grading coefficient	17
MOD. AASHTO	
Max dry density (kg/m^3)	2113
OMC (%)	10,1
MMC (%)	9,8
Dry density (kg/m^3)	2107
% Max dry density	100
100% Mod CBR	98
% Swell	1,2
NRB	
Dry density (kg/m^3)	2006
% Max dry density	95
100% NRB CBR	58
% Swell	1,0
PROCTOR	
Dry density (kg/m^3)	1929
% Max dry density	91
100% Proctor CBR	28
% Swell	1,3
CBR VALUES	
100% Mod AASHTO	101
98%Mod AASHTO	81
97%Mod AASHTO	73
95%Mod AASHTO	58
93%Mod AASHTO	40
90%Mod AASHTO	22

When a dust ratio for the material is calculated, a value of 0,51 is found which is indicative of dustiness, a fact confirmed by site observation. Road maintenance involved ad-hoc grading and watering of the road.

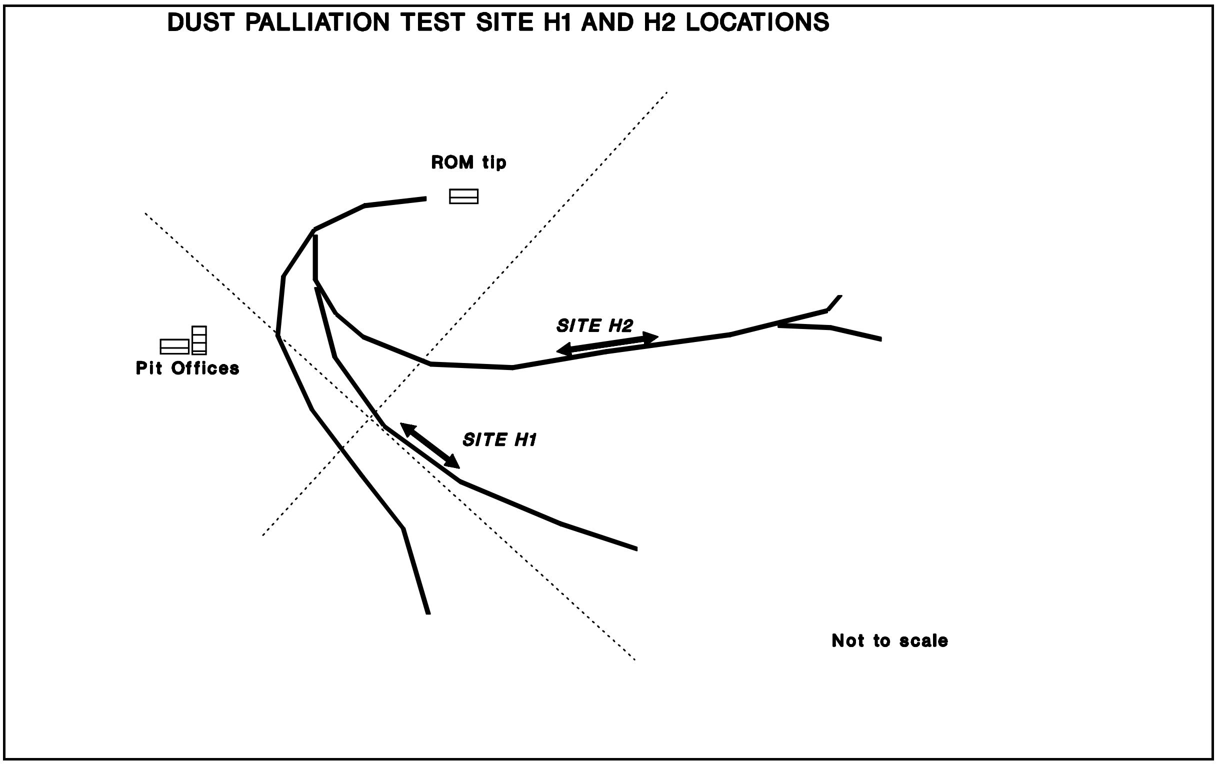
Traffic Volume

The hauling fleet comprised Bell B25 and B30 (double rear axle with dual wheels) articulated trucks of 25t and 30t capacity respectively. Maximum traffic volumes at the test site are variable but can be equated to a maximum of approximately 580 truck repetitions per month using an average truck load of 27t.

Road Geometrics

From this data, two test sites of 200m length were identified to complete critical factor level combinations envisaged in the experimental design. The sites are summarised below and the locations given in Figure 3.14.

SITE H1	Bench 2 ramp haul road, approximately level, laden side of road.
SITE H2	Bench 5 ramp haul road, approximately level, laden side of road.


DUST PALLIATION TEST SITE H1 AND H2 LOCATIONS

Palliative Treatment

Site H1

The site was treated with a lignosulphonate product, at a rate of 1,0l/m^2 using a spray-on technique for establishment, to achieve 1,0l/m^2 product on the road after application. Re-treatments were applied as maintenance applications at 0,5l/m^2 at 3:1 dilution over 2 passes at a frequency dictated by traffic volumes and wearing course dust generation rates.

The site was treated initially with water for dust suppression and as such was used as a source of data for water-based suppression efficiency model generation, before the chemical palliative was applied.

Site H2

The site was treated with a hygroscopic product at a rate of 1,0l/m^2 using a spray-on technique for establishment, to achieve 2,0l/m^2 product on the road. No re-treatments were applied, although maintenance applications would normally be scheduled at the same rates and frequency as dictated by traffic volumes and wearing course dust generation rates.

Test Site I

Wearing Course Material

Local mine ferricrete was used for the construction of the wearing course at test Site I. Table 3.15 gives the results of the laboratory analysis of the wearing course material. The material exhibited a top size of 13,2mm and a relatively higher proportion of finer material than the discard wearing courses seen elsewhere. When the laboratory analysis of the material was considered in terms of the TRH14 requirements, the wearing course was classified as comprising a G7 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials, the material exhibits a shrinkage product of 164 and grading coefficient of 28,8 which are indicative of a tendency to form dust and slipperiness when wet. The dust ratio for the material is 0,55 which approaches the upper limit of the recommendations.

Road maintenance involved ad-hoc grading and watering of the road. No palliatives have been applied or tested on the roads and considerable coal spillage was observed on the laden side of the road. The roads are ripped and redressed over the winter months.

Table 3.15 Laboratory Analysis of Wearing Course Material - Site I

SAMPLE SITE: I	**Site I Main haul road**
SAMPLE DESCRIPTION	Pale red ferricrete. Sand.
SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	100
26.50	100
19.00	100
13.20	96
4.75	80
2.00	64
0.425	47
0.075	26

SOIL MORTAR	
Coarse sand 2.00-0.425mm	27
Coarse fine sand 0.425-0.250mm	10
Medium fine sand 0.250-0.150mm	10
Fine sand 0.150-0.075mm	12
Material <0.075mm	41
CONSTANTS	
Grading modulus	1,37
Liquid limit	23
Plasticity index	7
Linear shrinkage (%)	3,5
Sand equivalent	
Classification - TRB	A-2-4(0)
Classification - TRH14	G7
Classification - TRH20 Shrinkage product	164
Classification - TRH20 Grading coefficient	28,8
MOD. AASHTO	
Max dry density (kg/m^3)	2188
OMC (%)	7,6
MMC (%)	7,5
Dry density (kg/m^3)	2197
% Max dry density	100
100% Mod CBR	79
% Swell	0
NRB	
Dry density (kg/m^3)	2112
% Max dry density	97
100% NRB CBR	28
% Swell	0,1
PROCTOR	
Dry density (kg/m^3)	2013
% Max dry density	92
100% Proctor CBR	13
% Swell	0,1
CBR VALUES	
100% Mod AASHTO	71
98%Mod AASHTO	41
97%Mod AASHTO	32
95%Mod AASHTO	22
93%Mod AASHTO	15
90%Mod AASHTO	9

Traffic Volume

The haulage fleet consisted of Euclid R170 (single rear axle with dual wheels) and Euclid CH120/130 (horse single rear dual wheel axle and trailer single dual wheel axle) trucks, depending on the particular haulage route operated. This may be equated to between 3 280 and 1 070 truck repetitions using an average laden load factor of between 115t and 127t per truck.

Road Geometrics

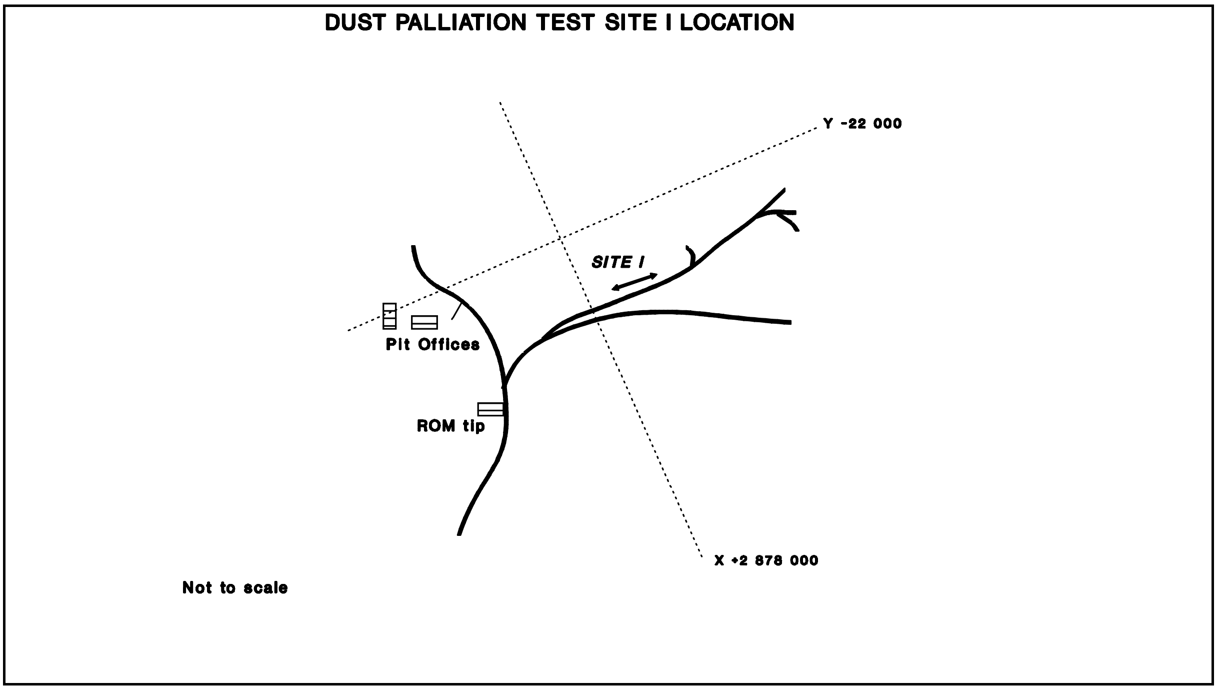
Approximately level road sections are only available, grade sections all being less than 200m in length. From this data, a test site was located to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the location given in

Figure 3.15.

SITE I Haul road 200m level and approximately 150m on grade (laden ascending).

Palliative Treatment

The site was treated only with water for dust suppression and as such was used as a source of data for water-based suppression efficiency and dust defect model generation.


DUST PALLIATION TEST SITE I LOCATION

Not to scale

Test Site J

Wearing Course Material

All roads were constructed using local mine ferricrete for the wearing course. Table 3.16 gives the results of the laboratory analysis of the wearing course material at site J. As can be seen, the grading of the material is similar at sites J1 and J2 whilst at site J3 the material is slightly coarser, containing a smaller proportion of material smaller than 0,075mm. Plasticity index (PI) values for site 1 and 2 are similar at 10 and 8 respectively whilst site 3 shows a lower value of 4 attributable to a lower liquid limit and higher plastic limit. Linear shrinkage varies accordingly, the materials exhibiting high PI values also exhibiting larger shrinkage values.

Bearing strength of the materials (in terms of California Bearing Ratio, using 7 day soaked CBR) are similar for sites 1 and 2 whilst site 3 exhibited greater bearing strengths over the range of compaction. Accordingly, sites 1 and 2 are accorded a classification following TRH14 of G7 (due primarily to low CBR values) whilst site 3 is classified as a G6 material (due to a low grading modulus). In terms of the modified TRH20 selection guidelines, sites 1 and 2 exhibit high shrinkage products and dust ratios and may be excessively dusty and slippery when wet. Site 3 on the other hand had a low shrinkage product of 82 but a high grading coefficient which suggests a tendency to ravel and form loose material. The dust ratio of 0,41 indicates little problem with dustiness in this case.

Traffic Volume

The hauling fleet consisted of Dresser-Haulpak 630E (single rear axle with dual wheels) trucks of 148t capacity. This may be equated to between 2020 and 2700 truck repetitions per month at site 1 and between 1010 and 1350 repetitions at sites 2 and 3.

Road Geometrics

Approximately level road sections were available on haul road 1 at a grade between 0,385% and 0,1%. Grade sections limited in length to about 200m at a grade of 1,7% only. From this data, a single test site was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.16.

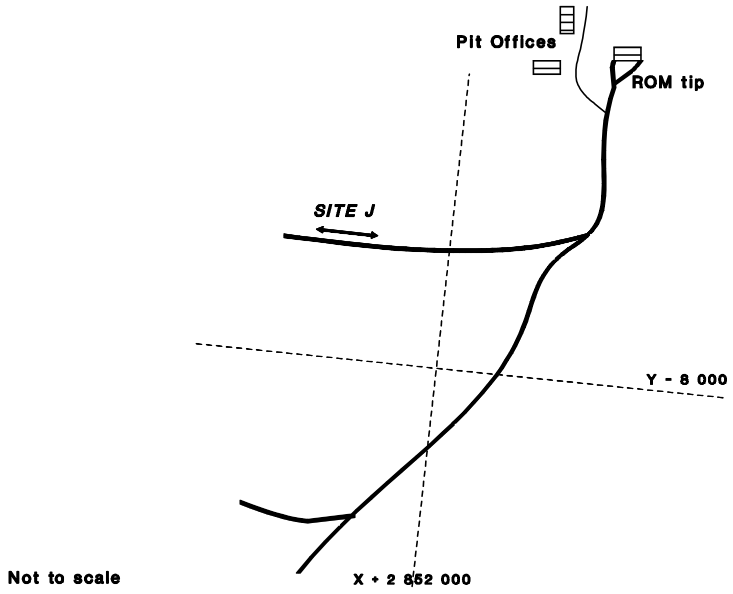
SITE J1	Mine constructed section of haul road. Level section only on laden side of road.

Table 3.16 Laboratory Analysis of Wearing Course Material - Site J

SAMPLE SITE: J	Site J1	Site J2	Site J3
SAMPLE DESCRIPTION	Dark red quartz. Sandy gravel.	Light red quartz. Sand	Light red ferricrete quartz. Fine gravel.
SCREEN ANALYSIS (%) PASSING			
75.00mm	100	100	100
63.00	100	100	100
53.00	100	100	100
37.50	100	100	100
26.50	100	100	100
19.00	100	100	100
13.20	100	100	100
4.75	98	97	86
2.00	63	78	65
0.425	44	49	41
0.075	26	29	17
SOIL MORTAR			
Coarse sand 2.00-0.425mm	30	37	36
Coarse fine sand 0.425-0.250mm	8	9	14
Medium fine sand 0.250-0.150mm	7	8	13
Fine sand 0.150-0.075mm	12	9	11
Material <0.075mm	43	37	26

CONSTANTS			
Grading modulus	1,33	1,56	1,23
Liquid limit	24	23	21
Plasticity index	10	8	4
Linear shrinkage (%)	4,5	4	2
Sand equivalent			
Classification - TRB	A-2-4(0)	A-2-4(0)	A-1-b(0)
Classification - TRH14	G7	G7	G6
Classification - TRH20 Shrinkage product	198	196	82
Classification - TRH20 Grading coefficient	36,2	21,3	30,1
MOD. AASHTO			
Max dry density (kg/m^3)	2221	2232	2229
OMC (%)	6,4	5,9	6,3
MMC (%)	6,3	5,9	6,4
Dry density (kg/m^3)	2212	2237	2216
% Max dry density	100	100	99
100% Mod CBR	46	50	162
% Swell	0	0	0
NRB			
Dry density (kg/m^3)	2075	2100	2094
% Max dry density	93	94	94
100% NRB CBR	20	23	44
% Swell	0	0	0
PROCTOR			
Dry density (kg/m^3)	1953	2030	2029
% Max dry density	00	91	91
100% Proctor CBR	7	11	32
% Swell	0	0	0
CBR VALUES			
100% Mod AASHTO	49	49	186
98%Mod AASHTO	37	38	116
97%Mod AASHTO	32	33	91
95%Mod AASHTO	25	26	57
93%Mod AASHTO	18	18	40
90%Mod AASHTO	10	9	29

DUST PALLIATION TEST SITE J LOCATION



Palliative Treatment

The site was treated only with water for dust suppression and as such was used as a source of data for water-based suppression efficiency and dust defect model generation.

Test Site K

Wearing Course Material

The mine haul road wearing course material at site K consisted of fine schist and granite. Table 3.17 gives the results of the laboratory analysis of the wearing course material sampled at site K1 as shown in Figure 3.17. The top size was 53mm, although 99% was finer than 37,5mm. When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, the site is classified as comprising a G7 type of material. In terms of the modified TRH20 requirements for mine haul road wearing course materials (Thompson, 1996), the material exhibits a low shrinkage product (13) and a slightly high grading coefficient (30) and no plasticity. The wearing course is thus liable to ravelling and corrugation. When a dust ratio for the material is calculated, a value of 0,26 is found which is indicative of low dustiness. However, site observation revealed a tendency to form excessive dust, due to the

Table 3.17 Laboratory Analysis of Wearing Course Material - Site K

SAMPLE SITE: K	Site K1: Main E haul road
SAMPLE DESCRIPTION	Fine schist and granite gravel

SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	99
26.50	95
19.00	92
13.20	89
4.75	71
2.00	53
0.425	24
0.075	6
SOIL MORTAR	
Coarse sand 2.00-0.425mm	64
Coarse fine sand 0.425-0.250mm	13
Medium fine sand 0.250-0.150mm	11
Fine sand 0.150-0.075mm	10
Material <0.075mm	12
CONSTANTS	
Grading modulus	2,17
Liquid limit	
Plasticity index	sp
Linear shrinkage (%)	0,5
Sand equivalent	
Classification - TRB	A-1-b(0)
Classification - TRH14	G7
Classification - TRH20 Shrinkage product	13
Classification - TRH20 Grading coefficient	30
MOD. AASHTO	
Max dry density (kg/m^3)	2232
OMC (%)	7,5
MMC (%)	7,2
Dry density (kg/m^3)	2236
% Max dry density	100
100% Mod CBR	95
% Swell	0,0
NRB	
Dry density (kg/m^3)	2206
% Max dry density	99
100% NRB CBR	53
% Swell	0,0
PROCTOR	
Dry density (kg/m^3)	2101
% Max dry density	94
100% Proctor CBR	24
% Swell	0,0
CBR VALUES	
100% Mod AASHTO	88
98%Mod AASHTO	46
97%Mod AASHTO	39
95%Mod AASHTO	28
93%Mod AASHTO	20
90%Mod AASHTO	12

generation of loose, fine material as a result of traffic- and weathering induced breakdown of the wearing course (typically the feldspar content weathering to kaolin). Road maintenance involved ad-hoc grading and watering of the road.

Traffic Volume

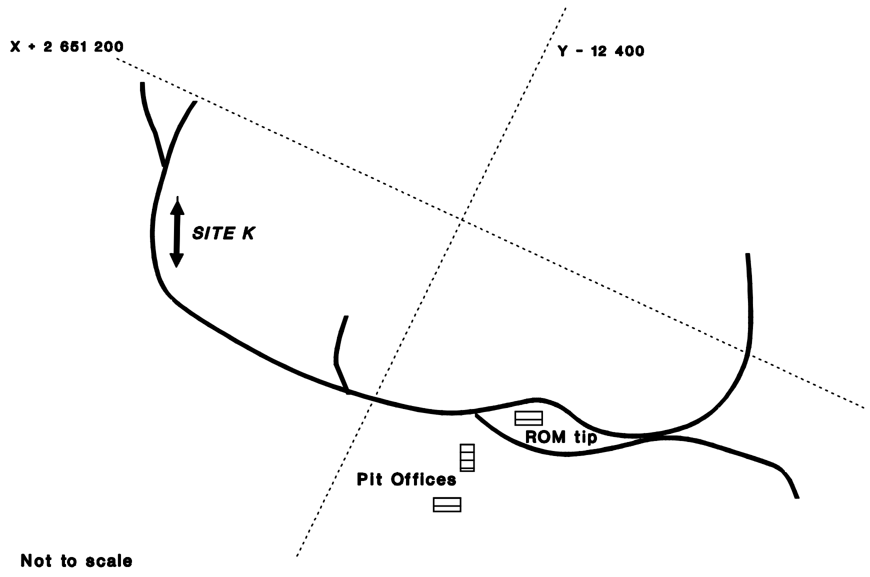
The hauling fleet comprised Komatsu 730E and Unit-Rig MK85 (single rear axle with dual wheels) trucks of 177t and 77t capacity. Maximum traffic volumes at the test site were variable but can be equated to a maximum of approximately 9560 truck repetitions per month using an average truck load of 102t.

Road Geometrics

From this data, a single test site of 200m length was identified to complete critical factor level combinations envisaged in the experimental design. The site is summarised below and the locations given in Figure 3.17.

SITE K Main E ramp haul road, laden (ascending) side of road, approximately level.

DUST PALLIATION TEST SITE K LOCATION



Palliative Treatment

The site was treated only with water for dust suppression and as such was used as a source of data for water-based suppression efficiency and dust defect model generation.

3.5 Summary of Test Site Locations

The primary objective of the study was to determine the most suitable haul road surface treatments which lead to a reduction in the generation of traffic-induced dust, within the constraints of cost effectiveness and maintainability. It was recognised that the extent of dust generation from hauling operations was attributable to a number of factors, namely;

- Wearing course material type
- Traffic volumes
- Road geometrics
- Climate
- Road maintenance activities.
- Type and application of palliative

The approach adopted for the study entailed the analysis of a number of in-service mine roads which covered the fullest range of these factors. Climate as a factor was eliminated from the study since most mines were located in the same physiographical region, as was the road traffic volume factor, primarily since the test site locations did not enable similar materials to be tested under a range of traffic conditions and due to the variable nature of the traffic itself. Traffic volume and road maintenance activities were thus recorded as independent variables for each test site. The class of palliative tested was limited by the selection (previously) made by the particular mine and little control could be exercised over the choice of palliative at each site.

Table 3.18 summarises the factor coverage envisaged in the experimental design in terms of wearing course material (weathering group) and palliative tested. From this it is seen that of the various weathering groups envisaged in the design, only pedocretes, argillaceous, acid crystalline, discards, carbonates and mixtures of materials can be analysed and no test sites at which modified waxes were used were assessed. Whilst this appears to limit the applicability of the results, the material types nevertheless form the predominant material type for road construction in the Mpumulanga coalfield region since the regional distribution of ferricrete (a pedogenic material) is limited by climatic region as defined by Weinert (1980) to where N≤5. The range of palliatives assessed was limited by the particular dust problems encountered and, to a lesser extent, the degree to which the particular product was marketed to the mines.

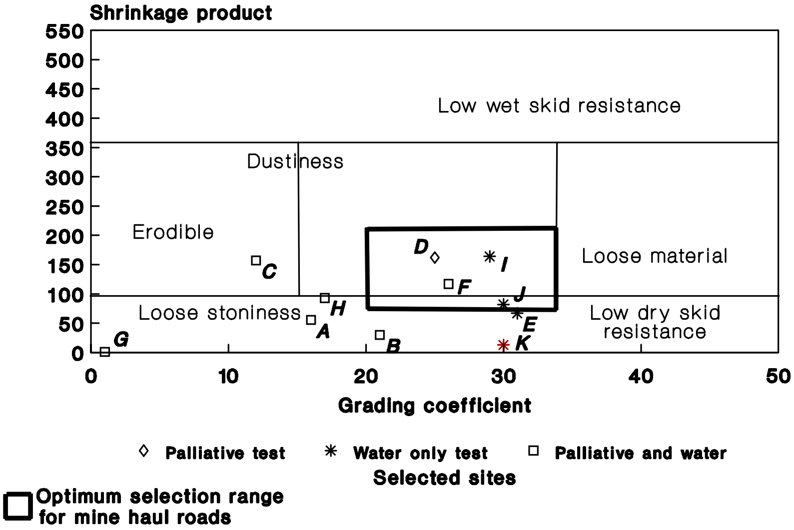
Table 3.18 Test Site Location Matrix for Assessment of Dust Palliatives

Wearing Course Material (weathering group)	Palliative Type

	Water	Hygroscopic Salts	Lignosulphonates	Modified Waxes	Petroleum Resins	Polymer Emulsions	Tars and Bitumens
Pedocretes	Site B C I J		Site B C				
Argillaceous	Site G						Site G
Arenaceous							
Basic crystalline							
Acid crystalline	Site K						
Carboniferous (coal discards)	Site A						Site A
Carbonates	Site F1 H1 H2	Site H1	Site H2		Site F1 F2		
Mixtures	Site D					Site D	

Since few test sites were available on grade sections of road, the study was thus limited to approximately level sections of road. It is anticipated that whilst the functional requirements of a road placed on grade may vary in comparison to a level road (especially in terms of wet and dry skid resistance requirements), it should be possible to gain an insight into the functionality of a particular palliative on both level and grade sections by considering grade sections alone (or vice-versa).

The variation in wearing course material types for each test site analysed is presented in Table 3.19 and in Figure 3.18 in terms of shrinkage product and grading coefficient. It is evident that a wide variation in wearing course material existed and for the purposes of the experimental work the most feasible approach would be to evaluate the widest possible range of each material type. Using this approach, twelve test sites were identified, seven of which were used for palliative testing and the generation of dust and watering efficiency models, 2 sites used for palliative testing only and 3 sites for the generation of dust and watering efficiency models only. These test sites form the basis of the evaluation of a number of dust palliatives as discussed in the following Chapters.



**SUMMARY OF MINE TEST SITE
WEARING COURSE MATERIALS
Following mine haul road wearing course
material selection guidelines**

Table 3.19 Summary of Mine Test Site Wearing Course Material Parameters

SUMMARY OF MINE TEST SITE WEARING COURSE MATERIAL PARAMETERS

Material Parameter	Recommended Range		MINE TEST SITE										
	Min	Max	A	B	C	D	E	F	G	H	I	J	K
Shrinkage Product	85	200	55	30	157	162	67	117	1	93	164	82	13
Grading Coefficient	20	35	16	21	13	25	31	26	1	17	28	30	30
Dust Ratio	0,4	0,6	0,59	0,35	0,49	0,58	0,39	0,6	0,22	0,51	0,55	0,41	0,26
Liquid Limit (%)	17	24	22	-	18	27	18	35	np	21	23	21	sp
Plastic Limit (%)	12	17	18	SP	13	18	13	20	-	12	16	17	-
CBR at 98% Mod AASHTO	80		76	64	73	78	88	-	12,5	81	41	116	46
Maximum Particle Size (mm)		20	150	13,2	13,2	53	37,5	63	4,75	37,5	19	13,2	37.5
Wearing course material			Coal discards	Ferricrete	Ferricrete	Mixture	Coal Discards	Dolomite discard	Sand and calcrete	Dolomite	Ferricrete	Ferricrete	Weathered granite

CHAPTER 4

EVALUATION OF HAUL ROAD WATER-SPRAY BASED DUST SUPPRESSION STRATEGIES

4.1 Introduction

Water-spray based dust suppression is the most common means of reducing dustiness on mine haul roads. The combination of a water-car and regular spray applications of water providing a relatively inexpensive, but not necessarily efficient, means of dust suppression. To determine the base-case scenario, the degree of dust palliation achieved with watering is initially compared to the untreated dustiness of various test sections, to determine the average and instantaneous degree of dust palliation achieved under typical operating conditions. Acceptability criteria are introduced, based on mine personnel evaluations of the intervention dust defect levels and average degree of palliation achieved, from a safety perspective. This data is then used in subsequent Chapters to calculate suppression efficiencies of the various classes of palliatives evaluated. By combining these criteria with dust prediction models based on wearing course and traffic parameters, an estimate of water-spray based suppression re-application rates was determined. This Chapter concludes with an example calculation procedure for determining typical re-application frequencies as a precursor to the comparative evaluation of other types of dust palliatives.

4.2 Dust Suppression Using Water-car Sprays

Water based dust suppression is used on most surface mines as a means of reducing fugitive dust emissions from mine haul roads. Judicious watering assists in maintaining compaction and therefore strength of the wearing course, in addition to reducing the potential loss of wearing course material. Although watering itself is often seen as a cheap and simple approach to dust suppression, equipment and operating costs often escalate the cost of suppression. Water retention on mine roads is generally poor, more so during adverse conditions where a combination of high temperatures, high wind speeds and low humidity are prevalent. These conditions necessitate more frequent watering to maintain dust suppression and applications at hourly intervals are not uncommon on Highveld surface mines during early and late summer when precipitation is low and temperatures high. The degree of dust palliation achieved with watering is a function of;

- ■ The amount of water applied per unit area of road surface

- The time between re-applications
- Traffic volumes
- Prevailing meteorological conditions.
- The wearing course material
- Extent of water penetration in to the wearing course

Water acts by surrounding and adhering to adjacent particles, making it more difficult to dislodge them. The period of effectiveness, dependant on weather, wearing course and traffic volumes, ranges from between 30 minutes to 12 hours. Regular light watering at approximately 0,3-0,5l/m^2 is more effective than infrequent heavy watering. Heavy watering will generate additional run-off and will produce soft, muddy material in addition to pumping and washing away the finer binding fractions of the wearing course. Excessive watering will reduce functionality of the pavement, cause short term slipperiness and may lead to potholing and rutting. This in turn will require more road maintenance with the potential for greater dust emissions.

The degree of dust palliation is a measure of how "efficiently" the palliative suppresses the dust. Some control techniques decay almost immediately after application - typically water - whose degree of palliation decays from 100% to 0% in a matter of hours, whilst some chemical palliatives may decay to zero over several days or weeks. Consequently, a single-valued control efficiency is usually not adequate in describing the performance of most intermittent control techniques for open dust sources. The degree of palliation should be reported along with a time period over which the value applies.

Certain terminology is used throughout the following Chapters to describe the time dependence of dust control;

- Palliation lifetime - the time period required for a palliative effect to decay to zero (or to the base case untreated level of dustiness).
- Degree of palliation - the efficiency of a palliative at a point in time, compared to a base case or untreated level of dustiness, at a specific point in time.
- Average degree of palliation - the average control over a given period of time (or number of vehicle passes).
- Suppression efficiency - the efficiency of a palliative at a point in time, compared to a water-spray based suppression level of dustiness, at a specific point in time.
- Average suppression efficiency - the average control efficiency, compared to a water-spray based suppression level of dustiness, over a given period of time (or

number of vehicle passes).

$$D_p(X) = \frac{1}{X} \int_0^x D_{p'}(x)\,dx$$

The average degree of palliation is thus;
where

D_p = average degree of dust palliation
x = time or number of vehicle passes after application
X = time or number of vehicle passes over which an average is required
D_p' = instantaneous degree of palliation

$$D_p(X) = a.\left(\frac{b}{2}\right).X$$

It is customary (Cowherd, 1986) to report this value as a linear value of time such that;

An empirical model for the performance of watering as a control technique has been developed, based on the work of Cowherd et al (1986), using public unpaved roads in the United States as

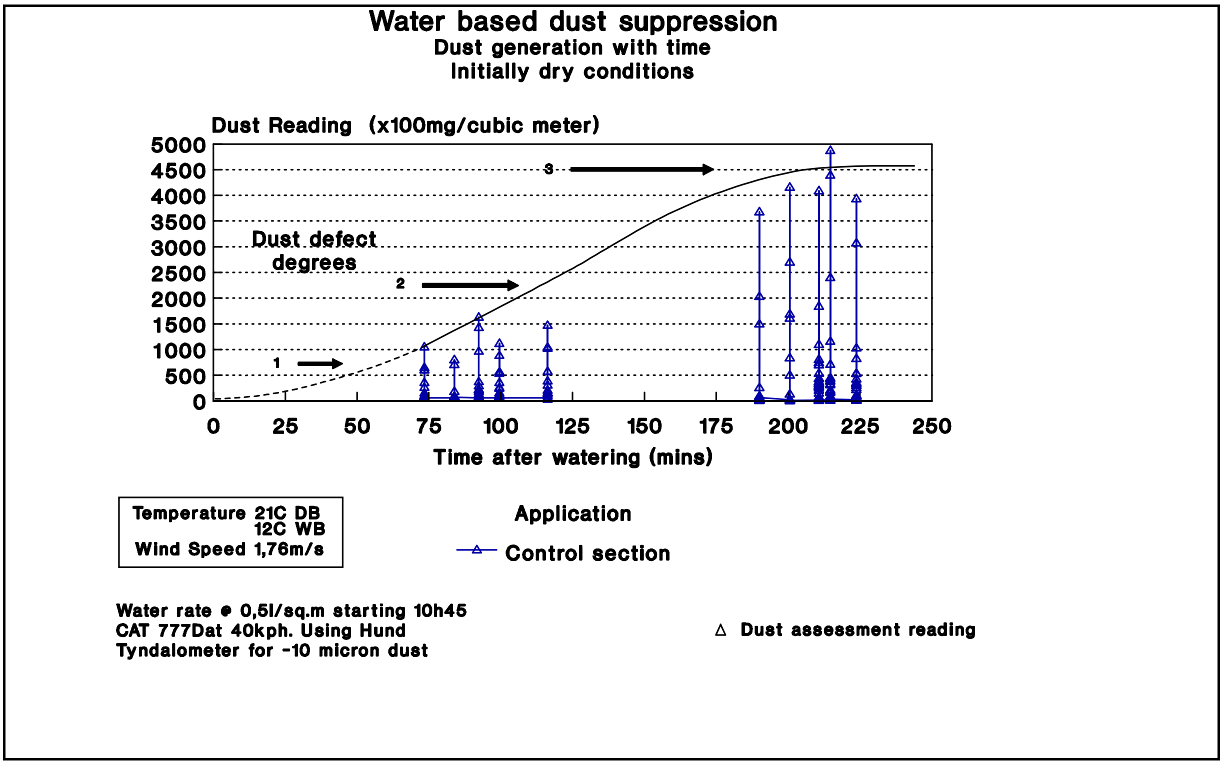
$$D_p = 100\ -\ \frac{0,8p.d.t}{i}$$

the study area. The average degree of dust palliation can be found from;
where
D_p = average degree of palliation (%)
p = potential daytime average hourly evaporation rate (mm/hr)
d = average hourly traffic rate (vehicles per hour)
t = time interval between applications (hours)
i = application coverage (l/m^2)

The model implies that for a fixed application interval, coverage and climatic conditions, reduced average efficiency is seen as traffic volume increases. On mine haul roads, hourly traffic volumes will remain essentially similar, being a function of total tonnage (ore or waste) mined and cannot easily be modified to test over a range of values. The applicability of the above model can be ascertained by comparing individual mine watering test average palliation efficiencies, associated traffic volumes and climatic conditions with those derived directly from the model.

4.3 Watering Tests

Five test sites were evaluated in terms of the efficiency of the water-spray based dust suppression method. The test methodology involved the use of a Hund Tyndalometer to measure the dust plume generated by a haul truck as it passed at a set distance and speed from the monitor. Water was applied to the road at a rate dependant on the type of tanker and spray equipment used, the application rate being determined from the pump feed rate, average vehicle speed and area covered. Where gravity-fed systems were used, the total time and distance covered on a full tank were noted and the coverage estimated. In all cases, only a single application of water was applied. Additionally, time between reading, temperature (wet and dry bulb), wind speed and barometric pressure data were also taken at intervals throughout the test, and this was later correlated to the average monthly class "A" pan evaporation rate for the site (or the nearest meteorological station), calculated over the last 10 years. Tests were discontinued if the wind exceeded 4m/s or if it varied by more than 30° from a direction perpendicular to the test section. Table 4.1 summarises the conditions at each site to characterise the average water-spray based suppression efficiencies. Results from each test site are summarised in Figures 4.1 to 4.5. As can be seen from the graphs, the rate of increase in dustiness after watering follows an approximate logit or s-shaped function bounded by an initial minimum dustiness of approximately zero and a maximum related to the inherent dustiness of the wearing course material (the base case untreated dustiness) and the vehicle speed. Throughout each test, vehicles were limited to a speed of 40km/h and dust measurements were only taken for laden haul trucks. By recording the time, direction and type of vehicle as it passes the test point, the monitoring data could be correlated with traffic and plume data extracted for the specific vehicle in question.



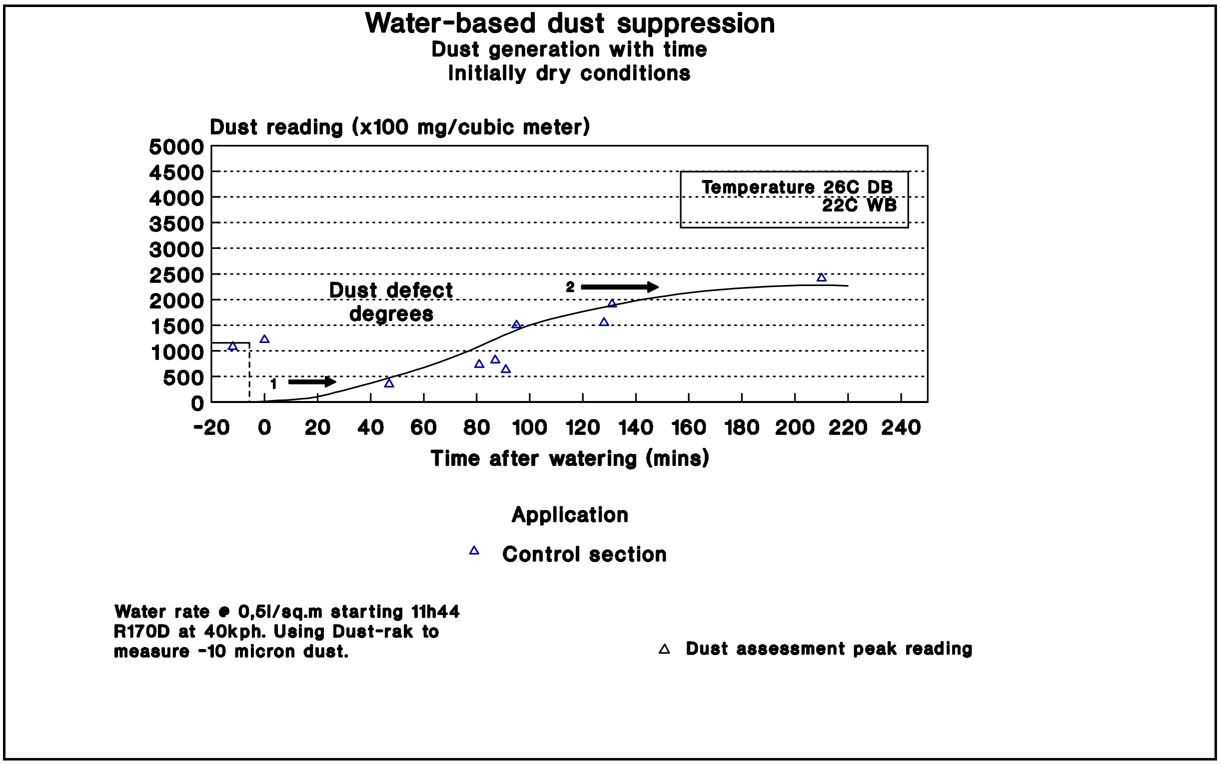
The management strategy for water-spray based dust suppression was based on user defined levels of dust defect acceptability, both from a health and safety point of view. Previous work (Thompson and Visser, 1996) has established the functional defect acceptability limits for a number of functional defects, amongst these dust, as shown in Figure 4.6. The dust defect limits are expressed based on the notion of the product of degree (how bad the dust defect is) and extent (what portion of the road is affected), as summarised in Chapter 3.2 and Tables 3.2 and 3.3. Mine personnel were requested to identify the intervention level, or maximum acceptable level of dustiness on the road, both during the water-spray based suppression experiments and during normal treated and untreated road monitoring. As a result of the large number of variables affecting the generation of dust, a visual classification system was developed for the degree of dust defect based on the road user's experience from the point of view of a haul truck travelling at 40km/h. Table 4.2 gives these descriptions.

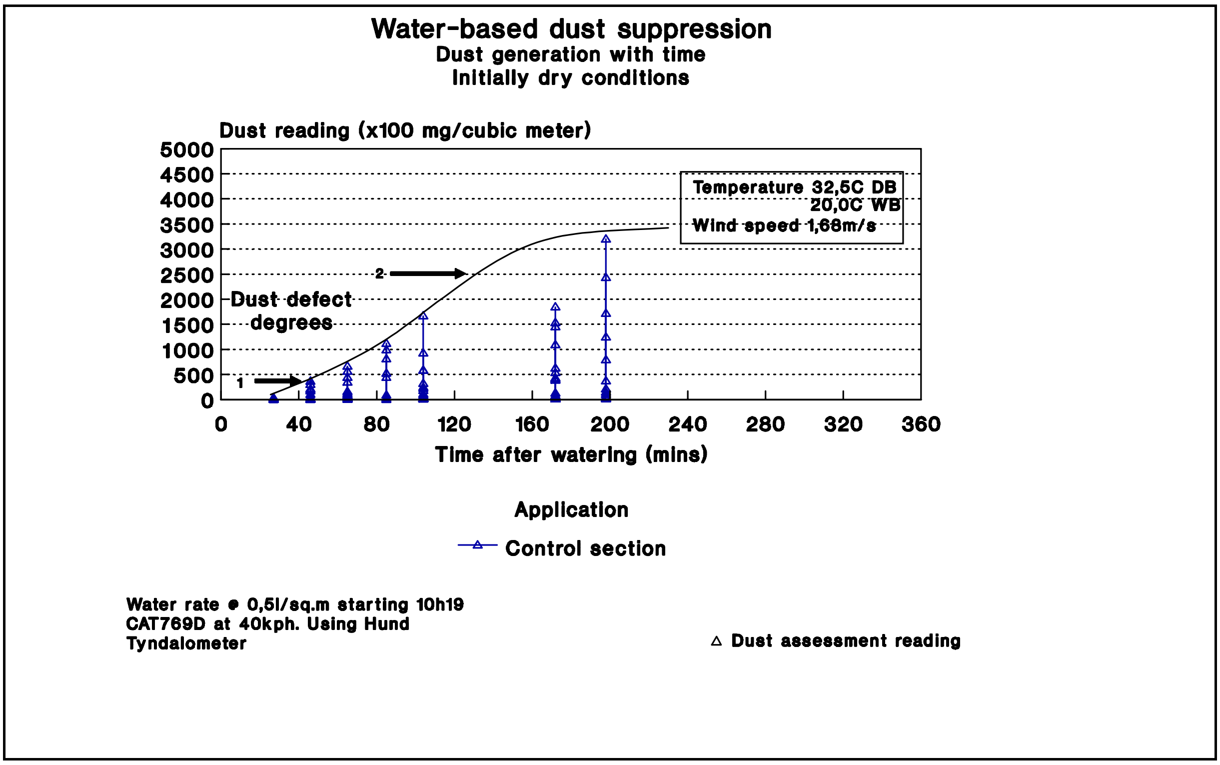
Table 4.1 Test conditions at each site used for the determination of the average water-spray based suppression efficiencies.

Site	**Starting time**	Temperatures		Wind speed	Barometric pressure (mBar)[1]	Hourly[2] traffic (veh/hr)	Truck type	Water coverage (l/m^2)	Class A pan evaporation rate (average for time of year) (mm/month)	Initial surface moisture condition
		Average WB °C	Average DB °C	Average m/s						
A	10h45	12	21	1,76	862	13	CAT 777	0,5	100,4 (Jun)	Dry
D	11h44	22	26	-	-	27	Euclid R170	0,35	276,3 (Dec)	Dry
F	10h19	20	32,5	1,68	872	13	CAT 769	0,5	161,5 (Mar)	Dry
G	13h10	20,5	30,5	1,4	881	16	CAT 789	0,5	298,5 (Jan)	Dry
H	14h10	25	34	1,4	858	8	BELL B25	0,5	257,1 (Oct)	Dry

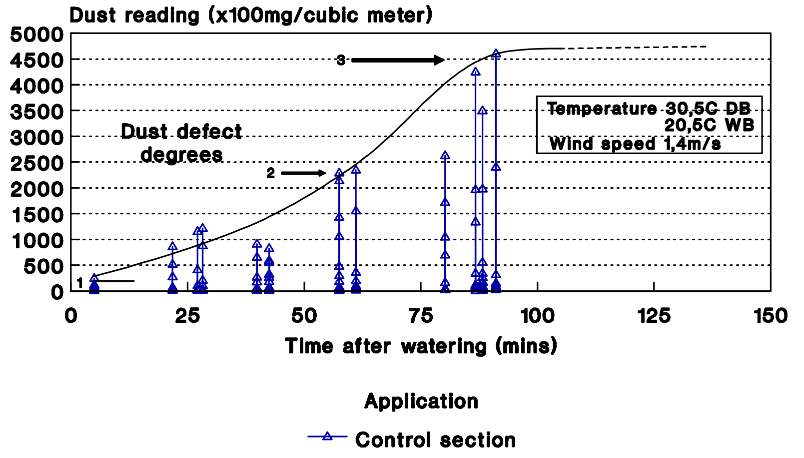
Notes

1. Average for date of test, taken from records at nearest meteorological station
2. Number of haul trucks (laden) during duration of test. Does not include unladen or other vehicles types


Water-based dust suppression
Dust generation with time
Initially dry conditions
Dust reading (x100 mg/cubic meter)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Temperature 26C DB
22C WB
Dust defect
degrees
1
2
-20
0
20
40
60
80
100
120
140
160
180
200
220
240
Time after watering (mins)
Application
△ Control section
Water rate ● 0,5l/sq.m starting 11h44
R170D at 40kph. Using Dust-rak to
measure -10 micron dust.
△ Dust assessment peak reading


Water-based dust suppression
Dust generation with time
Initially dry conditions
Dust reading (x100 mg/cubic meter)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Temperature 32,5C DB
20,0C WB
Wind speed 1,68m/s
Dust defect
degrees
1
2
0
40
80
120
160
200
240
280
320
360
Time after watering (mins)
Application
Control section
Water rate ● 0,5l/sq.m starting 10h19
CAT769D at 40kph. Using Hund
Tyndalometer
△ Dust assessment reading

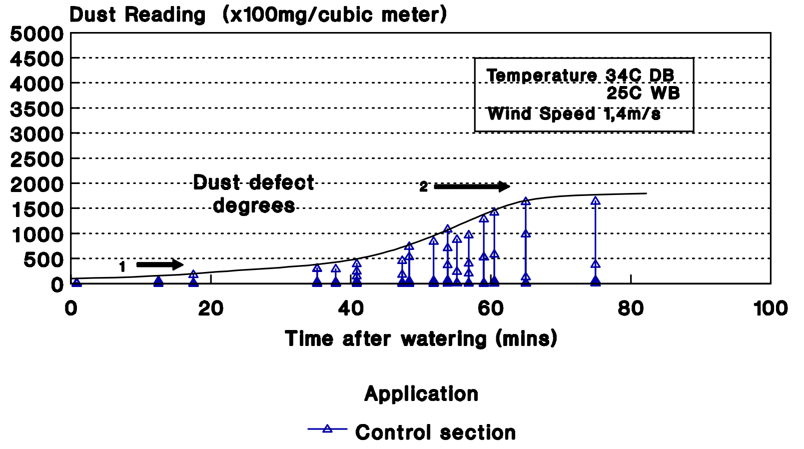
Water-based dust suppression
Dust generation with time
Initially dry conditions



Water rate @ 0,5l/sq.m starting 13h10
730E/CAT789 at 40kph. Using Hund
Tyndalometer measuring -10 micron dust

△ Dust assessment reading

Water-based dust suppression
Dust generation with time
Initially dry conditions



Water rate @ 0,5l/sq.m starting 14h10
Bell B25/B30 at 40kph. Using Hund
Tyndalometer measuring -10 micron dust

△ Dust assessment reading

Table 4.2 Classification of the Degree of Haul Road Dust Defect

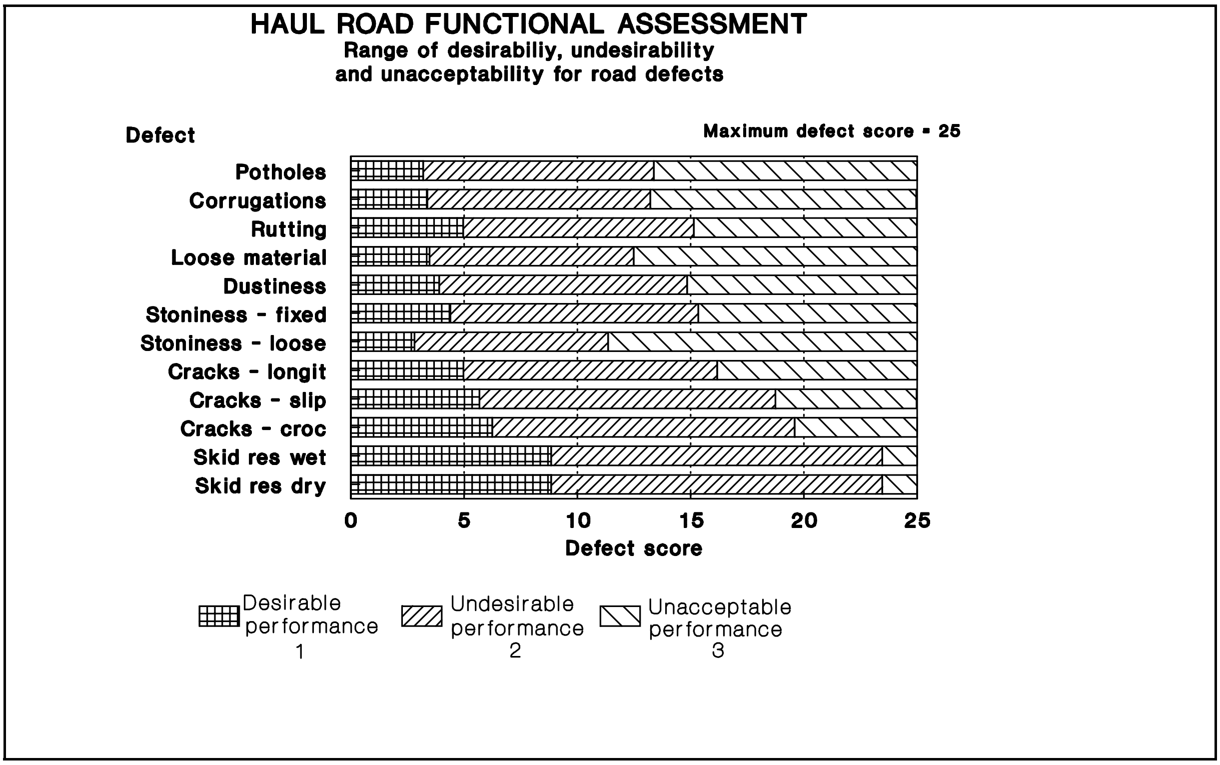
DUST DEFECT DEGREE DESCRIPTIONS AND ASSOCIATED HUND PEAK DUST LEVELS (approx.

mg/m^3 x100 for -10 m dust)				
Degree 1 <350	Degree 2 351 to 2350	Degree 3 2351 to 4500	Degree 4 4501 to 5750	Degree 5 >5751
Minimal 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, window closed in oncoming vehicle, visibility poor and hazardous, overtaking not possible.

It is seen from Figure 4.6 that the acceptable defect score limits for dust extend from 0-4 whilst the desirable limits from 4-15 and undesirable from 16-25. Mine operating personnel's opinion was used to attach these scores to specific peak dust readings as shown in Figures 4.1 to 4.5 and summarised in Table 4.2. Using Figure 4.6, it may be seen that if the extent of dustiness on a section of road is given a score of 5 (whole road affected), a desirable performance limit of 1 applies (in terms of degree). Undesirable (although operable) lies at between degree 2 and 3. If a maximum dust defect degree score of 2 is desired, then with reference to Figures 4.1 to 4.5, watering must take place every 1-3 hours, depending on the inherent dustiness of the wearing course, the climatic factors prevailing at the time of the test and the traffic types and volumes. For calibration purposes, Figures 4.7 to 4.11 illustrate typical field dustiness conditions associated with defect scores of 1-5.

In general, the consensus was that a dust defect score of 2-3 would represent a typical dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact. The implications of this intervention level, in terms of the peak and average respirable dust levels they represent, will be discussed in the following Chapters.

Using the concept of degree of dust palliation, Figures 4.1 to 4.5 can be redefined in terms of the degree of palliation achieved over time and the average degree of dust palliation and the associated frequency of watering required to maintain the average required. Two approaches to calculating the degree of palliation are possible; the use of peak values, or the use of the sum of an individual dust reading and time product (total dustiness), over the duration of a plume.


HAUL ROAD FUNCTIONAL ASSESSMENT
Range of desirabiliy, undesirability
and unacceptability for road defects
Defect
Maximum defect score = 25
Potholes
Corrugations
Rutting
Loose material
Dustiness
Stoniness - fixed
Stoniness - loose
Cracks - longit
Cracks - slip
Cracks - croc
Skid res wet
Skid res dry
0
5
10
15
20
25
Defect score
Desirable performance 1
Undesirable performance 2
Unacceptable performance 3

In this work, the plume duration and total dustiness approach is used since peak values may only be transient, whilst the plume duration is an important consideration, especially where interaction with other traffic is concerned. The effect of plume duration is typically illustrated in Figure 4.12

where two plumes generated by a haul truck are compared, the first just after watering and the second as the road approaches its (original) dry state. As can be seen, the plume duration is much longer as the road dries out, hence the overall dust defect much greater, both in terms of peak and period.

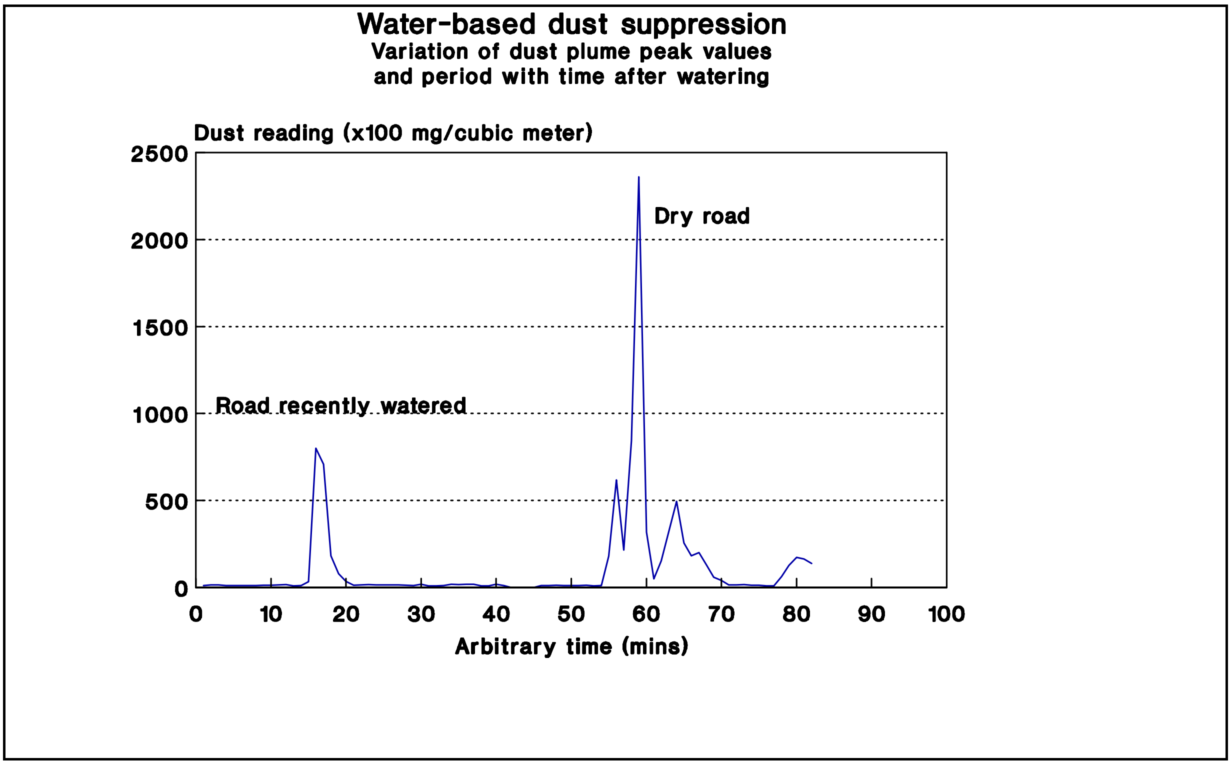


Figure 4.13 illustrates the degree of dust palliation thus calculated for each test site. If water re-application is considered at a point where the degree of palliation is equal to zero (equivalent to an average degree of palliation of 50%), together with the data presented in Table 4.1, an equivalent value can be calculated from the formula presented earlier by Cowherd et al (1986). The results are presented in Table 4.3 from which it is seen that the equation presented by Cowherd et al significantly overestimates the average degree of palliation achieved. This may be ascribed to the dissimilar test conditions (total suspended particulate compared with respirable fraction and different traffic types and possibly wearing course materials and climatic conditions) used to generate the data. Since only four test sites were used in this analysis, the data, although giving an insight into typical average degrees of palliation achieved with water and typical watering frequencies required, should also be applied with caution and, where possible, be validated with further field experimentation.

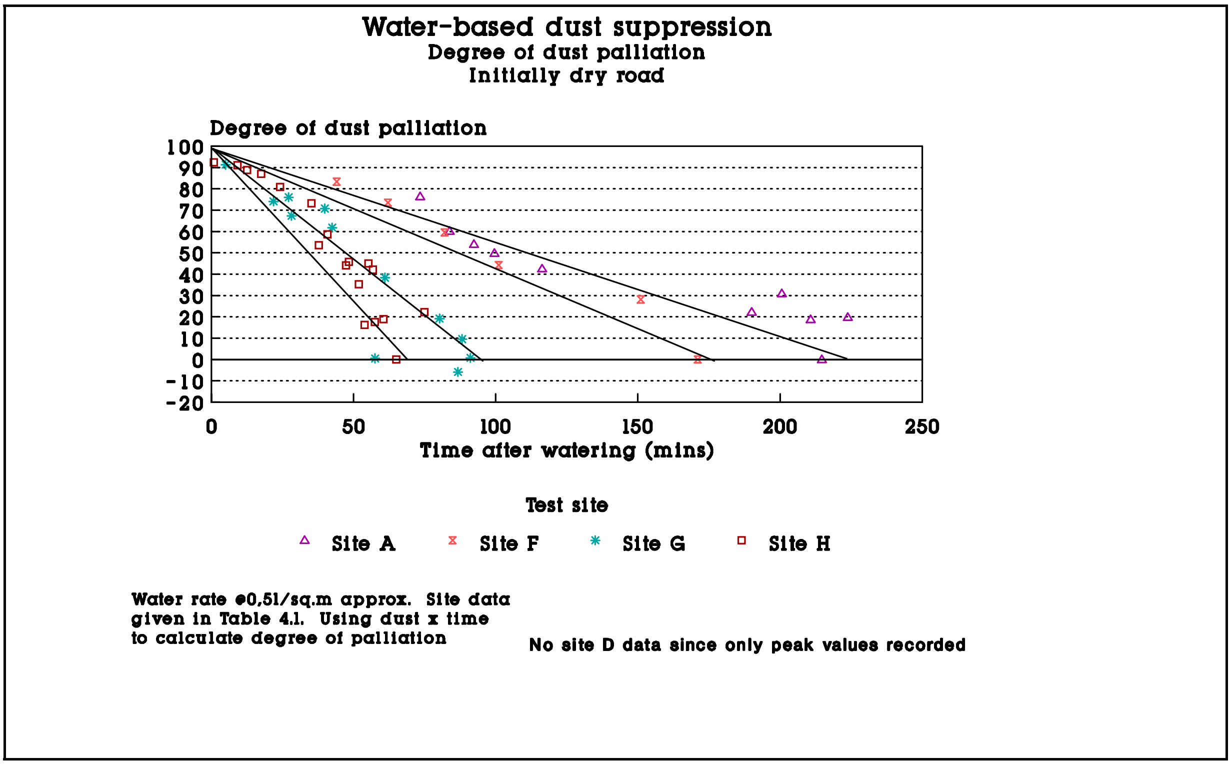


Table 4.3 Comparison of average degrees of palliation achieved

Test Site	Re-application at time t (mins)	Average degree of palliation following field measurements[1].	Average degree of palliation (following Cowherd et al, 1986)[2]
A	225	50%	90%
F	125	50%	87%
G	95	50%	84%
H	75	50%	94%

Notes
1. Using plume peak and duration to calculate degree of palliation
2. Using data presented in Table 4.1

An approximate appreciation of the role of climatic condition, expressed as mean monthly evaporation rates, on the time taken for water-spray based suppression to degenerate to zero may be obtained from Figure 4.14 which shows the range of typical summer and winter evaporation rates for stations in the region N=2 to 5 (following Wienert, 1980). If all the other variables affecting dust generation rates are excluded, an initial estimate of re-application rates may be found, assuming (initially) that dust generation is independent of vehicle shape and aerodynamics (these effects being analysed in isolation later). Regression of time to zero palliation on monthly evaporation rates yields the formula;

$$X_0 = 286{,}8 - 0{,}73.E_m$$

Where;

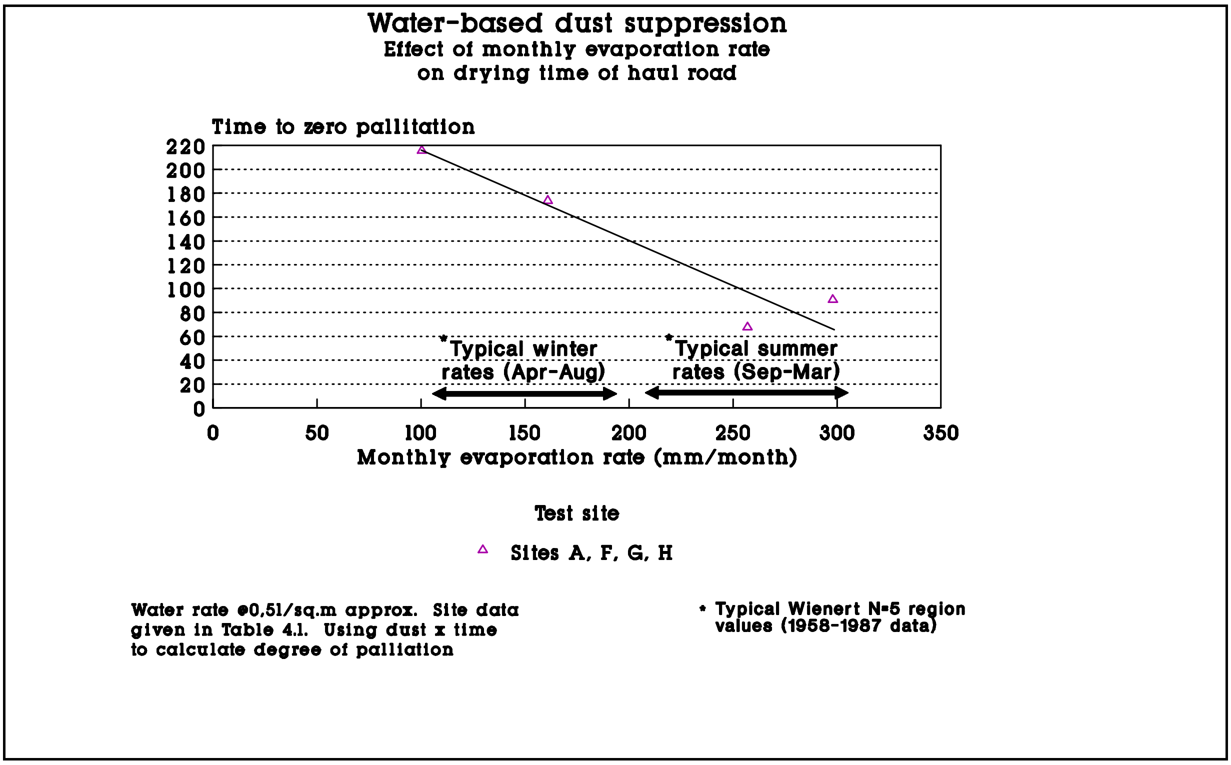
X_0 = Time to zero palliation (mins)
E_m = Average monthly evaporation rate (mm/month)

This model has an R-squared value of 89%. For the standard error of the model of 27,1, the approximate 95% confidence intervals for a time to zero palliation of 184 minutes lie between 130 and 238 minutes. If time to zero palliation is considered in terms of the degree of palliation as a percentage of total dustiness, in typical winter conditions, for an average degree of palliation of 50%, re-application is required at approximately 3-hourly intervals whilst in summer, this is reduced to approximately 1½-hourly intervals. These rates are based on an average of 50% average degree of palliation which, as was shown previously, does not accommodate the road-user preferred dust defect limit of 3, corresponding to a peak dustiness of about 7,5mg/m^3. To determine the re-application interval required under these circumstances and to therefore eventually model the cost-effectiveness of water-spray based suppression compared with other strategies, consideration needs to be given to the peak and total dustiness of various types of wearing course material and the effect of traffic speed on dustiness.

4.4 Modelling Dustiness as a Function of Wearing Course Material and Vehicle Speed

To provide an initial estimate of the dustiness associated with a particular wearing course material, seven test sites were selected from which data was recorded and analysed to model three parameters;

- Mass of dust as loose material on the road (g/m^2) (model MASS)
- Total dustiness (from consideration of peak and period of plume) (model TOTDST)
- Total dustiness as a function of vehicle speed and mass of loose material on the



road (model TOTDST/SPD).

By combining each of the above models, a generalised estimate of dustiness associated with vehicle type, speed and wearing course can be found, from which the required watering frequency (for water-spray based dust suppression) can be determined.

Test sites A, B, C, F, I, J and K were assessed and data concerning the following independent variables was collated in an attempt to identify suitable models. Table 4.4 gives the descriptions of those variables eventually selected as significant in each of the regression analyses.

(i) Wearing course material

- Shrinkage product
- Grading coefficient
- Percent material passing the 0,425mm sieve
- Percent material passing the 0,075mm sieve
- Dust ratio
- Plasticity Index
- Grading modulus
- Indicator for coal- or discard-based wearing course

- Indicator for excessive coal spillage on road
- Mass of loose material per square meter of road surface
    - Percent material passing the 0,425mm sieve
    - Percent material passing the 0,075mm sieve
    - Dust ratio
    - Grading modulus
    - Indicator for coal- or discard-based wearing course

(ii) Haul truck

- Indicator for truck type (bottom- or rear-dump)
- Number of wheels
- Gross vehicle mass
- Contact area for total number of wheels
- Tyre width
- Ground clearance
- Rear area
- Footprint area
- Wind shear area
- Vehicle speed

(iii) Dust reading

- Peak dustiness value (x100mg/m^3) minus 10 m dust)
- Total dustiness value (x100mg/m^3 minus 10 m dust) over plume period

A regression analysis was conducted using a least squares approach to determine the best-fit equation between the variables for each model. In using such a regression technique to derive statistical inferences regarding the association between dependent and independent variables the assumptions underlying the formulation of a best-fit linear model include linearity in the parameters (but not necessarily in the independent variables), independence of errors, constant variance and the normal distribution of the data points constituting a variable. The selection and assessment of a best-fit equation was based on the consideration of the Pearson correlation coefficient (R^2%) value in which 100% indicates perfect correlation and 0% no correlation. In general, a lower R-squared value increases in significance as the sample size increases.

Table 4.4 Independent Variables Used in the Regression Analysis of MASS and TOTDST

INDEPENDENT VARIABLE	DESCRIPTION
WCP425	Percentage of wearing course material passing the 0,425mm sieve
WCSP	Shrinkage product, defined as; $LS \ x \ P425$ where LS= Bar linear shrinkage
WCP075	Percentage of wearing course material passing the 0,075mm sieve
LP425	Percentage of loose wearing course material passing the 0,425mm sieve
PKDST	Peak dust reading (x100 mg/m^3) of the minus 10 micron dust fraction, measured by Hund Tyndalometer
TYPE	Indicator for truck type; 0 = Rear dump truck (RD) 1 = Bottom dump truck (BD)
WSHEAR	Wind shear (mm/s.mm) under the truck, defined as; $WSHEAR = \frac{SPD}{3,6x10^{-3}.GRCLEAR}$ where SPD = vehicle speed (km/h) GRCLEAR= Ground clearance (mm) under lowest part of vehicle
GVM	Gross vehicle mass (t) of fully laden haul truck
WHL	Number of wheels on truck
SPD	Speed of truck over test section (km/h)
VOL	Daily traffic repetitions on haul road

Additionally, the standard error of estimate (SEE) was used as a measure of scatter about the regression curve (analogous to the standard deviation). Where the sample size is large, the 95% confidence limits about the mean may be estimated as double the standard error of estimate. The F-statistic, being a ratio of explained (model derived) and unexplained (error derived) variances indicates the overall statistical significance of the model and was also used as a means of assessing the significance of the model, higher F values indicating a more significant model for larger sample sizes. Students' t-statistics were also assessed to determine the significance of each independent variable in the model.

For the regression of the independent variables on mass of loose material on the road surface,

$$MASS = 4202,68 - 630,56.WCP425 + 1548,55.WCP075 + 78,75.WCSP - 392,19.LP425$$

the following model was selected;

This model has an R-squared value of 98%, F value of 684 which is significant at the 0,001% level for a sample size of 44 . For the standard error of the model of 618,2, the approximate 95% confidence intervals for a mass of loose material (g/m^2 of road surface) of 6751 lie between

5514,6 and 7987,4. Full statistics for the model are given in Table 4.5. The model predicts an increase in the mass of loose material generated on the road when either the wearing course shrinkage product (representing plasticity and fines) or the percentage passing the 0,075mm sieve increase. The percentage of material passing the 0,425mm sieve is negatively correlated with the mass of loose material, both for wearing course and loose material samples.

For the regression of the independent variables on total dustiness, derived from consideration of the peak dustiness (x100mg/m^3 minus 10 m dust) recorded per vehicle pass, the following

$$TOTDST = 2{,}92.PKDST + 2260.TYPE$$

model was selected;

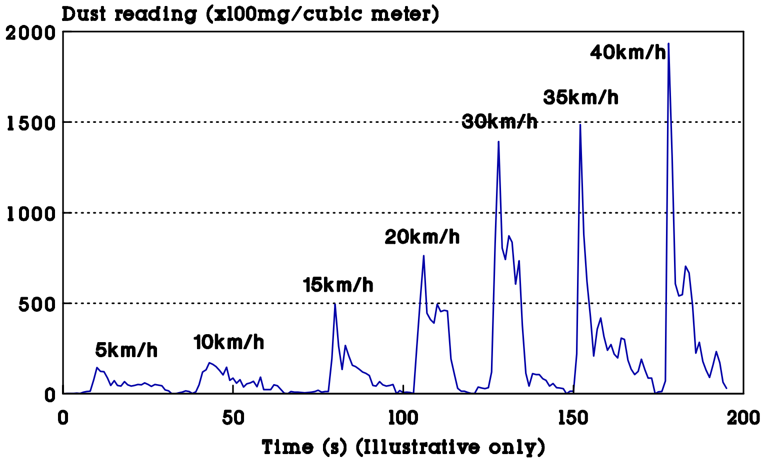
This model has an R-squared value of 95%, F value of 757,3 which is significant at the 0,001% level for a sample size of 73. For the standard error of the model of 2455,1, the approximate 95% confidence intervals for the total dustiness of 12 400 lie between 7489,8 and 17310,2. Full statistics for the model are given in Table 4.5. The absence of speed as an independent variable is partly explained with reference to Figure 4.15 in which a family of dust plumes for various truck speeds is presented. Although the peak values of dustiness measured increase with increasing vehicle speed, at the lower test speeds the peak is low, but the period or duration is similar or slightly longer than at high speeds. This may in part be attributed to a slow vehicle generating dust only from the finer fractions of dust on the road; at higher speeds, the effects of wind shear, etc. entrain larger particles which tend to settle out faster than the smaller diameter particles entrained at low speed. Figure 4.16 depicts the goodness of fit between observed and predicted values. When the model is used to predict the maximum allowable total dustiness from the peak value, the vehicle type indicator should be omitted.

For the regression of the independent variables on total dustiness, derived from consideration of the mass of loose material on the road, traffic volumes and vehicle parameters, the following model was selected;

$$TOTDST = SPD.(0{,}04.MASS + 38{,}33.WSHEAR + 0{,}12.GVM.WHEELS - 2{,}44.VOL$$

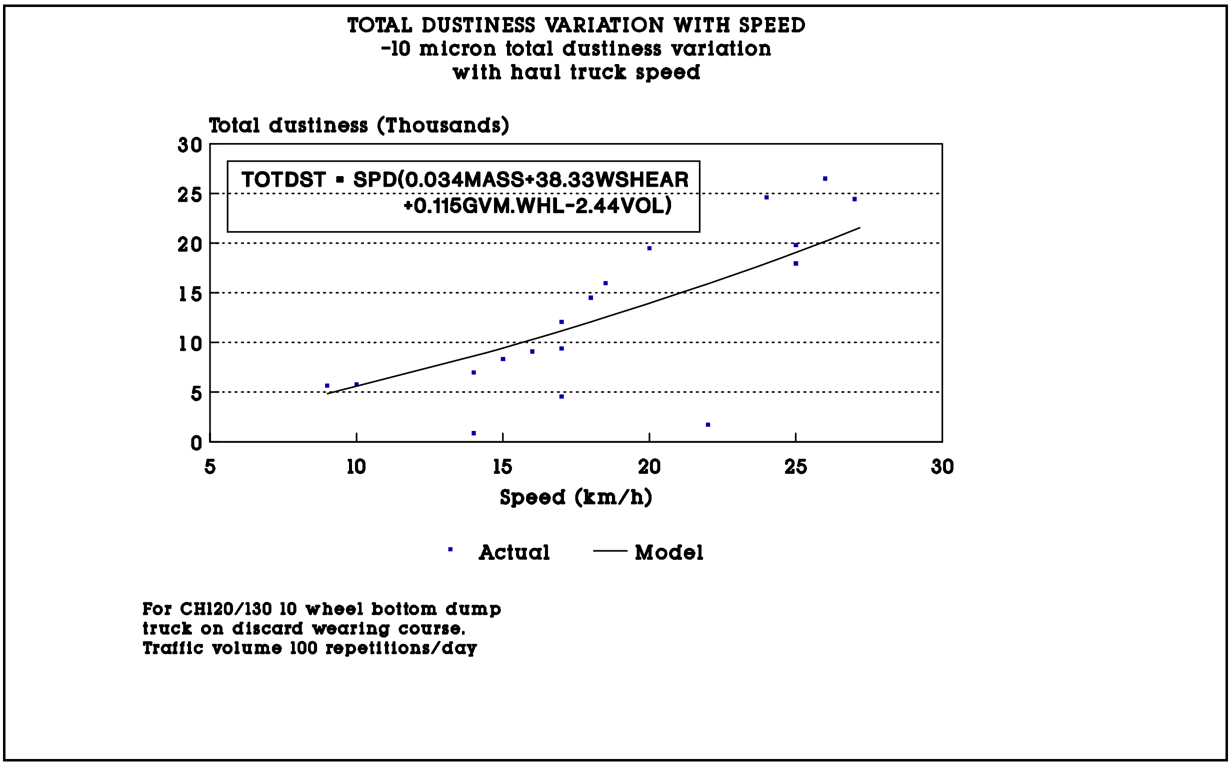
This model has an R-squared value of 88%, F value of 70,7 which is significant at the 0,01% level for a sample size of 44. For the standard error of the model of 221,9, the approximate 95%

confidence intervals for the total dustiness of 12 400 lie between 11 956,2 and 12 843,8. Full statistics for the model are given in Table 4.5 whilst Figure 4.17 illustrates the goodness of fit between observed and predicted data.



Dust generation variation with speed
Effect of truck speed on dust generation
rates and plume profile for Site H1

For single passes of Bell B30 at various speeds. Monitoring at road side using Hund Tyndalometer.



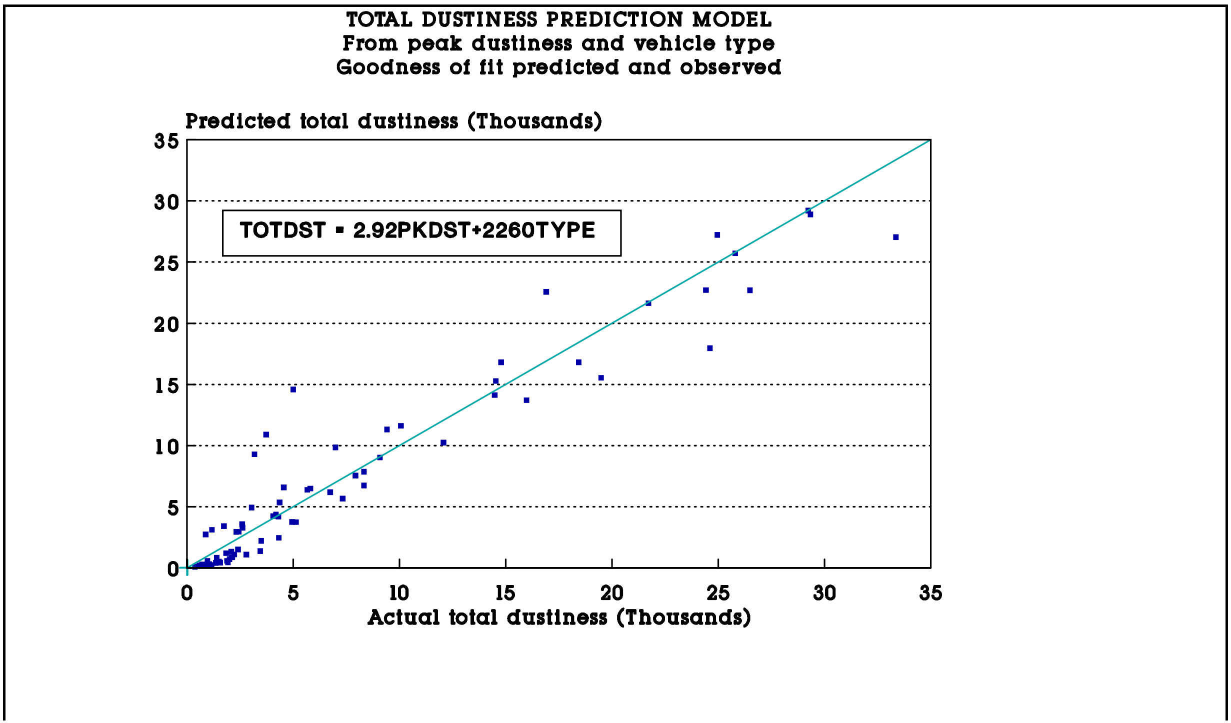
TOTAL DUSTINESS VARIATION WITH SPEED
-10 micron total dustiness variation
with haul truck speed

For CH120/130 10 wheel bottom dump
truck on discard wearing course.
Traffic volume 100 repetitions/day

The model predicts an increase in total dustiness with speed, mass of loose material on the road, wind shear (vehicles closer to the ground, travelling at higher speeds creating a higher wind shear effect), gross vehicle mass and the number of wheels. Traffic volume was negatively correlated with total dustiness, primarily due to the observation that higher traffic volumes led to a more compact wearing course and the removal of most loose material to the sides of the road.

Table 4.5 Regression statistics for dust models MASS, TOTDST and TOTDST/SPD

STATISTICS OF MODEL ESTIMATION FOR MASS, TOTDST AND TOTDST/SPD

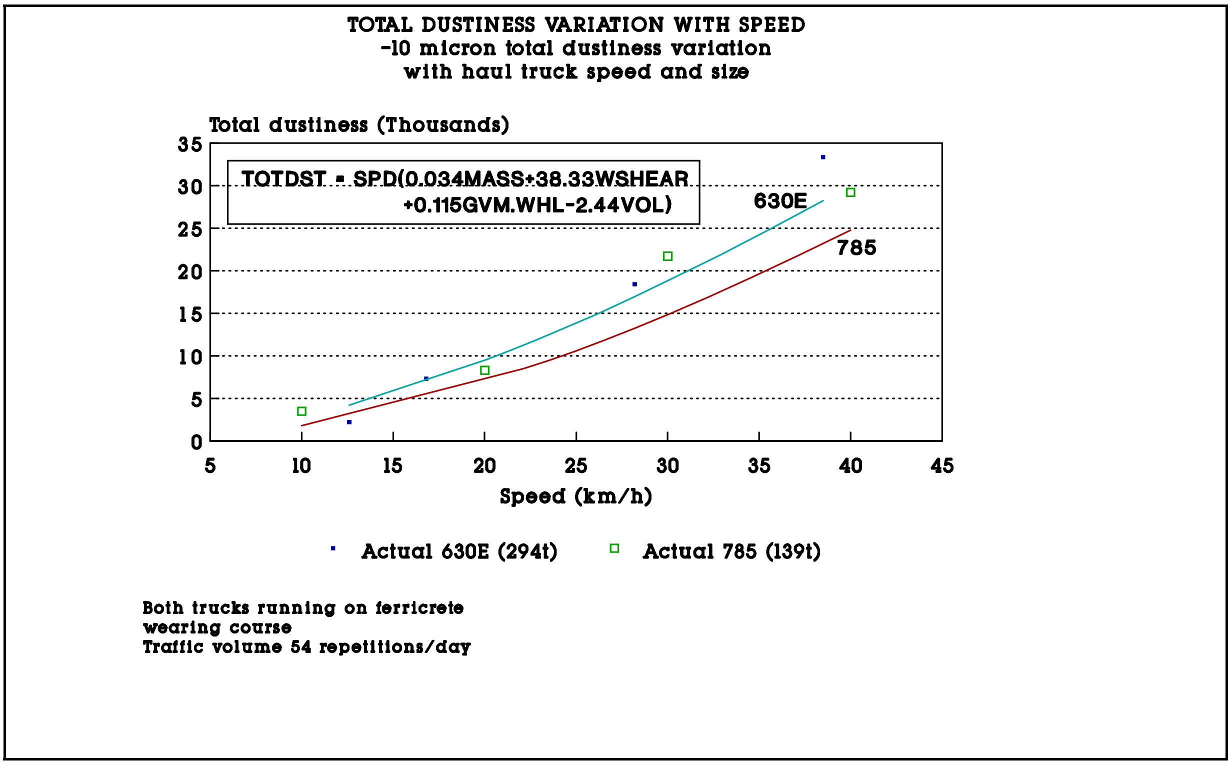


TOTAL DUSTINESS PREDICTION MODEL
From peak dustiness and vehicle type
Goodness of fit predicted and observed

	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 MASS	Intercept	0,0006	-27,28	0	-	-	-	-
	WCP425	0,0001	28,26	0	35,95	13,22	15	47
	WCSP	0,0001	25,63	0	147,43	55,22	55,5	225,0
	WCP075	0,0001	16,79	0	18,57	7,90	7	26
	LP425	0,001	9,58	0	38,61	9,62	24	51
2 TOTDST	PKDST	0,091	32,19	0	2308,58	2268,8	27	9999
	TYPE	545,72	4,14	0,001	-	-	0	1
3 TOTDST/ SPD	MASS	0,0076	5,22	0	6751,27	4966,6	1270	12056
	WSHEAR	7,0632	5,42	0	8,26	3,90	3,08	18,36
	GVM.WSHEAR	0,0675	1,72	0,096	1379,41	520,21	402	1944
	VOL	0,8826	-2,76	0,008	96,68	31,89	50	154
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODELS (1) TO (3)								
WHL					7,72	2,00	6	10
GVM					179,52	69,27	67	324

The number of days since last maintenance was not included as an independent variable in this analysis and steady-state conditions should be assumed when applying these models. A road that has just been bladed, or an excessively ravelled or poorly performing road cannot be reliably modelled using this approach. A more complete analysis of the effect of days since last maintenance on loose material generation and dustiness is presented by Thompson (1996) for mine haul roads and Paige-Green and Netterberg (1987) for unpaved public roads. However, the significant independent variables identified in this analysis correspond broadly to those previously identified.

Figure 4.17 illustrates the application of the combined models to a particular mine haul road where the wearing course is composed of a discard material, traffic being represented by a fleet of 10-wheel CH130 bottom dump trucks running at 100 repetitions per day. The predicted increase in total dustiness with speed is shown, compared to the observed data. The inverse hyperbola curve is in agreement with similar studies using small trucks and motor-cars (Jones, 1984 and Addo and Sanders, 1995) in which the aerodynamic factor, represented by wind shear, was found to either lead to storage under the vehicle (low wind shear or high ground clearance) or entrainment as a result of high speed and low ground clearance. This was coupled with turbulent effects created by the interaction of wind shear with wheel motion. In the case of haul trucks, the larger (in terms of GVM) trucks do not produce a proportionally larger increase in dustiness since, although wheel contact area increases, this is often accompanied by increased ground clearance (to accommodate the larger tyres sizes) and thus reduced wind shear. Figure 4.18 illustrates this effect, using actual and predicted data for Komatsu 785 (139t GVM) and Komatsu 630E (294t GVM) models of six-wheeled rear dump trucks.



4.5 Prediction of Water-spray Based Suppression Re-application Frequency

By combining the models established in sections 4.3 and 4.4, a first estimate of typical re-application frequencies for water-spray based dust suppression can be determined. The estimate is based on a combination of the evaporation rate - time to zero palliation model illustrated in Figure 4.14 and the models for mass of loose material on the road and total dust, as a function of vehicle type and speed. When combined with the total anticipated dustiness on the road, the maximum allowable dust defect score and the associated peak value can be expressed as a degree of palliation (as a percentage of total dustiness), the degree of palliation required thus being dependant on the total dustiness of the road - those roads with high total dustiness will have to be re-watered at more frequent intervals to maintain the required degree of palliation. Table 4.6 gives the typical calculation sequence required to determine application frequencies whilst Table 4.7 contains a pro-forma for the calculation.

From Table 4.6 it is seen that under summer operating conditions, with a monthly evaporation rate of 260mm/month, re-application of water is required at 32 minute intervals to maintain a dust defect score which does not exceed defect degree 2 (or 23,5mg/m^3 minus 10 micron dust). In winter conditions, using a lower evaporation rate of 150mm/month, the required re-application frequency decreases to 60 minute intervals. If average segment traffic speed is increased to 35 km/h, then re-application is required at 12 and 22 minutes respectively for summer and winter. When bottom dump trucks are used in place of rear-dump trucks, by virtue of their increased number of wheels and increased dust generation, re-application times decrease to 11 and 20 minutes respectively.

Whilst the combinations of models previously described gives an insight into the required watering frequencies for various combinations of vehicle types, speeds, traffic volumes, wearing course material types and evaporation rates, care should be taken to ensure that where other parameters are used for the calculation, they fall within the sphere of influence of the major independent variables analysed. Further refinement of these models, through the analysis of extra test sites would enable a greater range of variables to be reliably analysed and thereby improve the predictive capability of the models proposed.

4.6 Summary of Haul Road Water-spray Based Dust Suppression Strategies

Water-spray based dust suppression is the most common means of reducing dustiness on mine haul roads. The combination of a water-car and regular spray applications of water providing a relatively inexpensive, but not necessarily efficient, means of dust suppression. Five test sites were evaluated in terms of the efficiency of the water-spray based dust suppression method. The test methodology involved the use of a Hund Tyndalometer to measure the dust plume generated by a haul truck as it passed at a set distance and speed from the monitor. Analysis of the data enabled a first estimate to be made of the time taken for the degree of palliation to decay to zero and the role of climate, specifically evaporation rates, on this time.

The management strategy for water-spray based dust suppression was based on user defined levels of dust defect acceptability, both from a health and safety point of view. Mine operating personnel's opinion was used to attach defect scores to specific dust readings during the monitoring process. In general, the consensus was that a dust defect score of 2 would represent a typical dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

An approximate appreciation of the role of climatic condition, expressed as mean monthly evaporation rates, on the time taken for water-spray based suppression to degenerate to zero was determined from a number of test sites over the range of typical summer and winter evaporation rates for stations in the climatic region N=2 to 5. When time to zero palliation was considered in terms of the degree of palliation as a percentage of total dustiness, in typical winter conditions, for an average degree of palliation of 50%, re-application was required at approximately 3-hourly intervals whilst in summer, this is reduced to approximately 1½-hourly intervals.

Table 4.6 Determination of Water-spray Based Suppression Re-application Frequency

Water-spray Based Suppression Re-application Frequency determination

(Items calculated from formulae given in *italics*)

Basic Mine and Traffic Data

Mine	Example
Section	ROM to R1
Vehicle type (BD=1, RD=0)	0
Wheels	6
GVM (t)	294
Av Speed (km/h)	20
Gr Clear (mm)	690
Wind Shear (mm/s.mm)	8,05
Traffic volume (vpd)	54
Max allowable dust defect	2

Wearing Course data

WC shrinkage product	82
WC percent passing 0,425mm sieve	41
WC percent passing 0,075mm sieve	17
Loose material percent passing 0,425mm	24

Average monthly evaporation rate (mm/mth)	260

Dustiness calculations

Max allowable total dustiness	*6103*
Max predicted mass loose material	*1717,2*
Max predicted total dustiness	*4207,5*

Watering frequency calculations

Average degree of palliation required	*66,0*
Time to zero palliation (mins)	*96,3*
Re-application rate (mins)	***32,0***

Table 4.7 Calculation Pro-forma for the Determination of Water-spray Based Suppression Re-application Frequency

Water-spray Based Suppression Re-application Frequency determination

Basic Mine and Traffic Data

Mine	Example
Section	ROM to R1
Vehicle type (BD=1, RD=0)	TYPE
Wheels	WHL
GVM (t)	GVM
Av Speed (km/h)	SPD
Gr Clear (mm)	GRCLEAR
Wind Shear (mm/s.mm)	WSHEAR
Traffic volume (vpd)	VOL
Max allowable dust defect	D_{max}Table 4.2

Dustiness calculations

Max allowable total dustiness ($TOTDST_{max}$)	$4584*D_{max}-1050$
Max predicted mass loose material (MASS)	*4202.7-630,6.WCP425+1548,5.WCP075+78,7.WCSP-392,2.LP425*
Max predicted total dustiness (TOTDST)	*SPD.(0,04.MASS+38,33.WSHEAR+0,12.GVM.WHL-2,44.VOL)+2260*TYPE*

Wearing Course data

WC shrinkage product	COAL
WC percent passing 0,425mm sieve	WCP425
WC percent passing 0,075mm sieve	WCP075
Loose material percent passing 0,425mm	LP425

Average monthly evaporation rate (mm/mth)	E_m

Watering frequency calculations

Average degree of palliation required D_p	$100-(TOTDST_{max}*100/TOTDST)$
Time to zero palliation (mins) X_0	$286,83-0,733*E_m$
Re-application rate (mins)	$(100-D_p)*X_0/100$

These rates are based on an average of 50% average degree of palliation which was shown previously to not accommodate the road-user preferred dust defect limit of 2. To determine the re-application interval required under these circumstances and to therefore eventually model the cost-effectiveness of water-spray based suppression compared with other strategies, the peak and total dustiness of various types of wearing course materials and the effect of traffic speed on dustiness was modelled.

To provide an initial estimate of the dustiness associated with a particular wearing course material, seven test sites were selected from which data was recorded and analysed to model three parameters; the mass of dust as loose material on the road (g/m^2), the total dustiness (from consideration of peak and period of plume) and the total dustiness as a function of vehicle speed and mass of loose material on the road. By combining each of these models with the maximum allowable dust defect score and the associated peak value, the degree of palliation required to maintain this maximum defect score, and the associated re-application time, was determined.

Whilst the combinations of models previously described gives an insight into the required watering frequencies for various combinations of vehicle types, speeds, traffic volumes, wearing course material types and evaporation rates, care should be taken to ensure that where other parameters are used for the calculation, they fall within the sphere of influence of the major independent variables analysed. Further refinement of these models, through the analysis of extra test sites would enable a greater range of variables to be reliably analysed and thereby improve the predictive capability of the models proposed. Nevertheless, the example calculation procedure for determining typical re-application frequencies can be used as a base case scenario with which to compare other types of dust palliatives.

CHAPTER 5

EVALUATION OF TEST SITE PALLIATIVE SUPPRESSION PERFORMANCE

5.1 Introduction

The experimental design described in Chapter 3.2 forms the basis of the palliative evaluations described in this chapter. Nine treated sections of road were evaluated and compared with the untreated (base case) dustiness levels, the degree of palliation achieved and suppression efficiency compared to a single application of water. The results are categorised according to the class of palliative evaluated.

The use of palliatives may also lead to improvements in road functionality as outlined in Chapter 2. To determine the extent of these benefits, results of the functionality and roughness monitoring exercise are also presented for each test site, compared to the untreated wearing course defect progression rates. Additional observations are offered, centred on the performance of the test site following palliation, in terms of dust suppression and road performance. The measures of palliative performance, in terms of reduced water-based spray applications and reduced haul road maintenance frequencies, can then be applied to model the cost effectiveness of a dust palliative as discussed in the following chapter.

5.2 Evaluation of Hygroscopic Salts

5.2.1 Site H2 Palliative Suppression Performance

Site H2 was evaluated over a period of 14 days from the initial spray-on application, encompassing predominantly dry weather in late summer. A single spray-on treatment of a hygroscopic salt was applied to the prepared road surface as specified in Table 5.1.

The base-case untreated dustiness readings are shown in Figure 5.1 from which it is seen that a peak dustiness concentration of approximately 16mg/m^3 was measured for each pass of a Bell B25 or B30, normalised to 40 km/h, following the speed model presented in Chapter 4. Dust readings were taken with the Hund Tyndalometer as described in Chapter 3, following application or re-application when the palliative had dried on the road and trafficking was feasible. Tests were repeated at various intervals, depending on the palliative re-application schedule (if appropriate) and traffic availability on the test section.

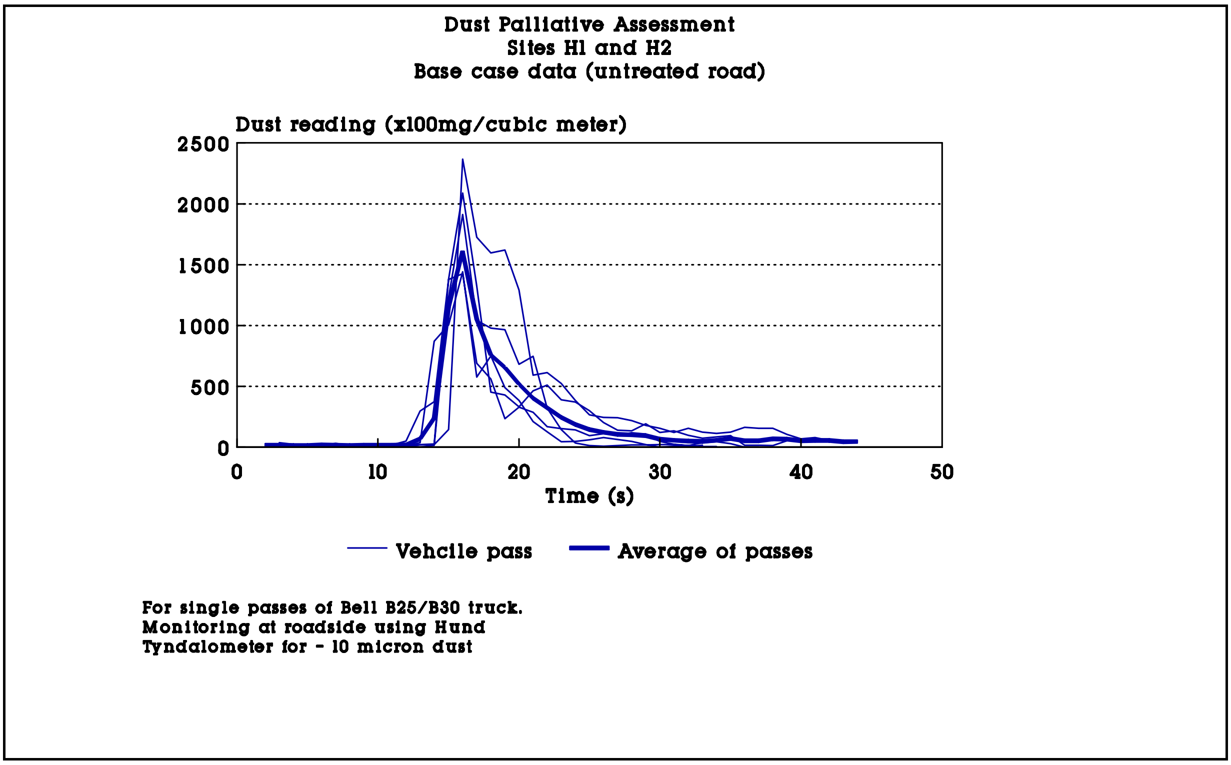
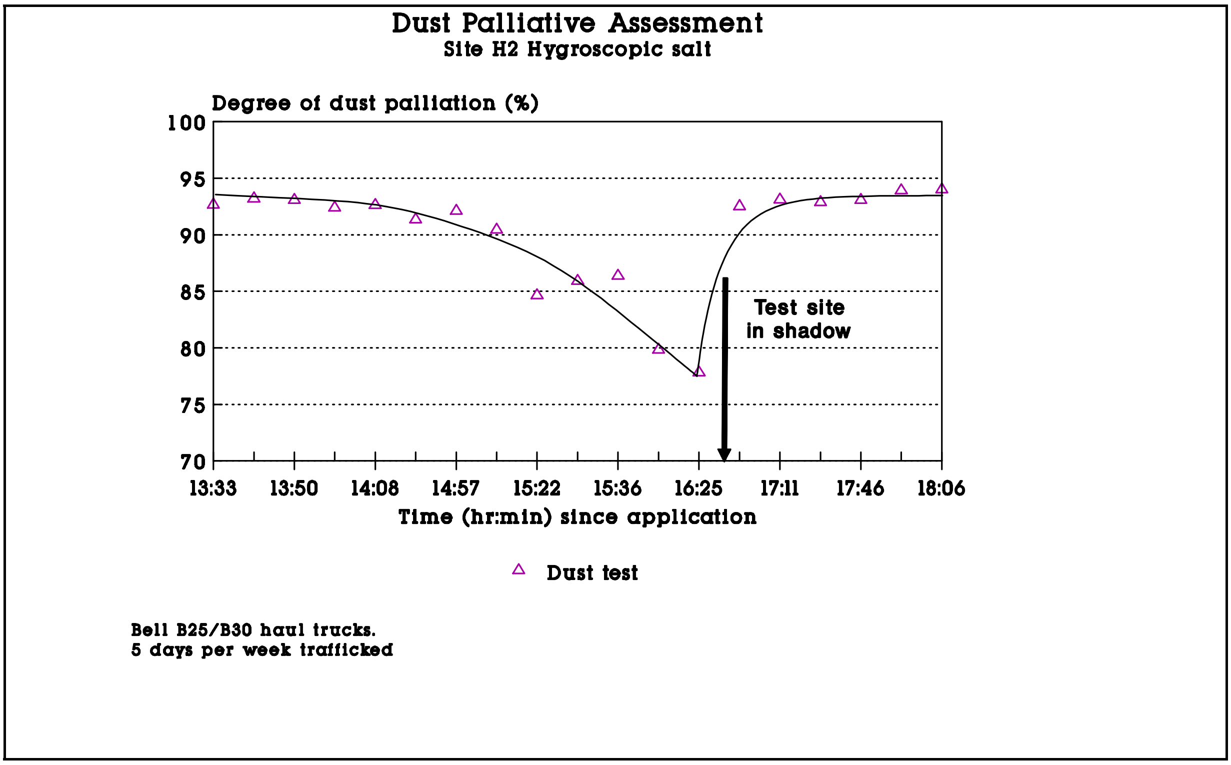
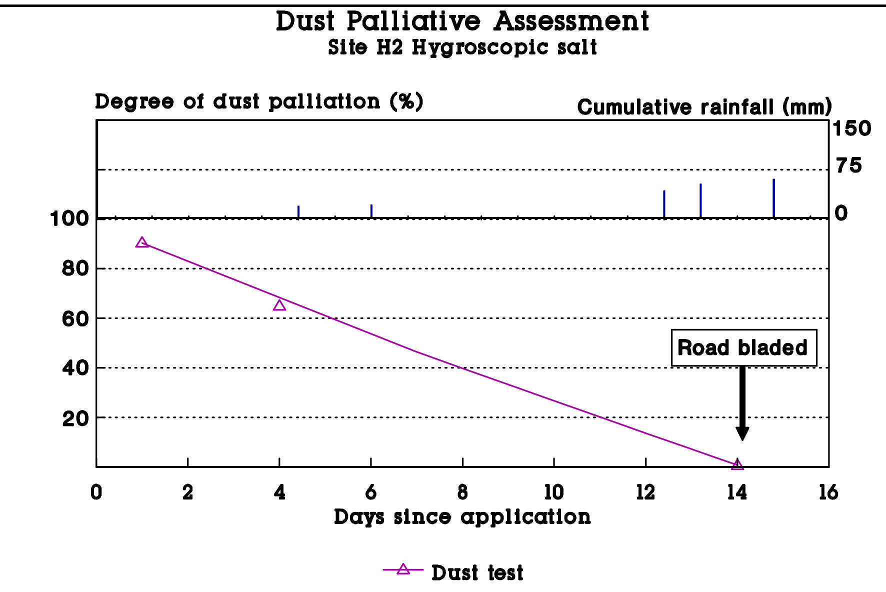


Table 5.1 Test site H2 palliative treatment details using hygroscopic salts

Treatment	Application rates
Establishment*	Road bladed, shaped and repaired prior to application. Spray-on application at 1,0l/m^2 over 4 passes of 1:1 dilution to give 2,0l/m^2 of product applied.
Re-applications	None (although monthly spray-on re-applications may be required of 0,5l/m^2 3:1 dilution, depending on traffic, climate and wearing course material) to further control dustiness
Total product applied (l/m^2)	2,0
Note * Application rates may vary from site to site, depending on wearing course, traffic volume and climatic conditions, together with practicality of technique. Water car speed, spray-coverage and feed system (gravity- or pump-fed spray-bar) will result in variations to application methodology. Dilution rates given as water to product ratio. A 2:1 dilution is equivalent to a 33% solution whilst a 9:1 dilution is equivalent to a 10% solution.	

During application it was noted that with the spray-on approach generated 20-25mm depth of penetration into the wearing course in most places. The CBR of the wearing course was between 58-72% (95%-97% Mod AASHTO), primarily as a result of the lower wheel loads applied by the small Bell trucks and the lack of proper compaction during construction. The road was trafficked immediately after application and Figure 5.2 illustrates the effect of increasing humidity on the degree of palliation achieved. Following application of the palliative, the test site was in full sun until 16h40, following which the air cooled noticeably and an increase in the degree of palliation was noted thereafter. This observation confirms the comments made in Chapter 2 regarding the improved performance of hygroscopic salts when ambient moisture or humidity levels increase. The test was not repeated during further evaluations on day 4, 9 and 14 and thus it is not known whether palliative degradation will reduce this effect over time.

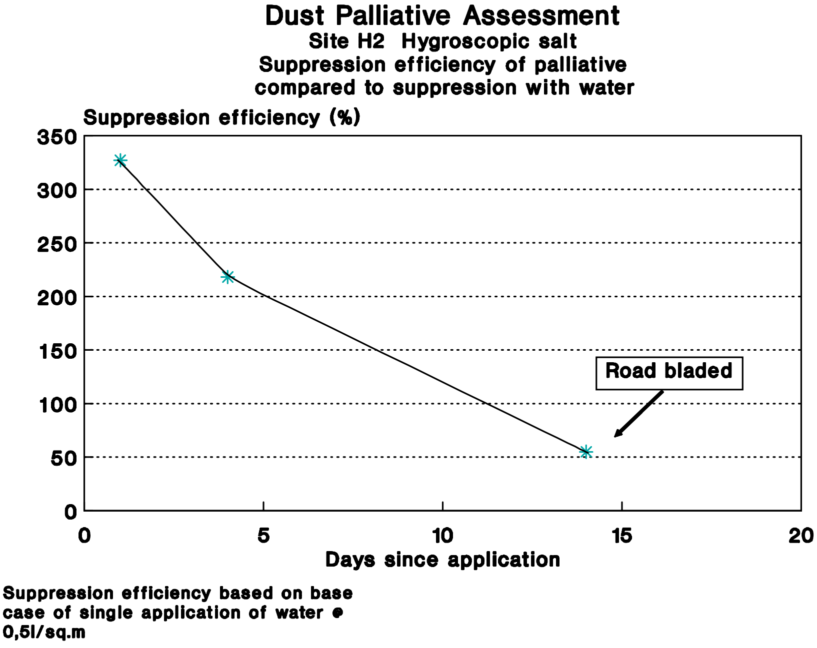




Bell B25/B30 haul trucks.
5 days per week trafficked

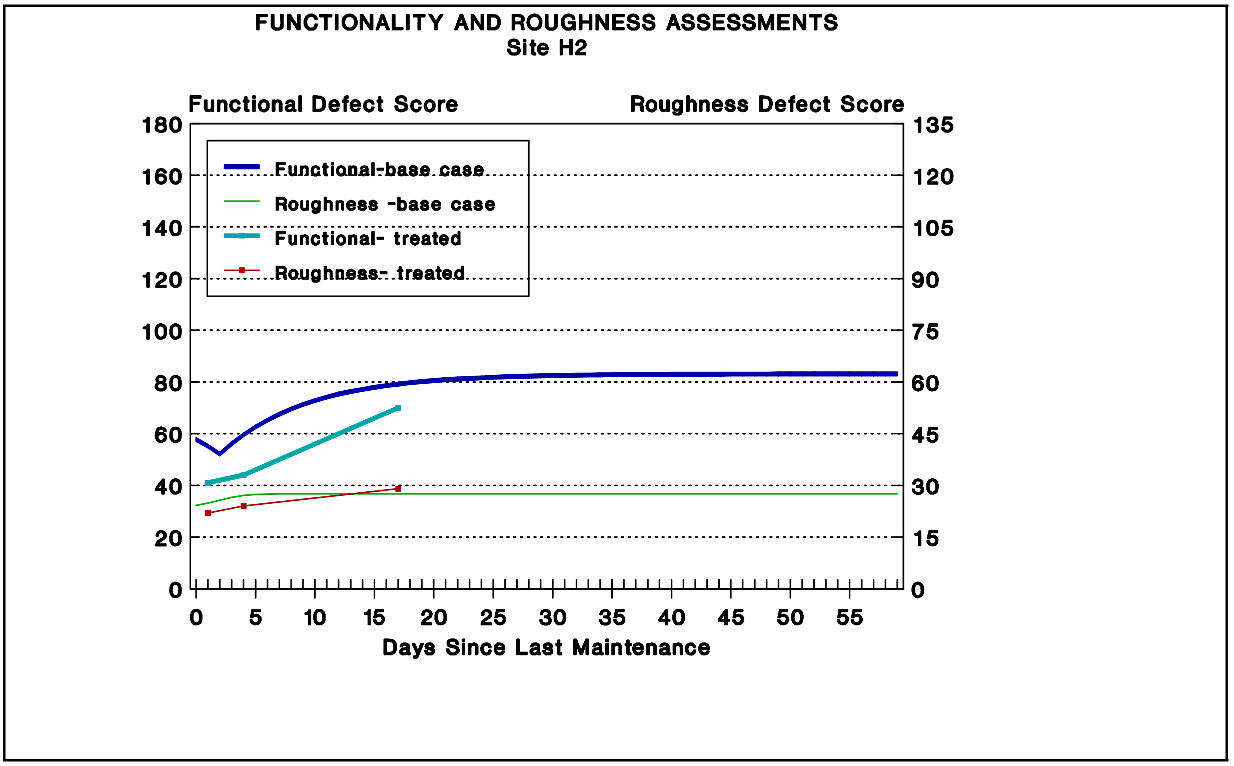
Following application of the palliative, the degree of dust palliation achieved was initially over 90% and this value decreased to 0% after 14 days, equivalent to a degeneration rate of 6,6%/day. The treatment resulted in an average degree of dust palliation of 45,5% over 14 working days or for 11kt hauled (equivalent to 406 Bell B25/B30 laden repetitions over the test period - daily traffic volumes varied as a result of production requirements). Rainfall during the test period is shown cumulatively in Figure 5.3 (days when rain fell being indicated by a bar whose size represents the cumulative rainfall up to and including that day). Significant rainfalls were encountered on day 12 onwards which probably reduced the performance of the palliative, through a combination of fines and erosion on the road and possible leaching of the palliative from the road. As a result, the road was bladed on day 14 to correct the effects of the rain-induced erosion. Mine staff however did not report any particular problems with wet skid resistance as has been alluded to in Chapter 2. This effect may be related to the fines content of the untreated wearing course - those materials with high fines content tending to generate wet skid resistance defects whilst the lower fines contents (as evidenced from the shrinkage product value of 93) of the wearing course at this site precluded the development of such.

Figure 5.4 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies of over 328% are initially achieved, decaying to under 50% on day 14, following which the road was bladed. Although high suppression efficiencies were achieved for a number of test sites, no cost implications were evaluated. To fully assess and compare performances, cost efficiency needs to be analysed in conjunction with the suppression efficiency of the particular palliative. This aspect is more fully developed in Chapter 7.



The effect of palliative application on road functionality and roughness is shown in Figure 5.5. Using the methodology described in Chapter 3, functionality was evaluated according to the five point degree and extent scales for each defect specified, to generate a total functional defect score for the road on the day of the analysis. The roughness defect score was derived from those defects which directly affect road roughness (or rolling resistance, following Thompson, 1996). The functional and roughness defect scores were plotted and compared to the predicted defect score progression models for the untreated test site wearing course to determine the extent to which palliation may improve functionality and reduce road roughness.

Rainfall significantly reduced functionality and increased roughness at site H2 from day 12 onwards due to the combined effects of erosion and a poorly compacted wearing course. The results emphasise the importance of applying a palliative to a well prepared road. Figure 5.5 confirms that the overall roughness of the road was little changed from the untreated estimate, whilst functionality was slightly improved, mostly by virtue of reduced dust defect scores from day 1 to day 11.



5.3 Evaluation of Ligno-sulphonates

5.3.1 Site B Palliative Suppression Performance

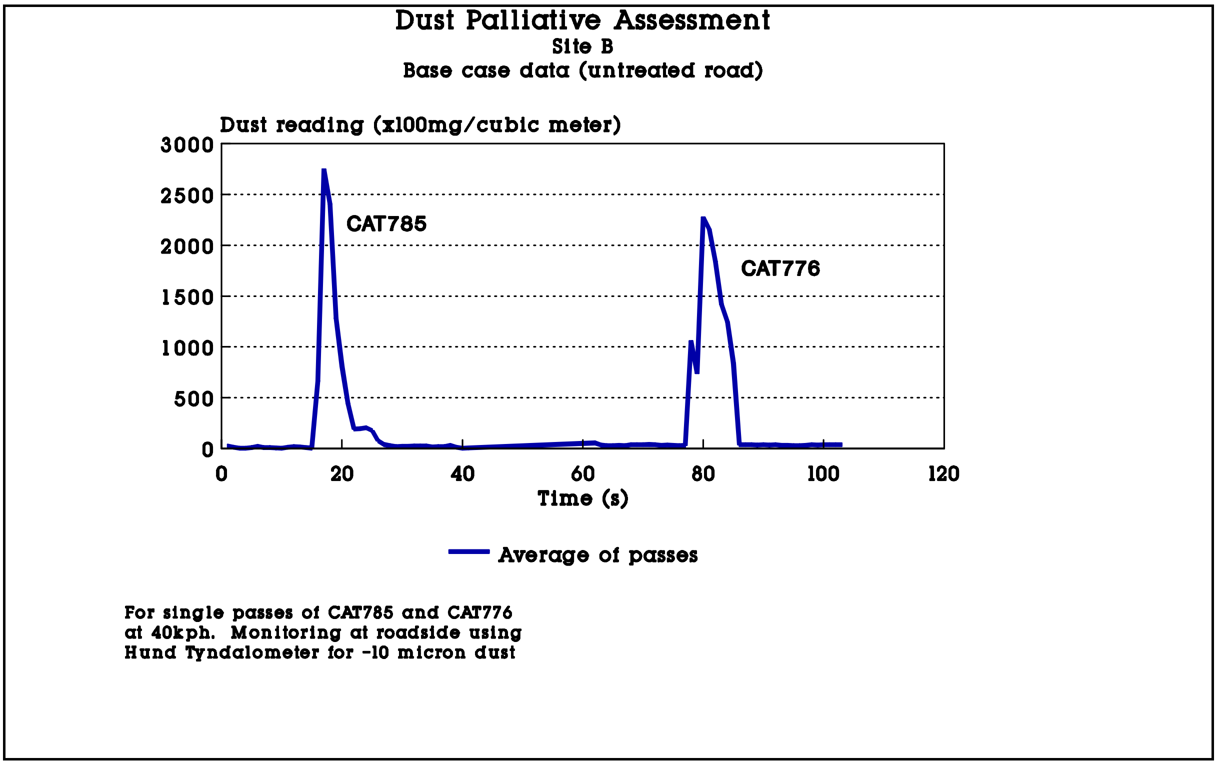
Site B was evaluated over a period of 23 days from the spray-on re-application applied to an already established palliated section of road as specified in Table 5.2. The analysis was conducted over the dry winter months and no rainfall was encountered over the period.

Table 5.2 Test site B palliative treatment details using ligno-sulphonates

Treatment	Application rates
Establishment	Road already established with an estimated 6l/m^2 applied over the previous season.

Re-applications	Approximately bi-monthly spray-on re-applications were applied at 0,4l/m^2 over 2 passes at 3:1 dilution to give 0,2l/m^2 product applied (re-application interval dependant on dustiness and traffic).
Total product applied (l/m^2)	Unknown

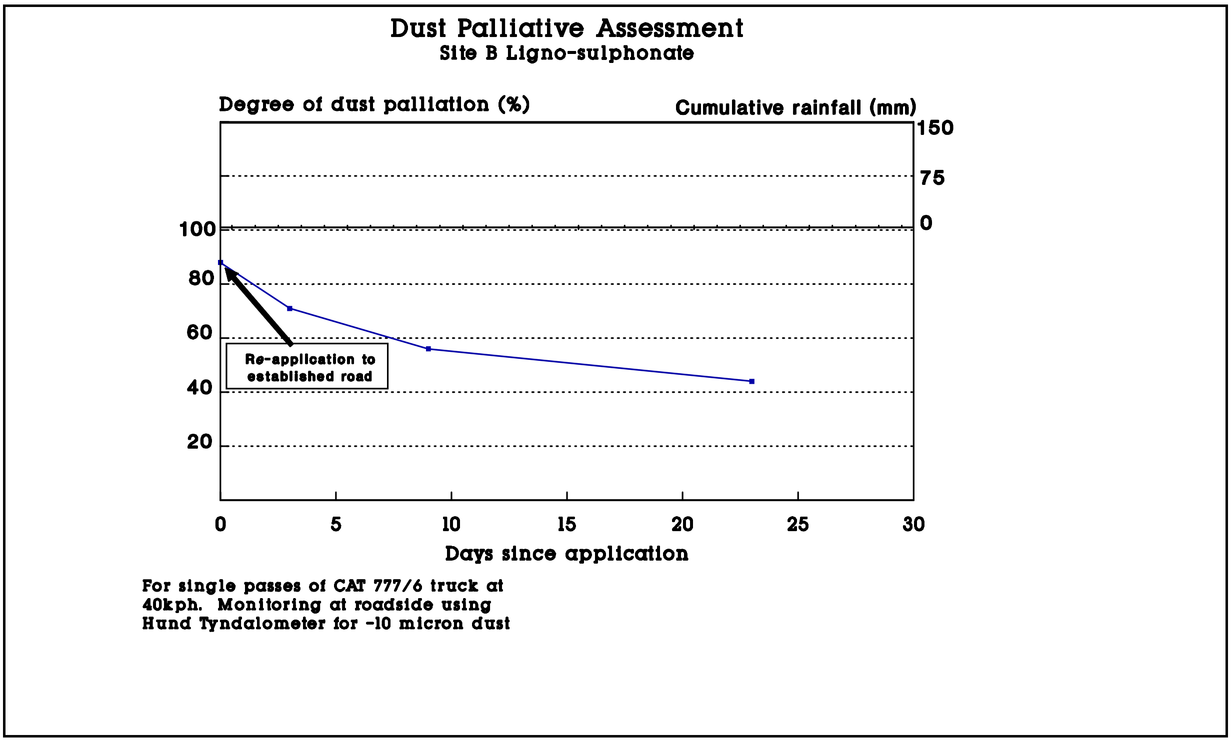
Since the test site wearing course material was previously treated, base case data was generated from an adjacent untreated ramp road. The wearing course material (ferricrete) was assumed to be sourced from the same borrow pit as the test section material. The base-case untreated dustiness readings are as shown in Figure 5.6, for both CAT 785 rear dump and CAT 776 bottom dump trucks, the rear dump truck showing a greater peak dust concentration but lower duration, whilst the bottom dump truck shows a lower peak value, but longer duration, as was discussed in Chapter 4. The following analysis was based on the average degree of palliation achieved for both types of truck.

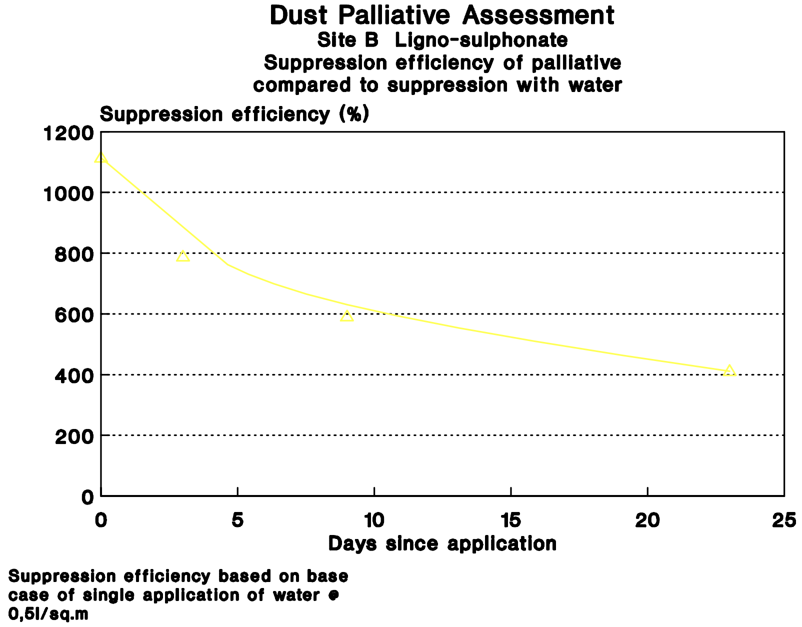


For single passes of CAT785 and CAT776
at 40kph. Monitoring at roadside using
Hund Tyndalometer for -10 micron dust

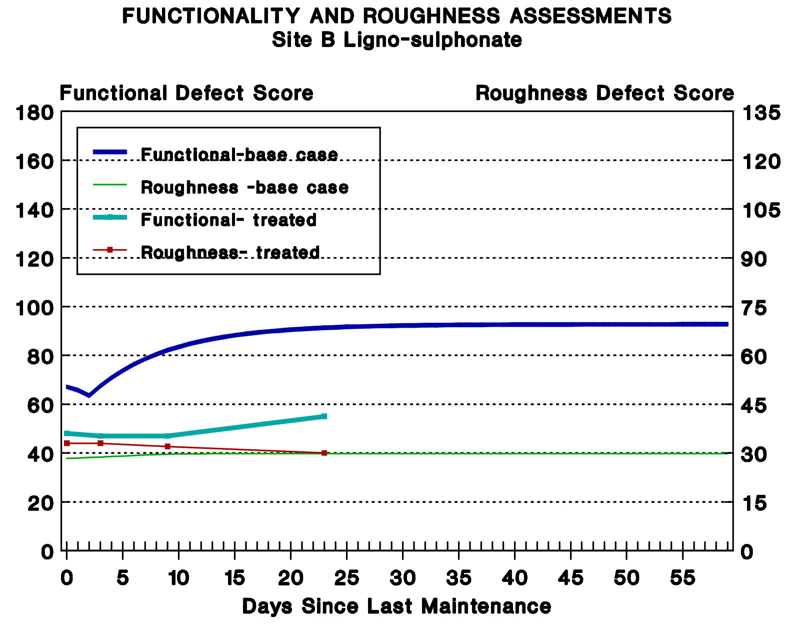
The test section had been previously treated with an unknown amount of ligno-sulphonate (estimated total product supplied and applied equates to about 6l/m^2 over the previous season). It was also unclear as to how much product remained in the road from the last treatment, however, there was a discernable difference between the upper 40mm of the test site wearing course colour and composition, compared to the untreated ramp area selected for base-case evaluations. During application it was noted that the spray-on re-application generated 10-15mm depth of penetration into the wearing course in most places and considerable ponding and run-off was noted. The road was trafficked immediately after application.

The re-treatment resulted in an average degree of dust palliation of 66% over 23 working days or for 60kt hauled (equivalent to 445 CAT 785/CAT776 truck laden repetitions over the test period - daily traffic volumes varied as a result of production requirements), as shown in Figure 5.7. Only a small rate of degeneration (1,9% per day) was seen over the 23 day test period, most probably due to the existing level of product already in the pavement and the absence of rain. Figure 5.8 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies maintained over the test period peak at approximately 1100% and average approximately 750%. Even though some damage was evident in wheel tracks towards the end of the evaluation period, it was evident that the accumulated depth of treatment prevented, to a certain extent, the generation of new untreated surfaces.





Following application, it was noted that from day 1 to day 3 the road tended to generate small potholes. These potholes appeared to self-repair after day 3 and were not seen as being so extensive on day 9. Little loose material was seen on the road until after day 9 and then only larger (2-4mm) pieces of material which were less easily entrained into the air. At the side of the road, initial spray-over reduced the dustiness recorded (especially with the bottom dump trucks), but latterly it was seen that considerable dust was generated from the now dry and exposed material at the side of the road. The effect of palliative application on road functionality and roughness is shown in Figure 5.9. This data was gathered over the dry winter months and as such no rainfall effects were seen, as were with other sites. The functionality and roughness defect progressions are therefore not directly comparable with the other sites analysed in this Chapter. Functionality also varied as a function of dustiness, reducing with the re-application of the palliative but degenerating at approximately the same rate thereafter. Nevertheless, the functionality of the treated wearing course showed a considerable improvement over the predicted performance of the wearing course in it's untreated state. Figure 5.9 confirms that the overall roughness of the road was little changed from the untreated estimate, although slightly rougher initially due to the small potholes observed and the absence of loose material with which they could be filled under the action of traffic.

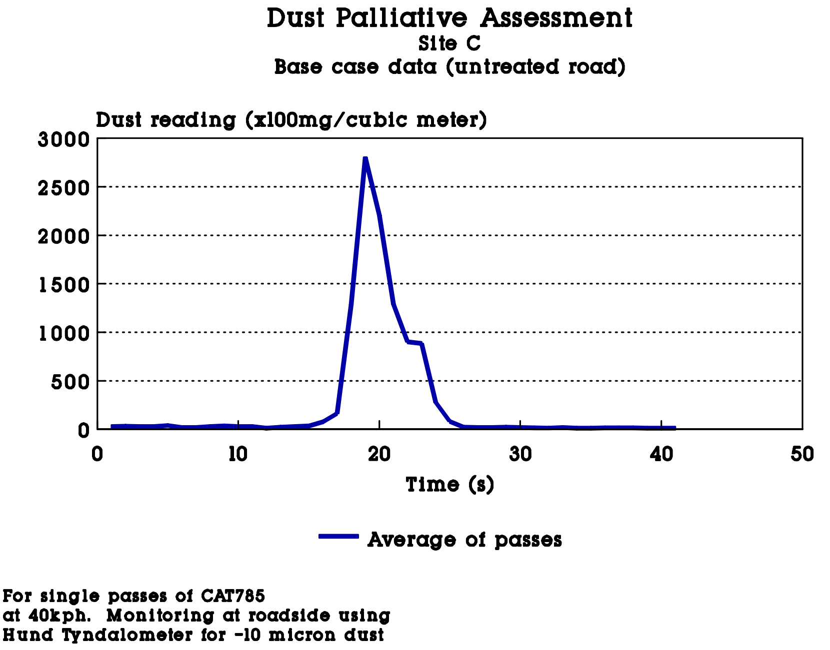


5.3.2 Site C Palliative Suppression Performance

Site C was evaluated over a period of 23 days from the spray-on re-application applied to an already established palliated section of road as specified in Table 5.3. The analysis was conducted over the dry winter months and no rainfall was encountered over the period. Since the test site wearing course material was previously treated, base case data was generated from an adjacent untreated section of main haul road. The wearing course material (ferricrete) was assumed to be sourced from the same borrow pit as the test section material. The base-case untreated dustiness readings are as shown in Figure 5.10.

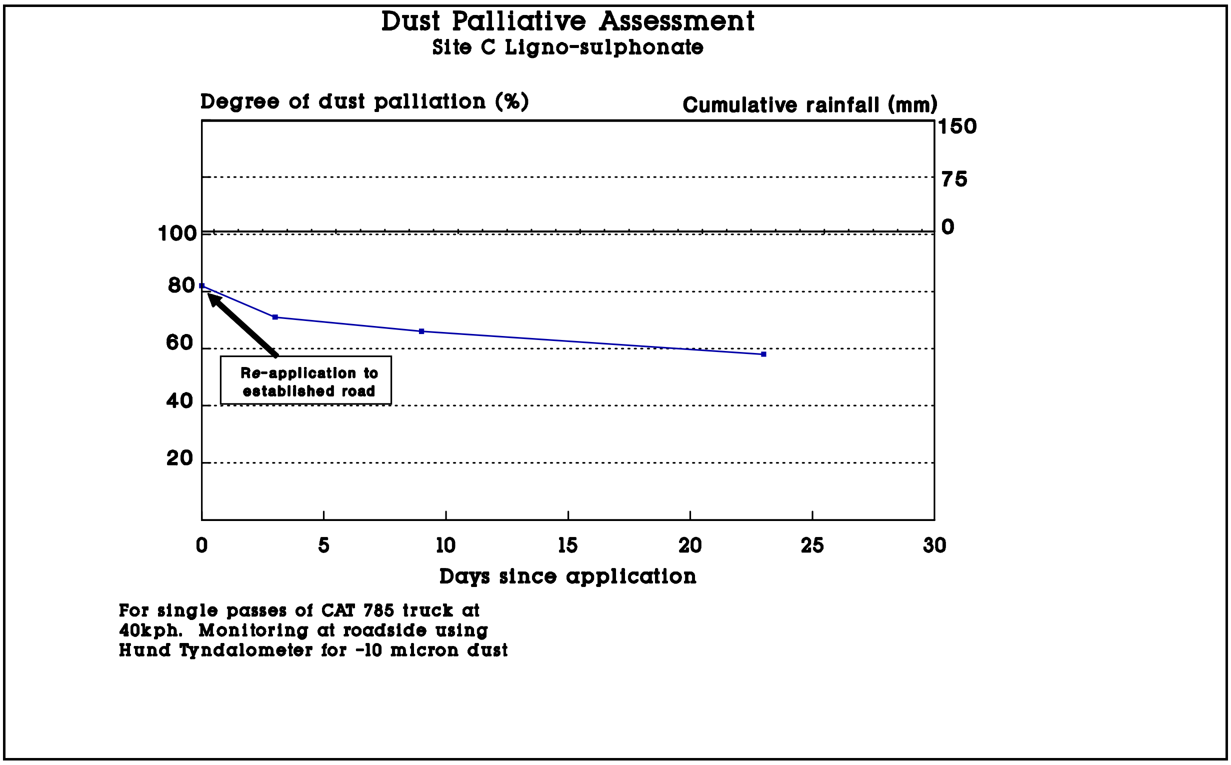
Table 5.3 Test site C palliative treatment details using ligno-sulphonates

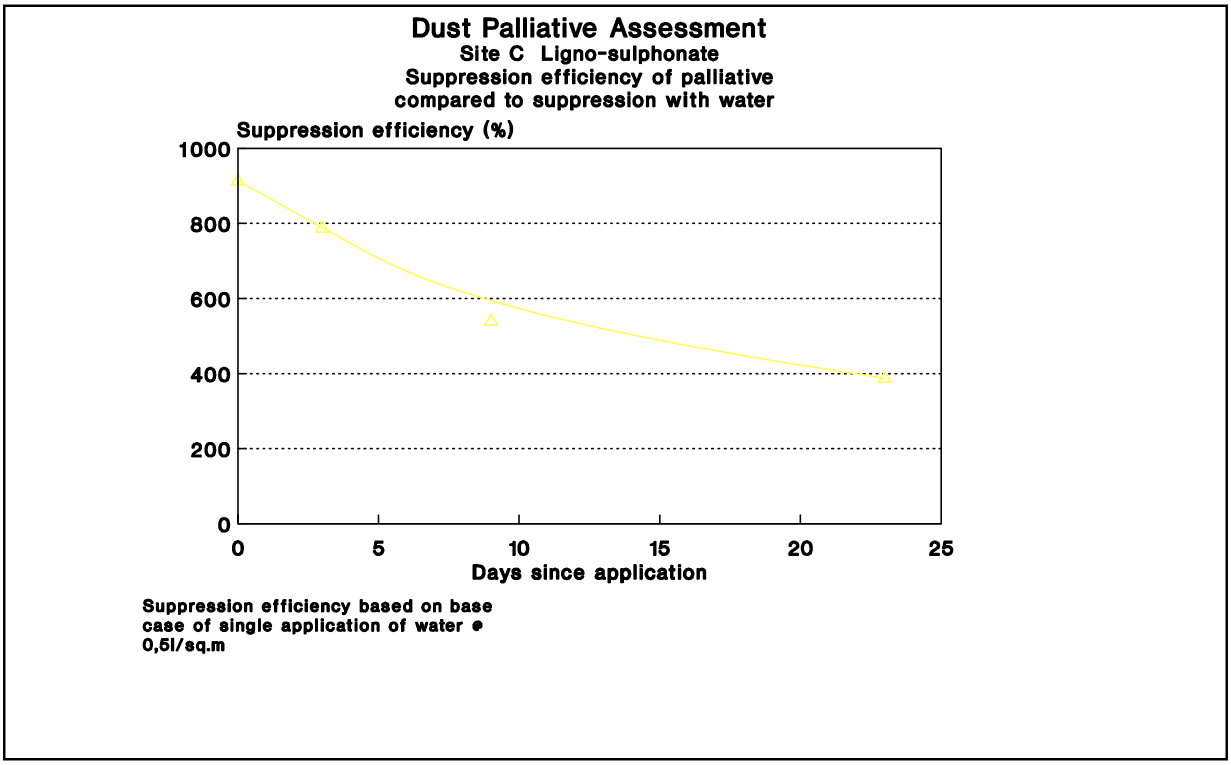
Treatment	Application rates
Establishment	Road already established with an estimated 3-4l/m^2 applied over the previous season.
Re-applications	Approximately bi-monthly spray-on re-applications were applied at 0,4l/m^2 over 2 passes at 3:1 dilution to give 0,2l/m^2 product applied (re-application interval dependant on dustiness and traffic).
Total product applied (l/m^2)	Unknown



The test section had been previously treated with an unknown amount of ligno-sulphonate (estimated total product supplied and applied equates to about 3-4l/m^2 over the previous season). It was also unclear as to how much product remained in the road from the last treatment. Considerable coal spillage was observed on the road in the vicinity of the test section and this was not removed prior to the re-application. During application it was noted that the spray-on re-application generated little depth of penetration into the wearing course with the result that run-off was considerable. The road was trafficked immediately after application.

The re-treatment resulted in an average degree of dust palliation of 70% over 23 working days or for 200kt hauled (equivalent to 1570 CAT785 truck laden repetitions over the test period), as shown in Figure 5.11. The degeneration seen over the 23 day test period was similar to that at site B, increased traffic volumes and coal spillage in the test section reducing slightly the initial peak value. Figure 5.12 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies maintained over the test period peak at approximately 900% and average approximately 650%.





Following application, it was noted that small potholes appeared as at site B, but these were no longer evident by day 3, spillage and loose material filling them. The spillage itself built-up on the road surface forming loose divots which later broke-up under the action of the haul trucks. This break-up created new untreated surface area and increased the dust emissions. Some loose material was seen on the road initially and this tended to increase with time, mixing with the spillage material. At the side of the road, initial spray-over reduced the dustiness recorded (especially with the bottom dump trucks), but latterly it was seen that considerable dust was generated from the now dry and exposed material at the side of the road, together with coal dust deposited from the traffic induced breakdown of road spillage, or from other local sources. The effect of palliative application on road functionality and roughness is shown in Figure 5.13. This data was gathered over the dry winter months and as such no rainfall effects were seen, as were with other sites. The functionality and roughness are therefore not directly comparable with the other sites analysed in this Chapter. Functionality also varied as a function of dustiness, reducing with the re-application of the palliative but degenerating at approximately the same rate thereafter. In this case, functionality was not so greatly improved as at site B. The predicted minimum functional defect score at day two was not evident during the analysis and, whilst no monitoring took place on that specific day, it is unlikely that the functionality further improved, due to the amount of spillage on the road which resulted in a poorer initial road surface. From day four the treated section began to show improvements in functionality over that of the untreated predicted performance, primarily as a result of reduced dustiness and loose material. Figure 5.13 confirms that the overall roughness of the road was little changed from the untreated estimate, although slightly rougher initially due to the small potholes and build-up of compacted spillage observed.

5.3.3 Site H1 Palliative Suppression Performance

Site H1 was evaluated over a period of 17 days from the initial spray-on application, encompassing predominantly dry weather in late summer. A single establishment spray-on treatment of a ligno-sulphonate was applied to the prepared road surface, followed by five lower dilution re-applications, as specified in Table 5.4.

The test site wearing course material was similar to that at site H2 and thus the base-case untreated dustiness readings are as shown in Figure 5.1. During application it was noted that the spray-on gave 15-20mm depth of penetration into the wearing course in most places.

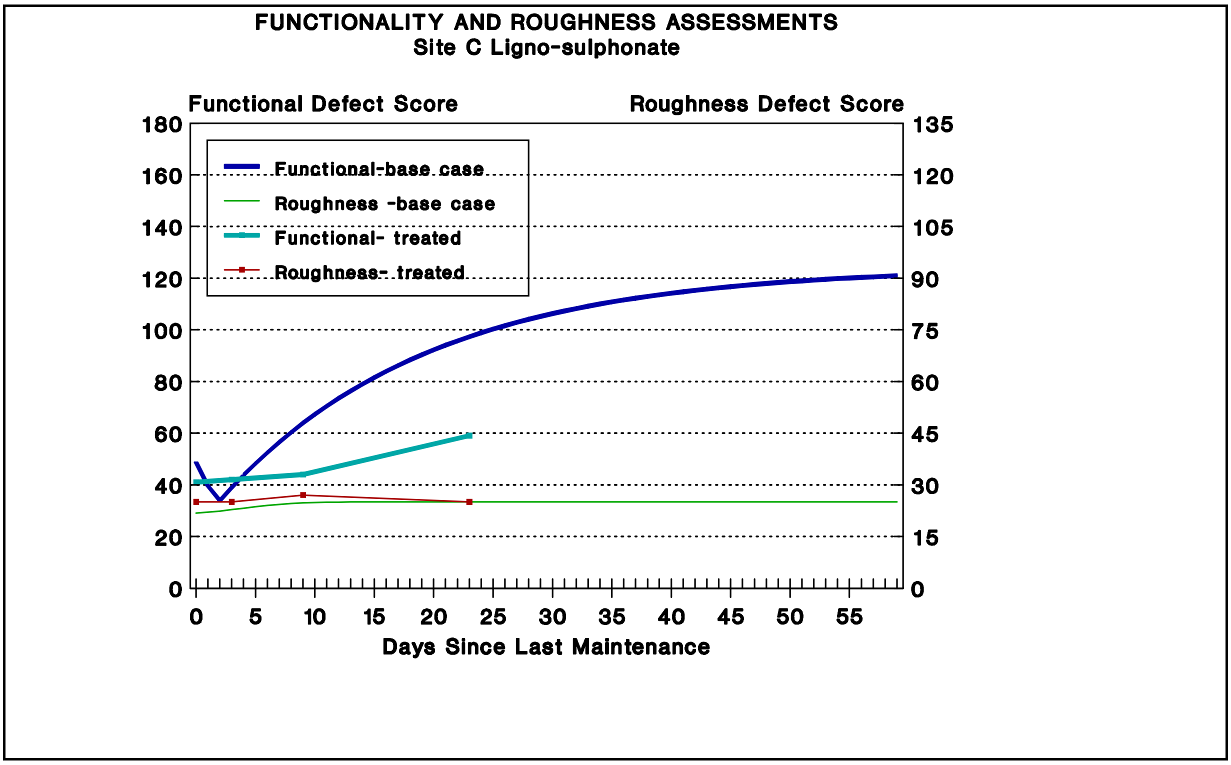


Table 5.4 Test site H1 palliative treatment details using ligno-sulphonates

Treatment	**Application rates**
Establishment	Road bladed, shaped and repaired prior to application. Spray-on application at 1,0l/m^2 over 3 passes of 2:1 dilution to give 1,0l/m^2 of product applied.
Re-applications	Approximately daily spray-on re-applications were applied at 0,5l/m^2 over 2 passes at 3:1 dilution depending on dustiness and traffic to further control dustiness. A total of 5 re-applications over 11 days.
Total product applied (l/m^2)	2,25

The CBR of the wearing course was between 52-68% (93%-95% Mod AASHTO), primarily as a result of the lower wheel loads allied by the small Bell trucks and the lack of proper compaction during construction. The road was trafficked immediately after application of the establishment and the re-treatments. Where excessive loose unbound material was left on the road after blading, this was sprayed over but quickly displaced by traffic, leading to the creation of new untreated surfaces on the road.

The treatment resulted in an average degree of dust palliation of 47% over 18 working days or for 13kt hauled (equivalent to 480 Bell B25/B30 laden repetitions over the test period - daily traffic volumes varied as a result of production requirements) as shown in Figure 5.14. The final application of palliative degenerated over 5 days from 88% to zero (equivalent to a rate of 17,6%/day) and this may have been influenced by heavy rain in the middle of the test period. Rainfall during the test period is shown cumulatively (days on which rain fell indicated by a bar) in Figure 5.14 from which it is seen that significant rainfalls were encountered on days 12-14 onwards which could have reduced the performance of the palliative, through a combination of fines and erosion on the road and possible leaching of the palliative from the road. As a result of a wet wearing course, the road had to be left to dry out before the final re-application. Throughout the test period it was noted that the road tended to generate small potholes or loose material immediately after application of the palliative and for the final 3 re-applications, penetration was poor and run-off and tracking-off on vehicle wheels excessive.

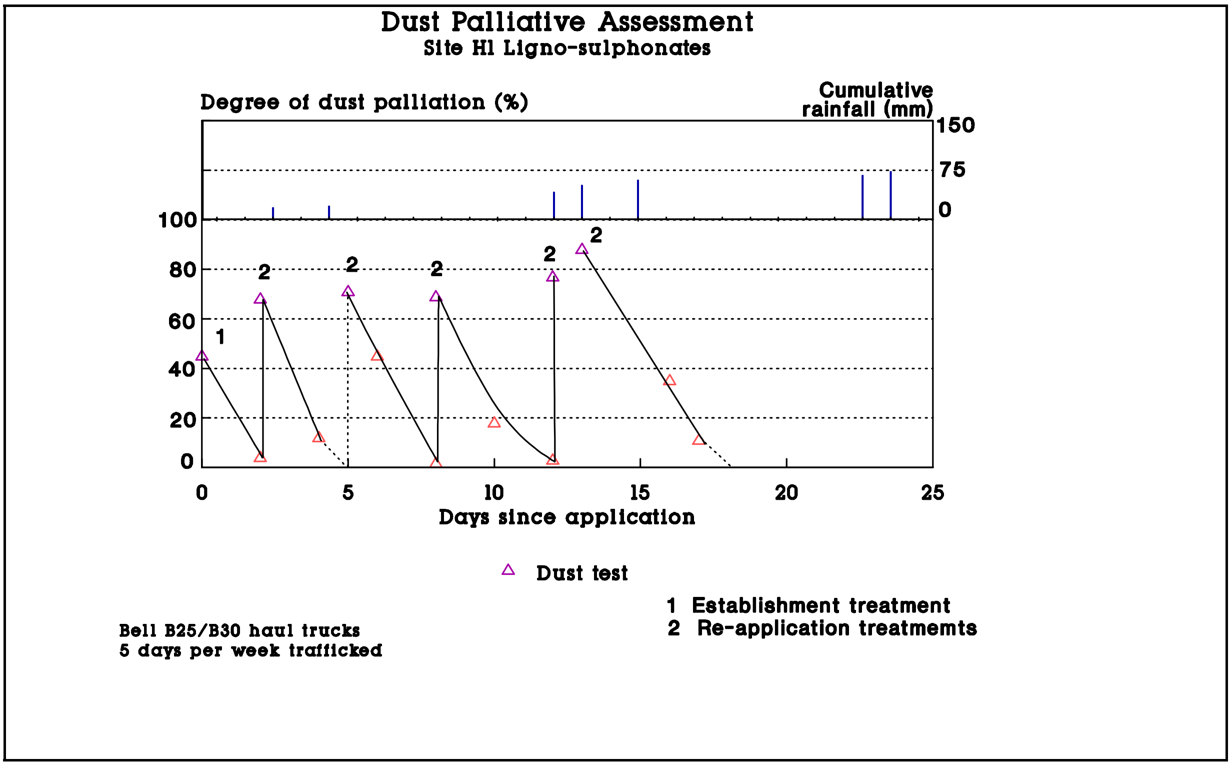
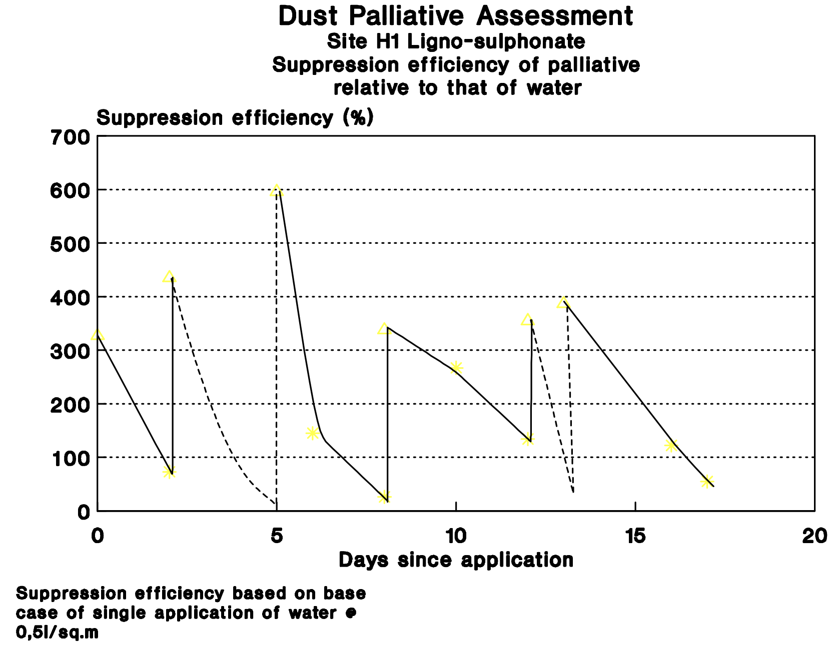


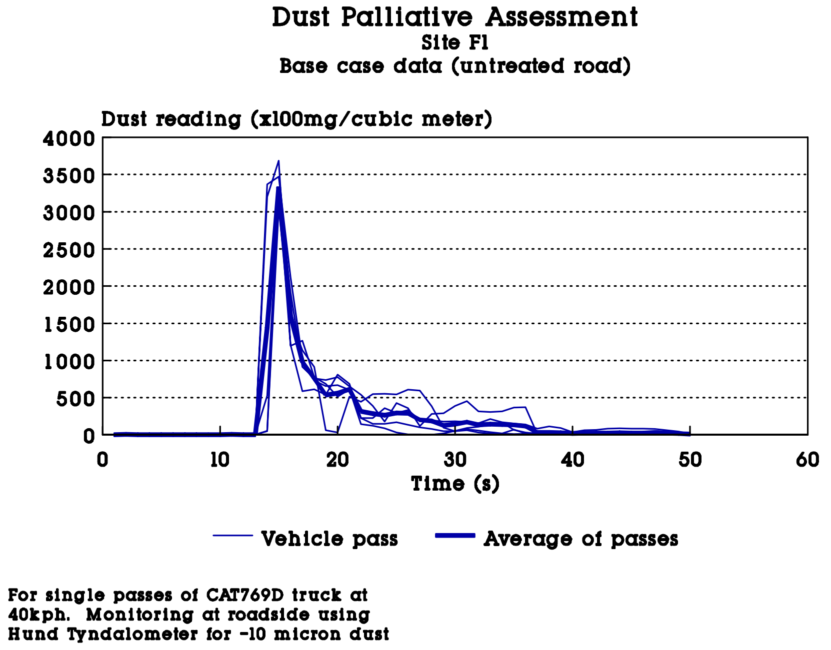
Figure 5.15 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies maintained over the test period peak at approximately 400% and average approximately 225%. Following the final application, the efficiency reduces from 400% to the water equivalent over a period of 4 days.



The effect of palliative application on road functionality and roughness is shown in Figure 5.16. Rainfall significantly reduced functionality and increased roughness during the test due to the combined effects of erosion and a poorly compacted wearing course. Functionality also varied as a function of dustiness, reducing with each re-application of the palliative, thereby offsetting the increase in degree and extent of the pothole and loose material defects, but degenerating at approximately the same rate thereafter. Figure 5.16 confirms that the overall roughness of the road was little changed from the untreated estimate, although slightly smoother due to the more regular blading of the road.

5.4 Evaluation of Petroleum Resins

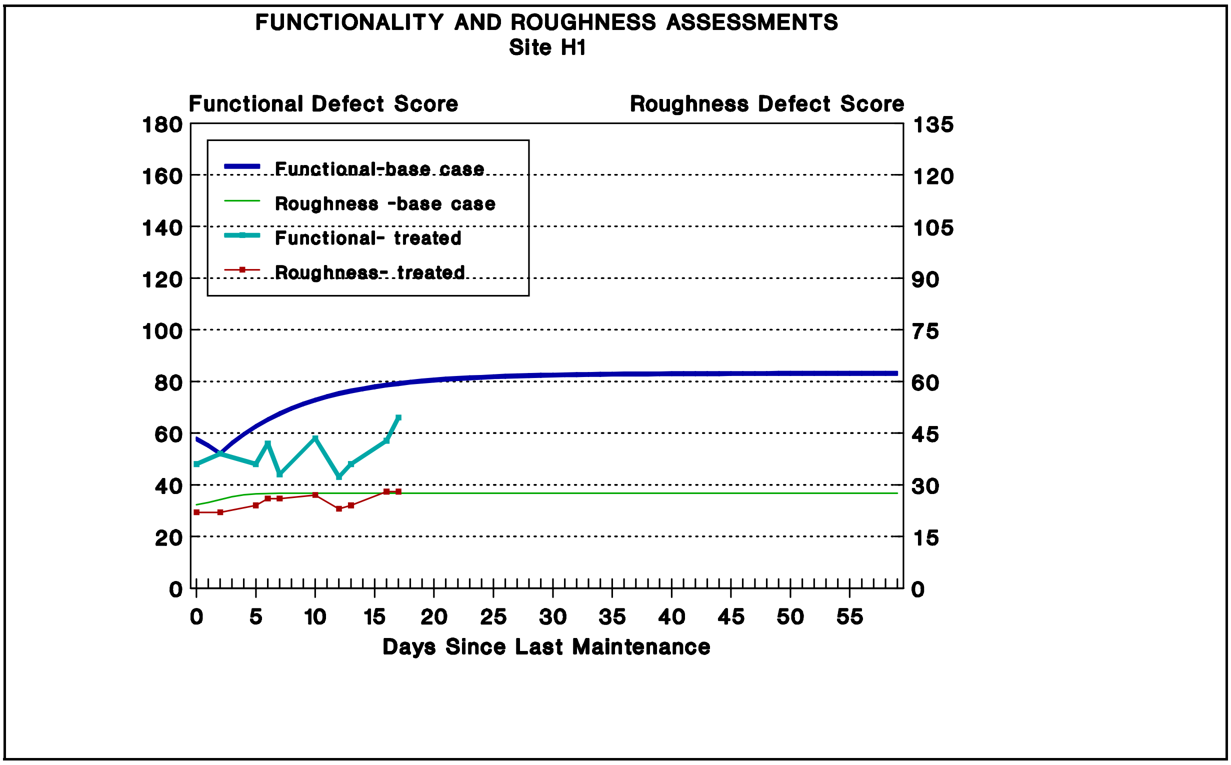
5.4.1 Site F1 Palliative Suppression Performance

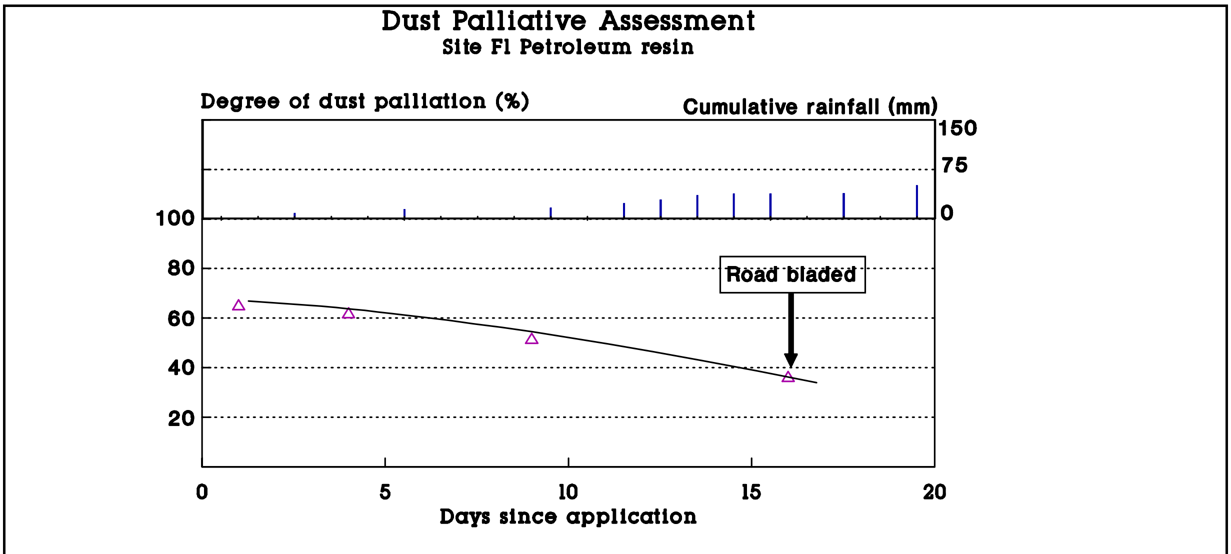


Site F1 was evaluated over a period of 16 days from initial application, encompassing initially dry weather up to day 6 of the assessment, followed by occasional heavy showers for the remainder of the period. A spray-on treatment of an emulsified petroleum resin was applied to the prepared road surface as specified in Table 5.5.

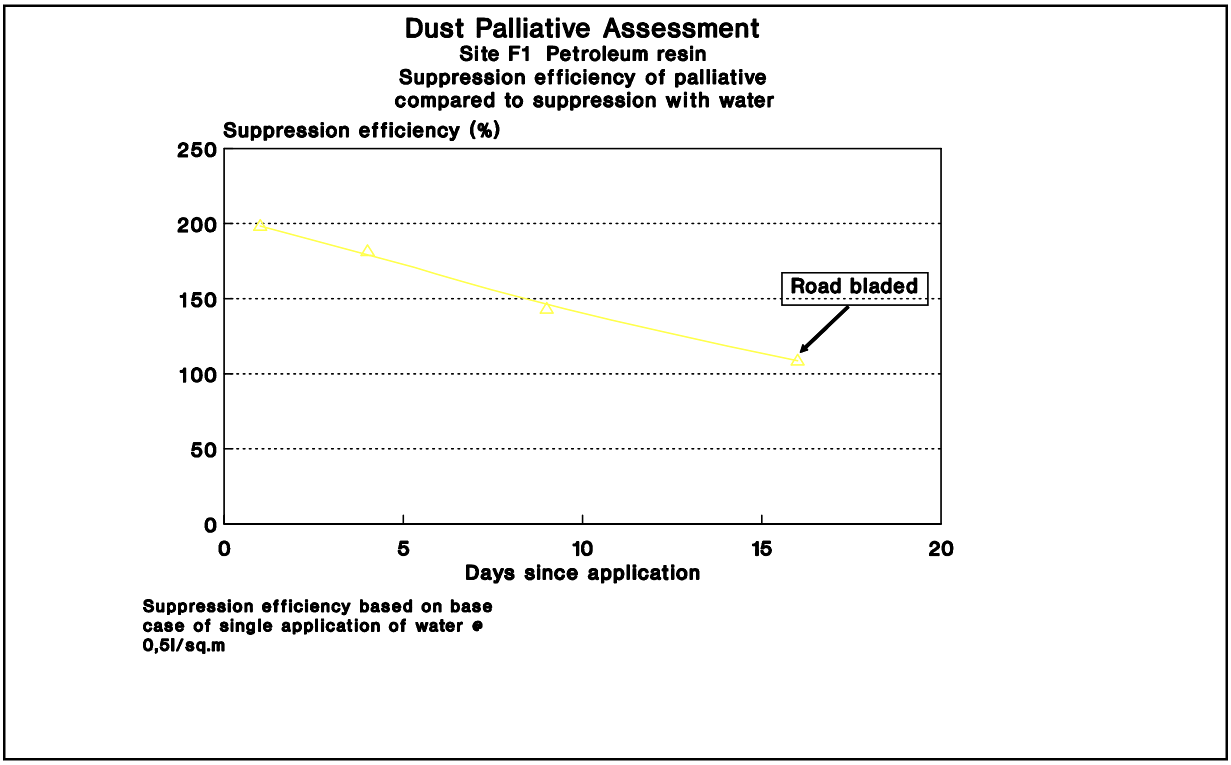
Table 5.5 Test site F1 palliative treatment details using a petroleum resin

Treatment	**Application rates**
Establishment	Road bladed prior to application. 4 daily spray-on applications of 0,78l/m^2 8:1 dilution over 2 days to give 0,7l/m^2 product applied.
Re-applications	None
Total product applied (l/m^2)	0,7





90% heavy haul trucks (CAT 769D)
5 days per week trafficked

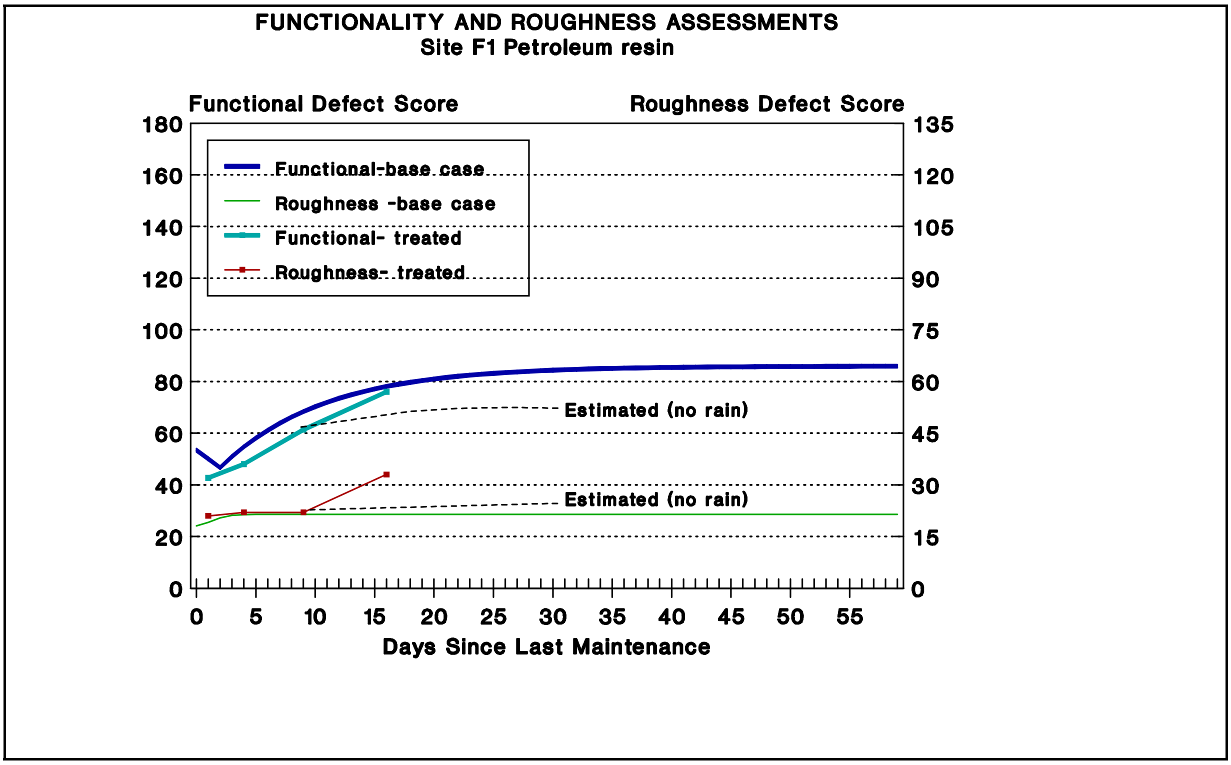


The base-case untreated dustiness readings are shown in Figure 5.17 from which it is seen that a peak dustiness concentration of approximately 30mg/m^3 was measured for each pass of a CAT 769D at 40 km/h. Following application of the palliative, the degree of dust palliation achieved was initially over 60% and this value decayed to 38% after 16 days, the degeneration rate being 1,6%/day as shown in Figure 5.18. The treatment resulted in an average degree of dust palliation of 52% over 16 working days or for 82 000t hauled (equivalent to 2330 CAT 769D laden repetitions). Figure 5.19 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2.

During application it was noted that the wearing course soon reached saturation and run-off of palliative occurred, despite the road being bladed prior to application. This may be attributed in part to the compactive effort of the trucks on this section of the road and the high CBR values encountered (95%) in the upper portion of the wearing course. This resulted in rapid removal of the surface application, especially in the wheel tracks and on bends, where higher horizontal shear forces at the wearing course/tyre interface were evident. Little penetration of the product into the wearing course beyond 3-5mm depth was achieved, except when sprayed over loose material. Trafficking over loose material however, quickly created new untreated surfaces. Nevertheless, some palliation was achieved over the longer term, primarily as a result of undamaged sections between wheel tracks, and spray-over into the centre and edges of the road, which resulted in significantly less dust being generated by truck-induced turbulence from these areas.

The rain encountered from day 6 was seen to cause a significant increase in dustiness, primarily as a result of loose material washing onto the road, severe cross erosion as a result of inadequate side drainage and removal of some of the treated surface material. Since trafficablility was adversely effected, the road was bladed on day 16 which resulted in destruction of the treated surface and dustiness readings reverting to approximately 80% of the base-case values shown in Figure 5.19. This may be indicative of some residual action of the palliative in the wearing course material.

The effect of palliative application on road functionality and roughness is shown in Figure 5.20 which echoes the finding that rainfall, especially on a badly prepared road, significantly reduces functionality and increases roughness. In this particular case, blading of the road was undertaken on day 16 due to the combined effects of traffic volumes and rain, but, without the effects of rain, it is estimated that the maintenance interval could have been extended to at least 20 days. Once the palliative effect had been destroyed, especially in the wheel tracks, the amount of loose material and ravelling increased significantly. However, where the road was not trafficked, this effect was much reduced in degree and extent.



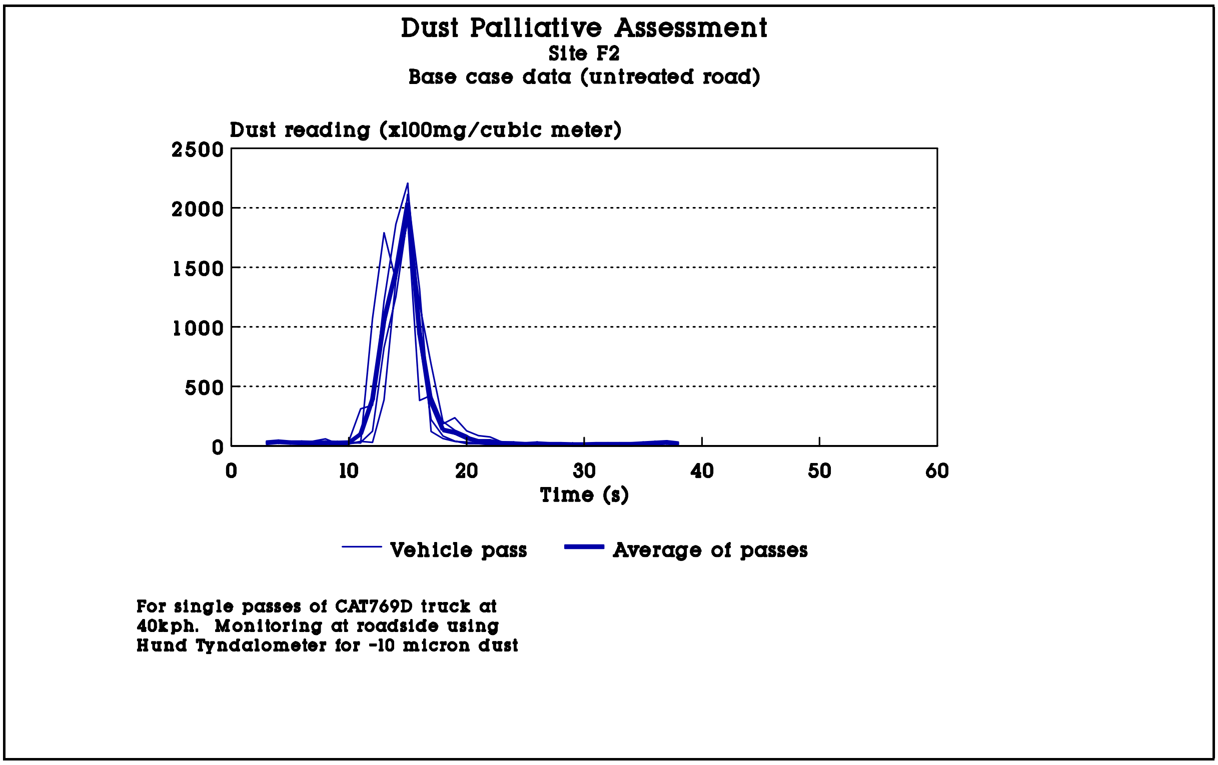
5.4.2 Site F2 Palliative Suppression Performance

Site F2 was evaluated over a period of 30 days from initial application, encompassing initially dry weather up to day 10 of the assessment, followed by occasional heavy showers for the remainder of the period. A spray-on treatment of an emulsified petroleum resin was applied to the prepared road surface as specified in Table 5.6.

Table 5.6 Test site F2 palliative treatment details using petroleum resins

Treatment	Application rates
Establishment	Road bladed prior to application. 2 daily spray-on application of 0,5l/m^2 4:1 dilution over 6 days to give 1,2l/m^2 product applied.
Re-applications	1 weekly spray-on application of 0,5l/m^2 8:1 dilution for 2 weeks only to give 0,11l/m^2 product applied
Total product applied (l/m^2)	1,31

The base-case untreated dustiness readings are shown in Figure 5.21 from which it is seen that a peak dustiness concentration of approximately 20mg/m^3 was measured for each pass of a CAT 769D at 40 km/h. Following application of the palliative, the degree of dust palliation achieved was initially over 80% and this value decayed to zero after 20 days. The rain encountered from day 11 was seen to cause a significant increase in dustiness, primarily as a result of loose material washing onto the road and severe cross erosion as a result of inadequate side drainage. Since trafficablility was adversely affected, the road was bladed on day 17 prior to the first of two 8:1 rejuvenation applications on day 20. This action implies that the use of dust palliatives may be more justifiable over the winter months only, when, in addition to drier roads, the lack of heavy showers will not necessitate frequent blading (on those roads carrying low traffic volumes). On roads carrying higher volumes, more frequent blading will be necessary due the functionality and roughness defect progression and thus the palliative should ideally be matched (performance-wise) to this blading frequency.



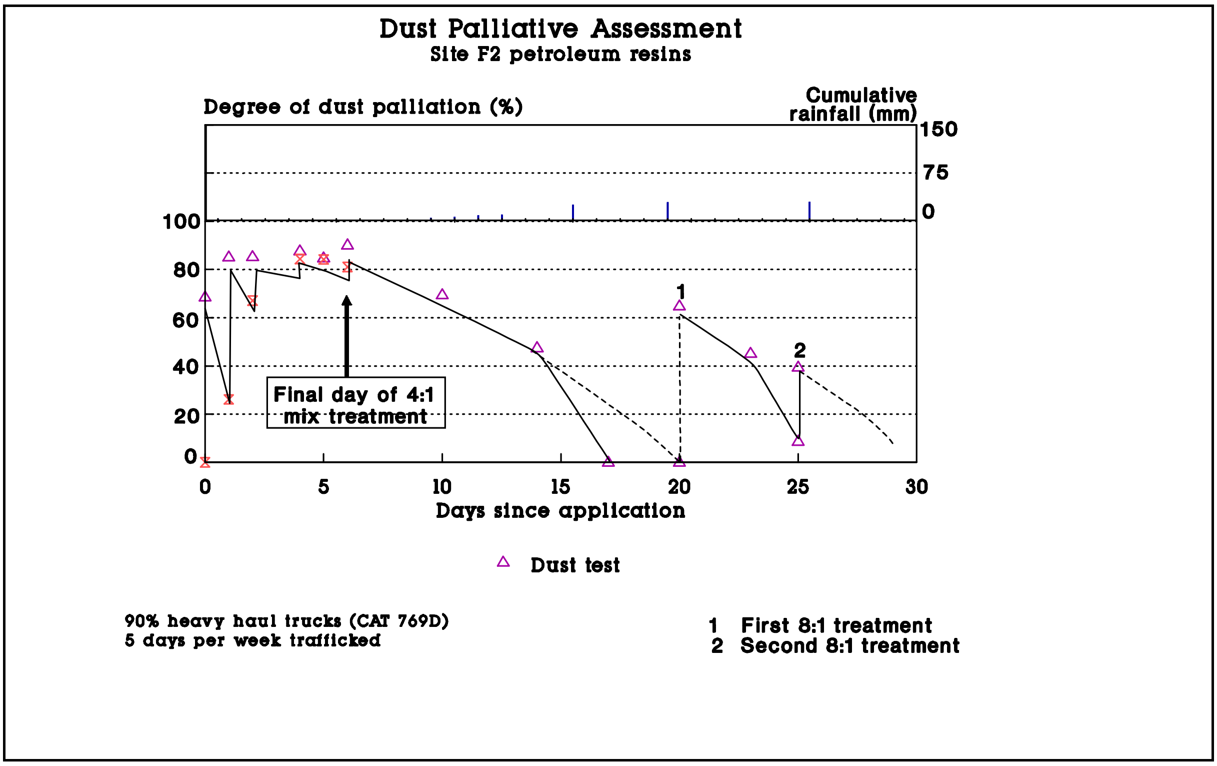
Dust Palliative Assessment
Site F2
Base case data (untreated road)

For single passes of CAT769D truck at 40kph. Monitoring at roadside using Hund Tyndalometer for -10 micron dust

The initial 4:1 treatment resulted in an average degree of dust palliation of 62% over 20 working days (1 calender month) or for 57 000t hauled (equivalent to 1620 CAT 769D laden repetitions), equating to a degradation rate of 4,5%/day as seen in Figure 5.22. With regard to the 6 initial 4:1 mix applications, it would appear that little immediate benefit was gained from the last three of these applications since the increase in the degree of palliation was only 5% and the readings

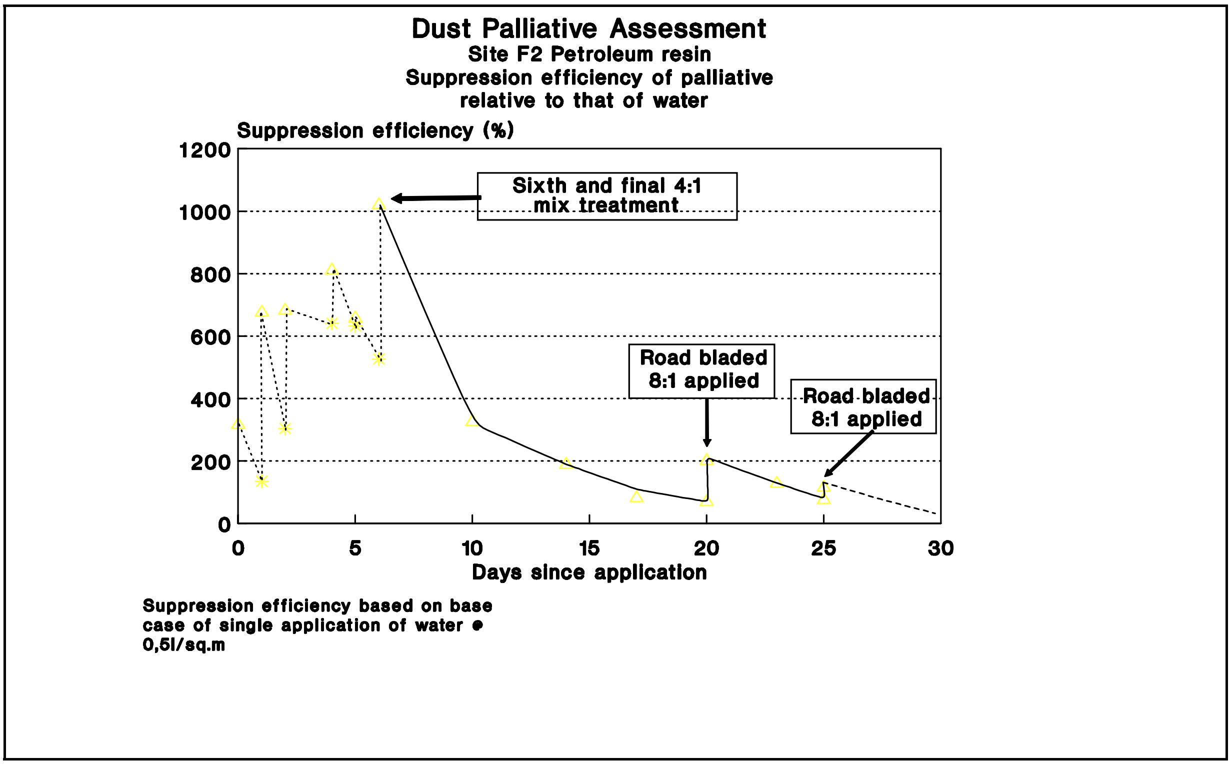
taken prior to each of these last three applications exhibited only marginal (1,5-4%) decreases in control, even when the road was heavily trafficked. Although it may be possible thus to dispense with the last three applications and thus apply only 0,61l/m^2, the long term deterioration profile of the 4:1 mix may not be similar.

Rejuvenation with the 8:1 mix resulted in an increase in the degree of dust palliation to 64%, but the rate of degeneration was greater than that of the 4:1 mix (10,8%/day), falling to 10% palliation over 5 working shifts (approximately 2000t hauled). A similar trend for the second 8:1 rejuvenation was assumed, since no monitoring could be undertaken due to a combination of no traffic on the road and rain. The fact that the second 8:1 rejuvenation did not restore the degree of dust palliation to its original value (only 40% compared with 62%) suggests that the 8:1 rejuvenation alone was not effective in reducing dust emissions over the long term. Figure 5.23 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2.



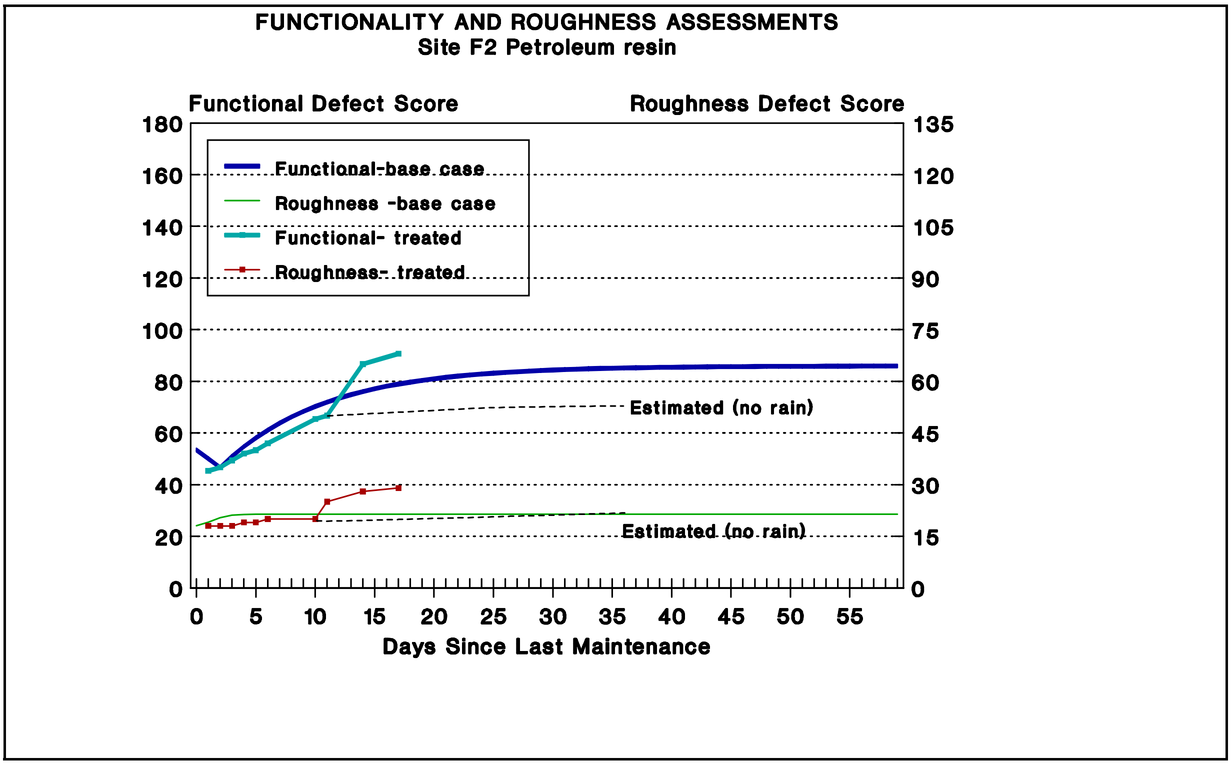
The rain on the road provided an opportunity of comparing the trafficability of the treated road with that of an untreated section and in general it was seen that the untreated section exhibited more churning and did not drain as rapidly as the treated section. However, the potholes on the treated section were rapidly enlarged as a result of the rain and blading of the road was thus necessary prior to rejuvenation. The effect of palliative application on road functionality and roughness is shown in Figure 5.24 which echoes the finding that rainfall, especially on a badly prepared road, significantly reduces functionality and increases roughness. In this particular case, blading of the road was undertaken on day 11 due to rain, but, without the effects of rain, it is estimated that the maintenance interval could have been extended to 20 days.

Gravimetric air sampling was conducted as described in Chapter 3 to establish the base case (untreated) dustiness in terms of dust generated per vehicle pass, and the threshold limit values (TLV) and air quality index (AQI) for both total and respirable fractions. The procedure was repeated on the test section 10 days after treatment commenced. From the results presented Table 5.7 it was seen that the 5,2 g total dust per vehicle pass represents a 78% reduction and the 4,2 g respirable fraction a 64% reduction, compared to the base-case (untreated) values. In terms of the resulting air quality index, a significant reduction (from 0,21 to 0,04 total and 0,1 to 0,03 respirable) was seen. The mass of dust per vehicle pass cannot be directly compared to the data generated with the Hund Tyndalometer since the sampling methodologies adopted were dissimilar and the manageability of the gravimetric tests (in terms of vehicular traffic on



Dust Palliative Assessment
Site F2 Petroleum resin
Suppression efficiency of palliative
relative to that of water

Suppression efficiency based on base case of single application of water @ 0,5l/sq.m



FUNCTIONALITY AND ROUGHNESS ASSESSMENTS
Site F2 Petroleum resin

the road, speed and weather conditions) was problematic. However, the degree of dust palliation of approximately 70% at day 10 can be compared to the percentage reduction in respirable dust sampled (64%), since the particle size measured is comparable. The sampling methodology used in gravimetric analysis was found to be inappropriate to the type of data required for a reliable assessment of reductions in dustiness. Since the degree of dust palliation was calculated on a percentage basis from the Tyndalometer data, little further benefit was gained by confirming the data using the time and labour intensive Gil air pump gravimetric samplers, thus no further tests were conducted.

Table 5.7 Gravimetric dust sampling results average dust generated per vehicle pass, site F2

Dust Filter Number[1]	**Treatment details site F2**	**Average dust per Vehicle pass[2] mg**	**AQI[3]**	**Percentage reduction from base case %**
M508T 27/1/98	Base case	0,0243	0,21	
M504R 27/1/98	Base case	0,0118	0,10	
M558T 12/2/98	Treatment +10 days	0,0052	0,04	79
M557R 12/2/98	Treatment +10 days	0,0042	0,03	64

Notes

1. Tested for either total (T) or respirable (R) fractions
2. 57 vehicle passes at approx 40km/h, 82% CAT769D, remainder light vehicles
3. Calculated as set out in Chapter 6

5.5 Evaluation of Polymer Emulsions

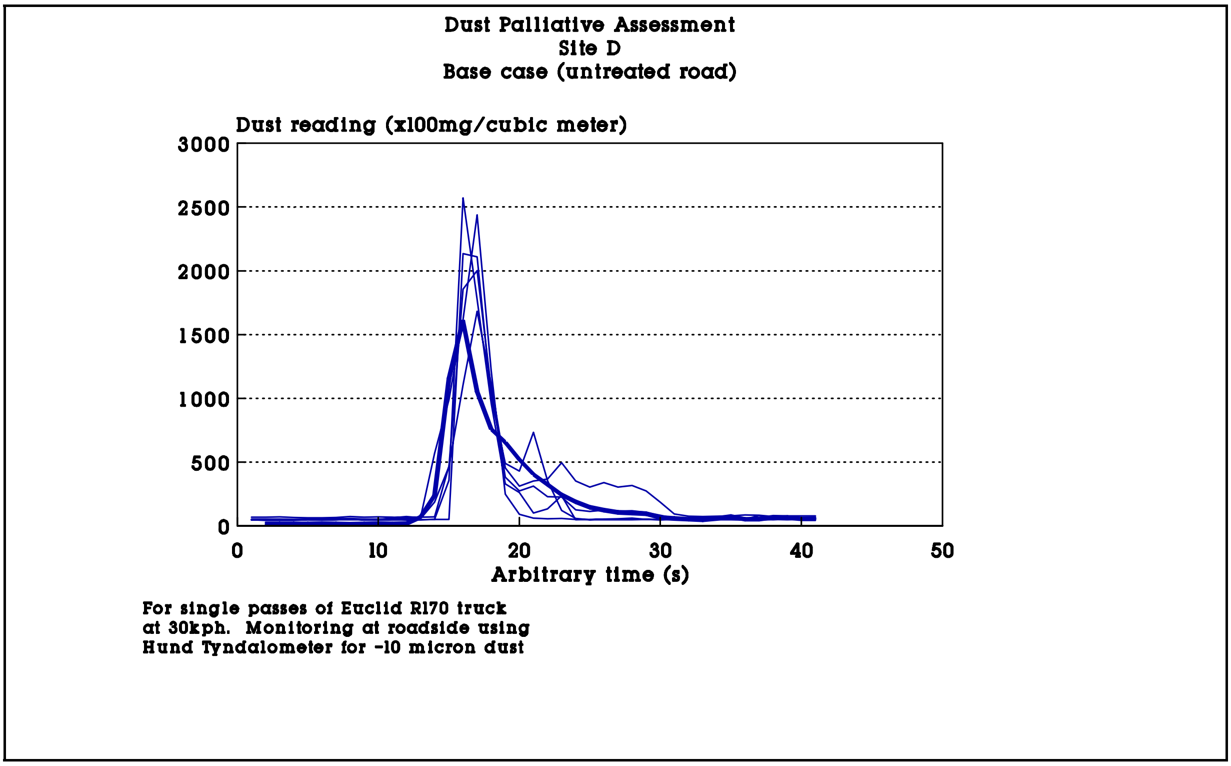
5.5.1 Site D Palliative Suppression Performance

Site D was evaluated over a period of 67 days from the initial establishment mix-in application, including six re-application spray-on mixes of a waterproofing polymer, as specified in Table 5.8. The analysis was conducted over the dry winter months and rainfall was limited to the last 10 days of monitoring.

The base-case untreated dustiness readings are as shown in Figure 5.25 for a number of vehicle passes and the average value, showing a peak of approximately 16mg/m^3.

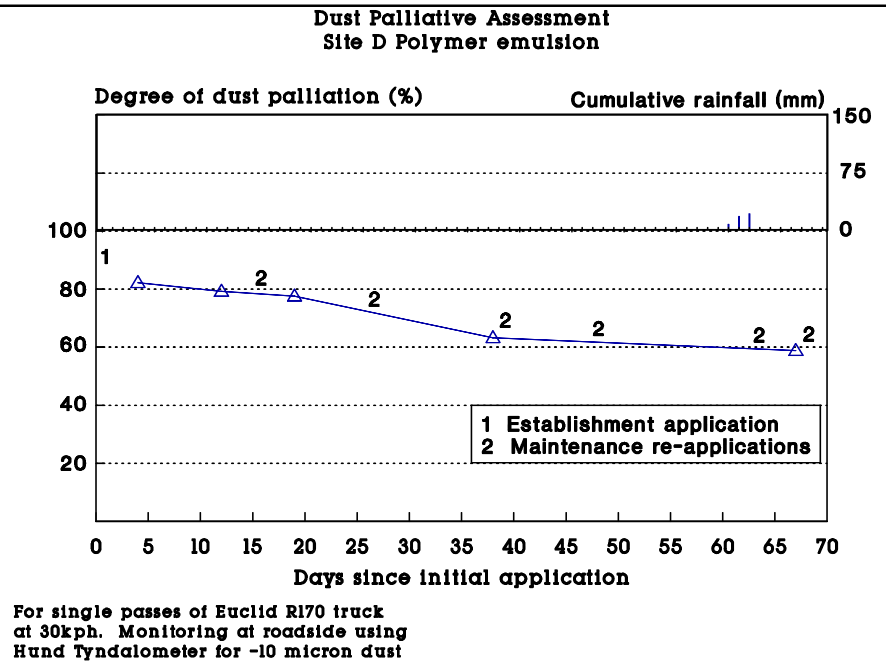
Table 5.8 Test site D palliative treatment details using polymer emulsions

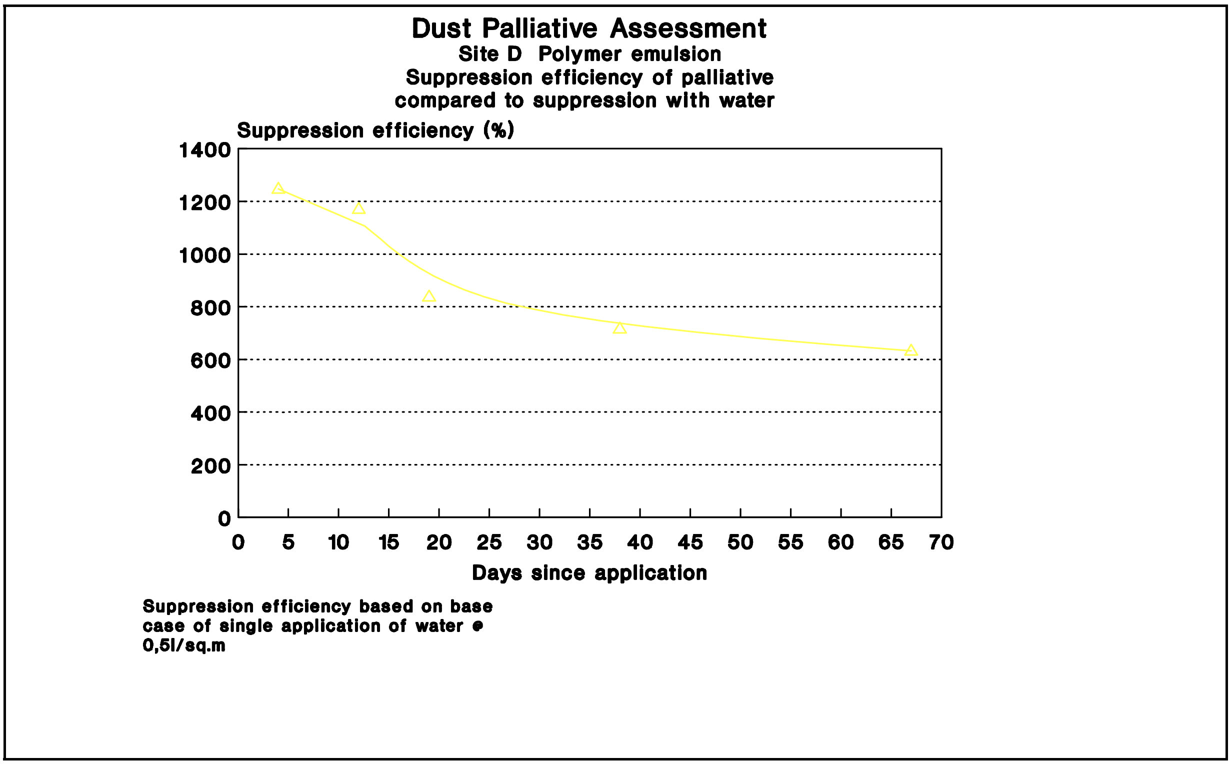
Treatment	Application rates
Establishment	Road ripped and scarified to a depth of 100mm prior to an establishment mix-in application at 0,5l/m^2 of a 16:1 dilution applied over 24 passes. Road shaped and compacted prior to final spray-on application over 8 passes at 0,5l/m^2 16:1 mix, to give a total of 0,95l/m^2 product applied.
Re-applications	Approximately monthly spray-on re-applications were applied at 0,5l/m^2 over 2 passes at 200:1 dilution to give 0,005l/m^2 product applied (re-application interval dependant on dustiness and traffic).
Total product applied (l/m^2)	1,0l/m^2 polymer emulsion and 0,3l/m^2 polymer spray-on re-application


Dust Palliative Assessment
Site D
Base case (untreated road)

For single passes of Euclid R170 truck at 30kph. Monitoring at roadside using Hund Tyndalometer for -10 micron dust

The test section was established with a mix-in application of 0,75l/m^2 over two working days, following which 0,2l/m^2 was applied as a surface wash following recompaction and shaping. The road was cured for 24 hours prior to resumption of trafficking on the fifth day. A peak degree of palliation of 82% was achieved on day five, following which palliation reduced progressively to 58% on day 67, giving an average degree of dust palliation of 70% over 58 working days, equivalent to a degeneration rate of 0,4%/day (four days untrafficked at start and five day no traffic from day 29-33). The traffic volume over the period equates to 2000kt hauled (equivalent to 15 400 truck laden repetitions over the test period), as shown in Figure 5.26. The degeneration seen over the 67 day test period was approximately 0,4% per day, although over the period non-traffic period slightly more degradation was seen, possibly as a result of loose material being blown onto the road from the road side. Rain in the last week of monitoring did not significantly effect the degree of dust palliation achieved. Figure 5.27 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies maintained over the test period peak at approximately 1250% and average approximately 940%. These calculations include the effect of re-applications of the polymer at intervals identified in Figure 5.26.



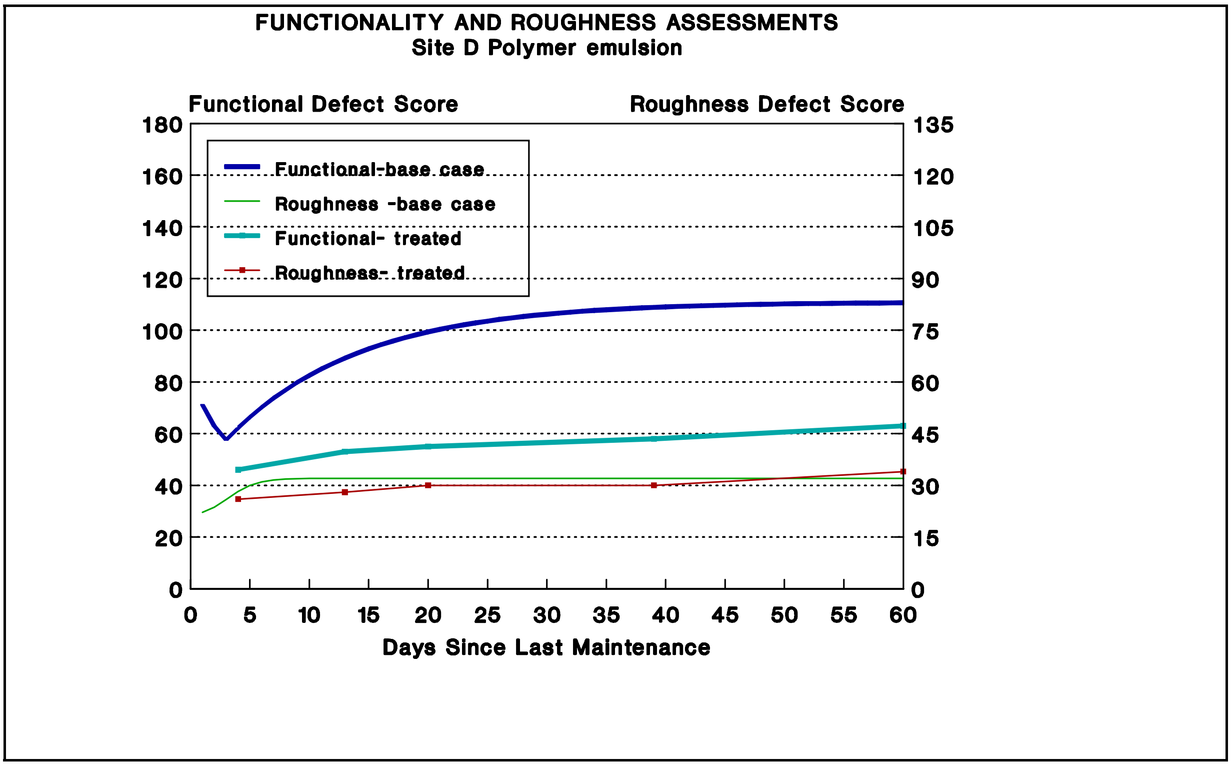


Small potholes appeared on day 19 which appeared to be associated with the re-application of the spray-on polymer and the immediate trafficking thereafter. Although the re-application reduced loose material on the road, it tended to adhere to truck tyres and small sections of wearing course were plucked-out and redeposited on the road. Although no untreated surface area was created, it led to a reduction in functionality and an increase in road roughness. Further re-applications did not resolve the potholing problem. Some loose material was seen on the road initially and this tended to increase with time, mixing with the spillage material. At the side of the road there was no initial spray-over (due to the mix-in application) and some dust was generated from this area by vehicle induced turbulence. The effect of palliative application on road functionality and roughness is shown in Figure 5.28 from which it is seen that, despite these defects, functionality is considerably improved. Roughness is comparable to the untreated wearing course except for the latter half of the test period where pothole material generated a higher roughness extent score. This data was gathered over the dry winter months and as such the only rainfall was from day 61. This was a small amount of rain and it did not generate any noticeable deterioration or trafficability problems, but may have exacerbated the small potholing previously seen.

5.6 Evaluation of Tar and Bitumens

5.6.1 Site A Palliative Suppression Performance

Site A was evaluated over a period of 105 days from initial establishment application, encompassing predominantly dry weather in early winter. A mix-in establishment treatment of a bituminous emulsion was applied to the prepared road surface as specified in Table 5.9.

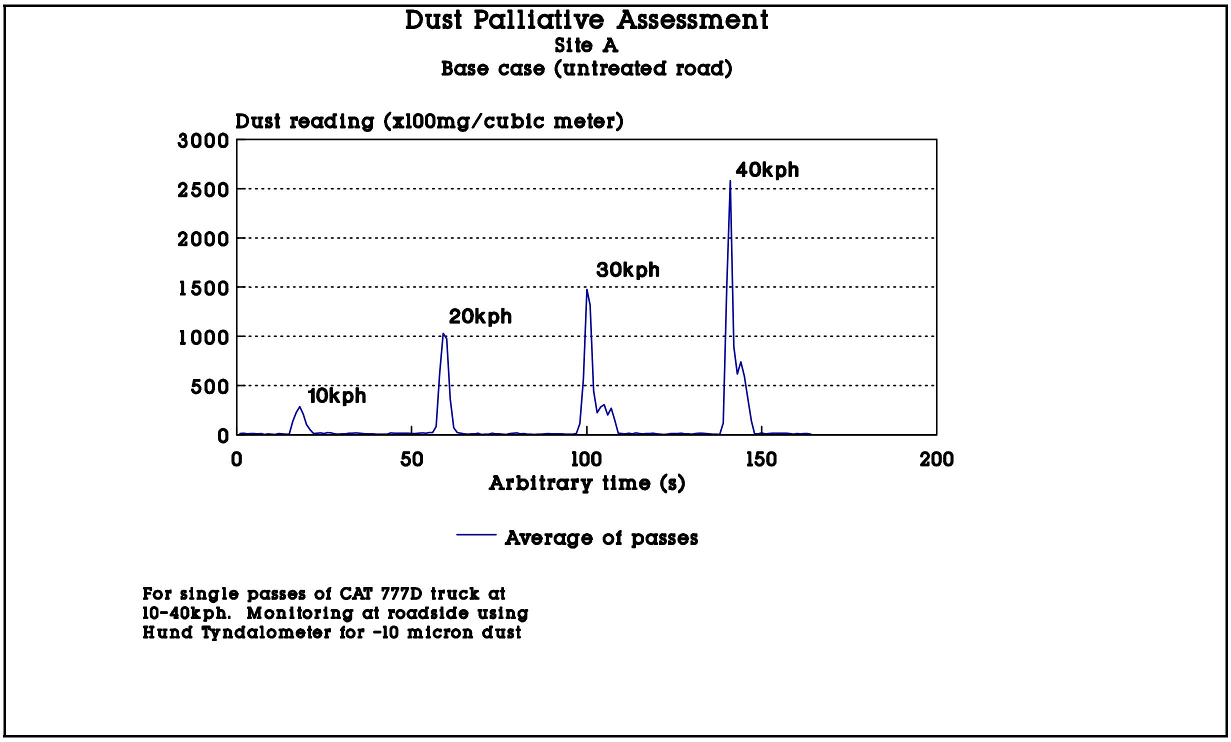


The base-case untreated dustiness readings are shown in Figure 5.29 from which it is seen that a peak dustiness concentration of approximately 25mg/m^3 was measured for each pass of a CAT 777D at 40 km/h, reducing to 3mg/m^3 at 10 km/h. Following application of the palliative, the degree of dust palliation achieved was initially over 70% and this value increased to 88% after the first maintenance re-application, as shown in Figure 5.30.

Table 5.9 Test site A palliative treatment details using tar/bitumens

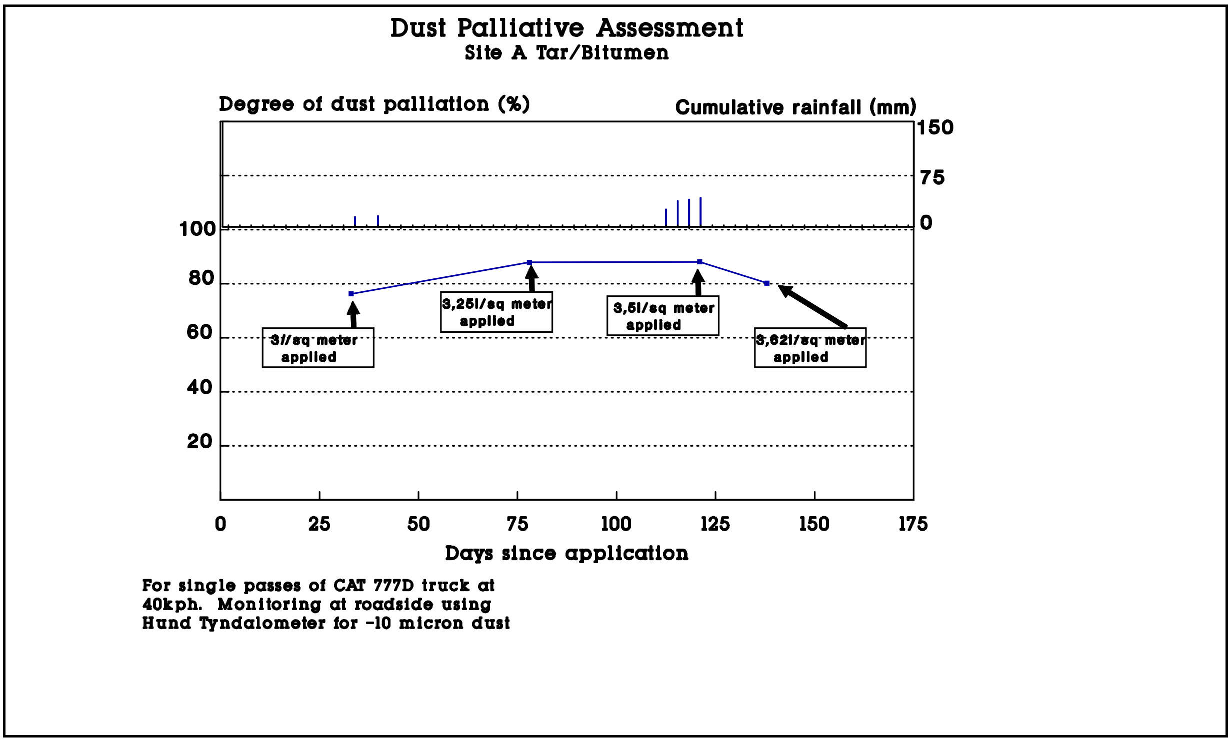
Treatment	**Application rates**
Establishment	Road bladed, shaped and repaired/rehabilitated prior to application. Mix-in applications of 0,5l/m^2 of various dilutions of product (20-25%) and cement (depending on wearing course characteristics and optimum moisture content) to give 3,0l/m^2 product applied.
Re-applications	Bi-monthly spray-on re-application of a 5% dilution (19:1) to give 3,0l/m^2 additional treatment over one year
Total product applied (l/m^2) (one year)	6,0

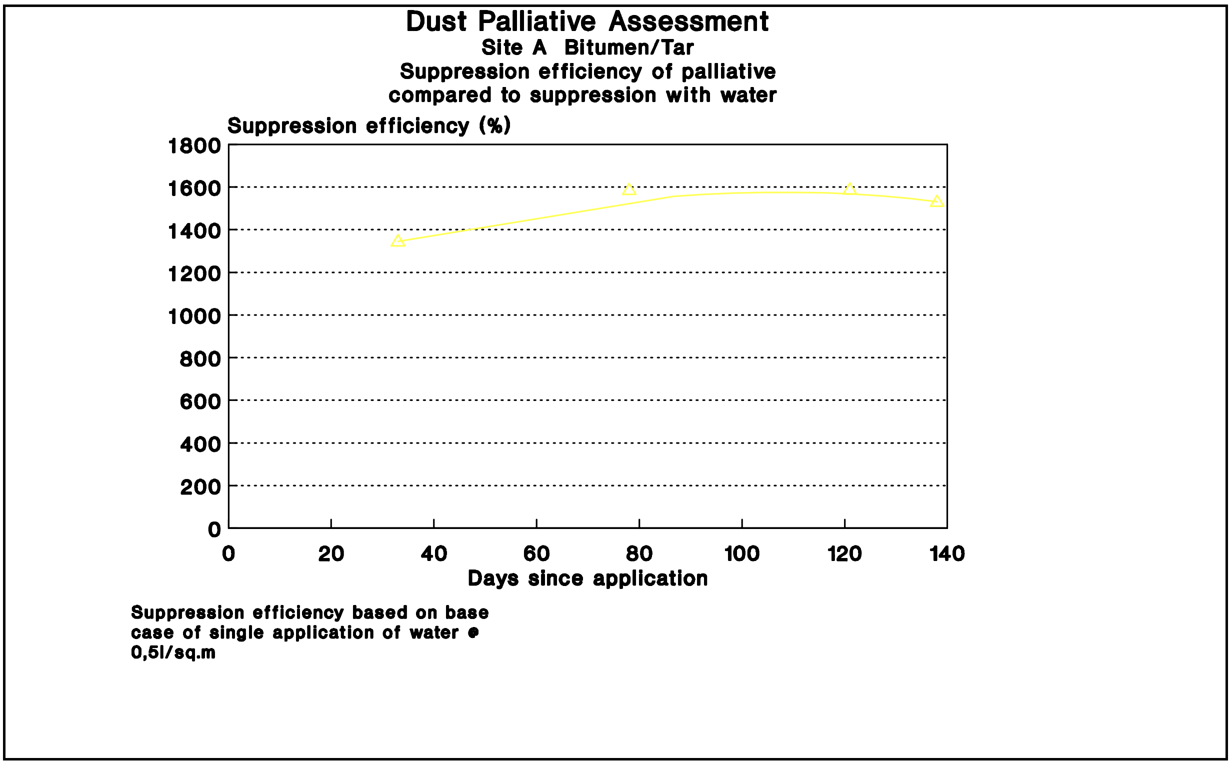
During application it was noted that with the mix-in approach gave good penetration and depth of treatment was over 250mm in most places. Establishment involved extensive rehabilitation of the road wearing course, geometry and drainage at the side of the road, together with recompaction of the ripped and scarified wearing course. A high degree of dust palliation was achieved initially with only small sections of road ravelling and generating new untreated surfaces. The first maintenance application effectively repaired these areas and the degree of palliation increased. Localised spillage on the road (coal fines mostly) and damage caused by tracked dozers was the main source of uncontrolled dust generation following treatment.



The rain encountered during the test period caused no marked reduction in trafficability and only a slight reduction in the degree of palliation achieved, primarily as a result of the establishment of adequate drains at the roadside and maintenance of a suitable road prism. Some spillage on the road was noted, probably derived from material adhering to the truck tyres.

The treatment resulted in an average degree of dust palliation of 75% over 86 working days or for 290kt hauled (equivalent to 3520 CAT 777 laden repetitions over the test period - daily traffic varied as a result of the ramp producing no coal at times). Figure 5.31 illustrates the suppression efficiency achieved relative to a single application of water, using the methodology described in Chapter 4.2, from which it is seen that efficiencies of over 1700% are achieved, primarily as a

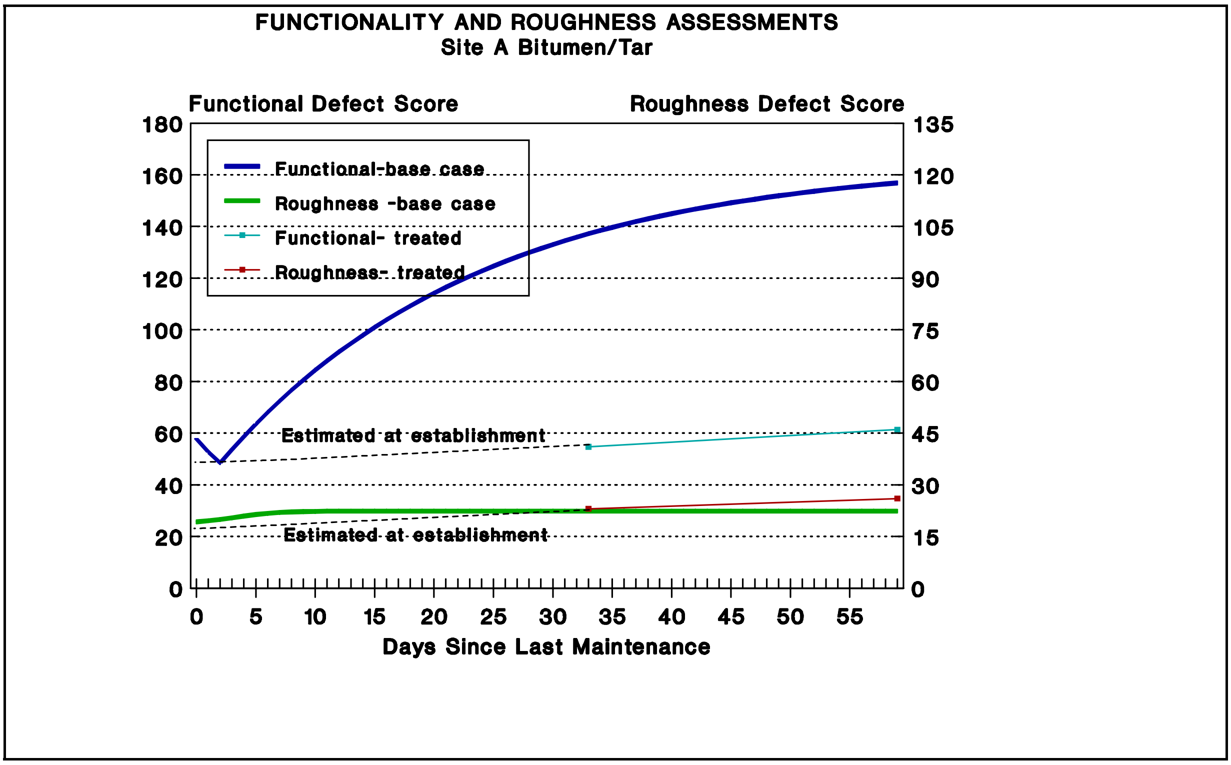




result of the inherent dustiness of the wearing course material in its untreated state.

The effect of palliative application on road functionality and roughness is shown in Figure 5.32.

Rainfall did not significantly reduce functionality or increase roughness and the results emphasise the importance of applying a palliative to a well prepared road. Maintenance activities associated with the use of the palliative included bi-monthly scarifying or blading, depending on the condition of the road. Figure 5.32 confirms that the overall functionality and roughness of the road were considerably improved. This may to some extent be a reflection of the significantly different characteristics of the wearing course following treatment which, with the addition of cement, is akin to stabilisation (strengthening) and palliation.



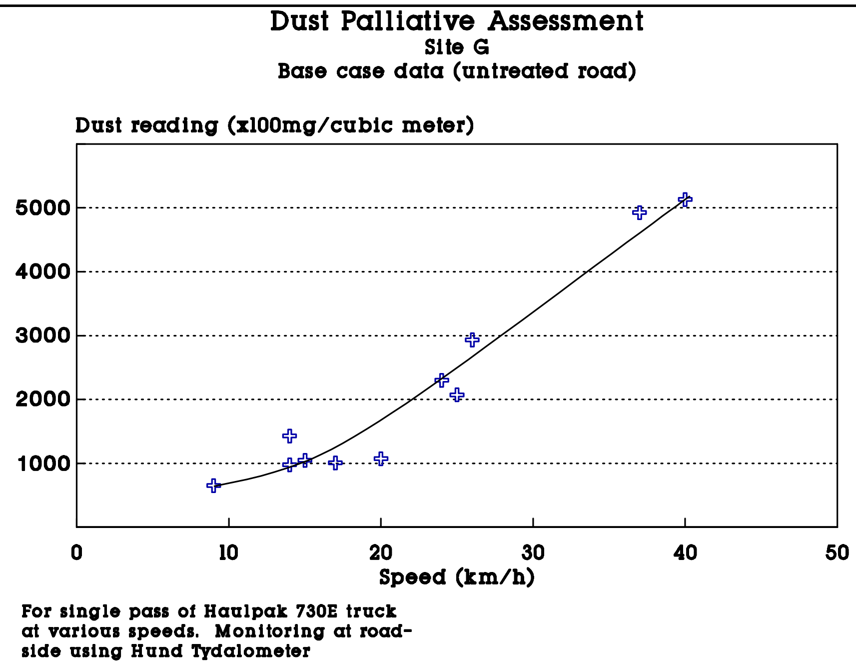
5.6.2 Site G Palliative Suppression Performance

Site G was evaluated over a period of 76 days from initial establishment application, encompassing predominantly dry weather in late winter. A mix-in establishment treatment of a bituminous emulsion was applied to the prepared road as specified in Table 5.10.

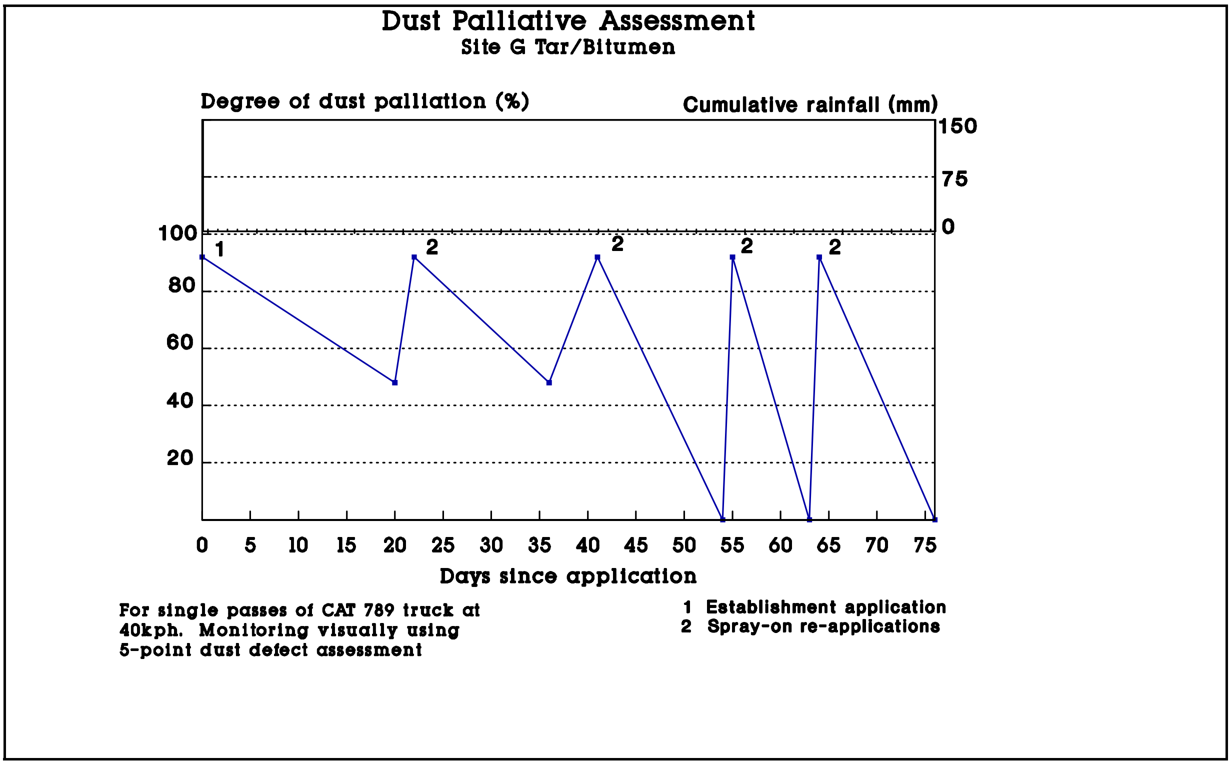
The base case dustiness readings are shown in Figure 5.33 from which it is seen that a peak dust reading of 45 mg/m^3 was measured for each pass of a Haulpak 730E at 40km/h. The effect of vehicle speed on dust generation rates is also shown for a range of test speeds.

Table 5.10 Test site G palliative treatment details using tar/bitumens

Treatment	Application rates
Establishment	Road bladed, shaped and repaired/rehabilitated prior to application. Mix-in applications of 0,5l/m^2 of various dilutions of product (20-25%) and cement (depending on wearing course characteristics and optimum moisture content) to give 3,0l/m^2 product applied.
Re-applications	Re-application of a 5%-10% dilution (19:1 or 9:1) as required
Total product applied (l/m^2) (over test period)	4,5



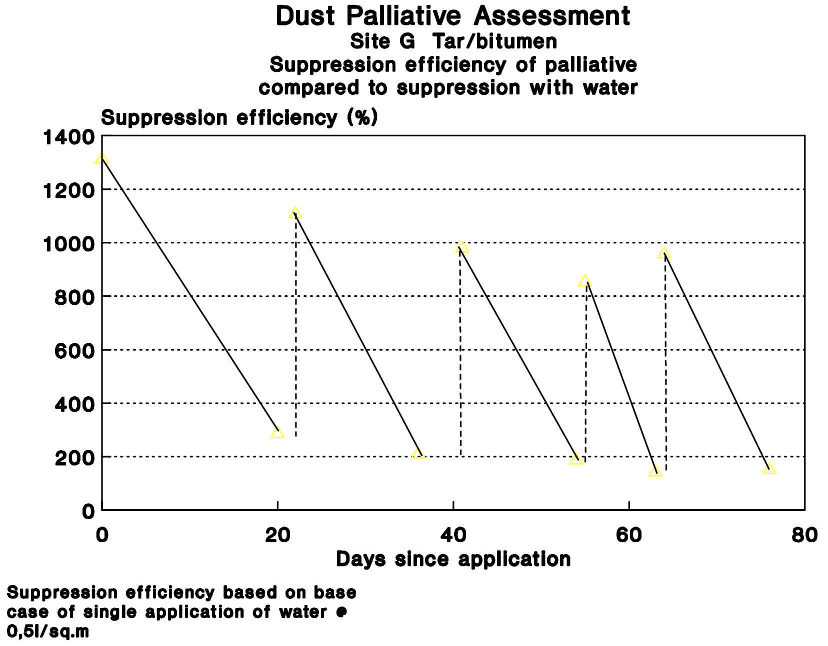
Establishment of the test section prior to treatment involved ripping the road to 200 mm depth, mixing the products at 3.0l/m^2, reshaping and recompacting. The dust measurement were recorded following the visual dust defect evaluation strategy described in Chapter 4 and Table 4.2. A high degree of dust palliation was achieved initially, but then degenerated rapidly over 20 days (or 308kt hauled, equivalent to 1740 repetitions) to a defect score or 3, as shown in Figure 5.34. This can be equated to a rate of degeneration of 2,2%/day. The first maintenance spray-on re-application effectively increased the degree of palliation to 92% again, but rapid degeneration followed over a period of 10 days (or 154kt hauled, equivalent to 870 truck repetitions). A similar trend was seen for the remaining re-applications. The fine wearing course material eroded under the action of traffic, especially in the wheel tracks and whilst the un-trafficked sides and centre of the road retained the treatment, the displacement of loose material and creation of exposed, untreated surface area, effectively reduced the degree of palliation across the full road width. Over the test period, an average degree of dust palliation of 58% was achieved. This was realised by using a high re-application rate which, if continued for 12 months, would have placed 41l/m^2 in the road. Suppression efficiency over the period averaged 422%, between an initial maximum of 1314% (after establishment) to 288% on completion, as can be seen from Figure 5.35. Given the high product application rate, the cost efficiency associated with these suppression efficiency values becomes an important consideration.



Dust Palliative Assessment
Site G Tar/Bitumen

For single passes of CAT 789 truck at 40kph. Monitoring visually using 5-point dust defect assessment

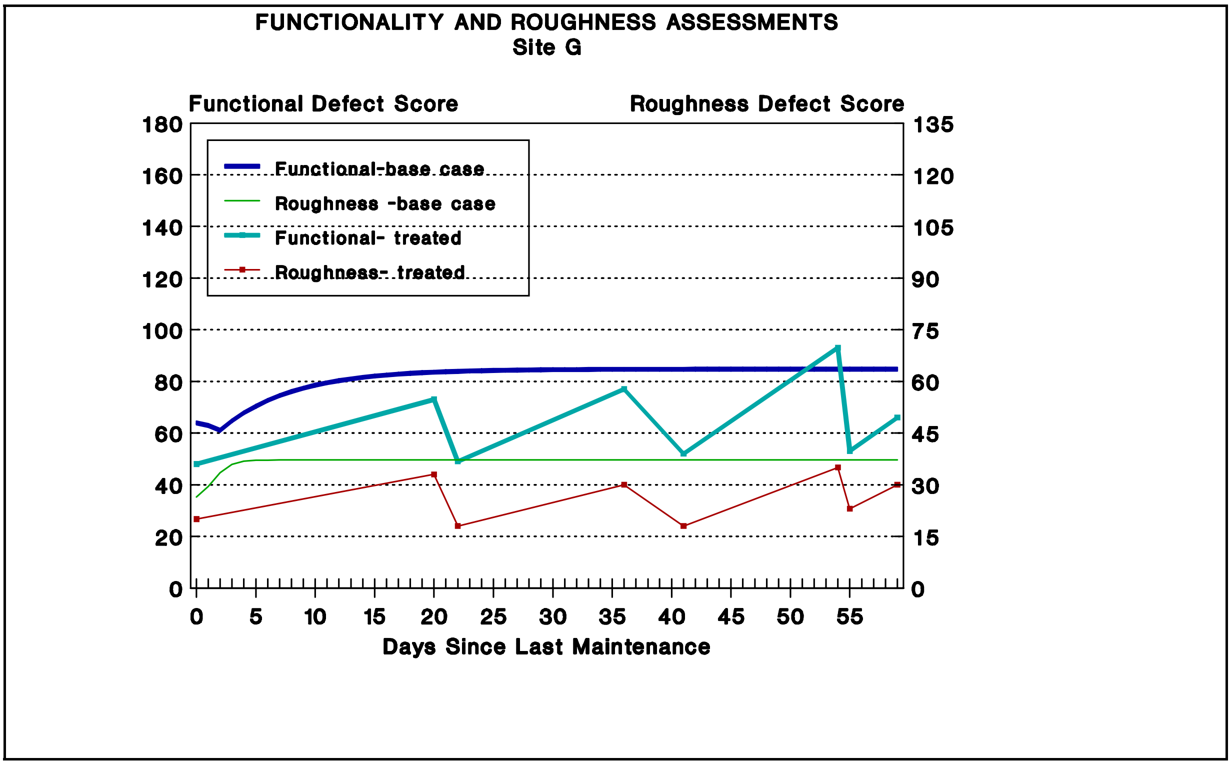
1 Establishment application
2 Spray-on re-applications



The findings of the dust assessment echoed the functionality and roughness assessments, summarised in Figure 5.36; little improvements in the long term were seen, only in the short term, associated with the immediate reduction in dust and loose material defects. As with other test sites whose wearing course material and/or road construction and maintenance is inadequate, little benefit is gained from the use of a dust palliative in the long term. In the case of site G, the combined effects of high traffic volumes on a wearing course deficient in binding material and with low CBR values (13% at 98% Mod AASHTO) leading to rutting, corrugation and erosion, negated the benefits that could otherwise be derived from the use of dust palliatives.

5.7 Summary of Palliative Performance Evaluations

Table 5.11 summarises the analysis of the nine test sites in terms of palliative type and application methodology, together with a summary of the maximum and average degrees of palliation achieved and the time period, together with the degeneration rates found, expressed in terms of time from initial establishment and re-application (if appropriate). A degeneration rate expressed as a function of daily traffic volume is also included, but, due to the variability encountered in traffic volumes over the analysis period, this data could be misleading: Where traffic is not constant over the test period, or where smaller trucks or a better "quality" wearing course is used, artificially low traffic-induced degeneration rates are seen.



The highest instantaneous control efficiency measured was 92% immediately after application for the tar/bitumen class of palliative. The highest average efficiency measured was 75% over 86 days for tar/bitumen palliatives which was also the longest control period evaluated. Generally, for the palliative applications using spray-on techniques for establishment, the average degree of palliation hovered in the 40% to 60% range for the first two weeks, then decreased rapidly with time, whilst for the classes of palliatives using mix-in techniques for establishment, the average degree of palliation hovered in the 60% to 70% range for the first 7 weeks, then decreased at a slower rate with time. In all cases, a longer analysis period and follow-up re-applications would probably increase the degree of palliation achieved and reduce its degeneration rate, due to build-up of residual product in the road. This was illustrated by sites B and C where a long application history existed prior to testing. These results may therefore under-estimate the degree of palliation that can be achieved over the long term and therefore, as will be seen in the following Chapter, over-estimate the cost of a long-term chemical dust suppression program compared to water-spray systems.

Table 5.12 Summary of palliative test section analysis

Palliative	Site	Application technique			Degree of palliation (%)		Degeneration rate (%)	
		Application	Mix-in rate (l/m^2)	Spray-on (l/m^2)	Maximum	Average (%) and period (days)	Per day	Per vehicle repetition
Hygroscopic salts	H1	Establishment	-	2,0	90	45% over 14 days	6,6	0,15
		Re-application	-	0,5				
Lignosulphonates	B	Establishment	?	?	88	66% over 23 days	1,9	0,1
		Re-application	-	0,2				
	C	Establishment	?	?	82	70% over 23 days	1,04	0,01
		Re-application	-	0,2				
	H2	Establishment	-	1,0	88	47% over 18 days	17,6	0,18
		Re-application	-	0,5				
Petroleum resins	F1	Establishment	-	0,7	64	52% over 16 days	1,6	0,03
		Re-application	-	-				
	F2	Establishment	-	1,2	82	62% over 20 days	4,5	0,04
		Re-application	-	0,11				
Polymer emulsions	D	Establishment	0,95	-	82	70% over 58 days	0,4	0,001
		Re-application	-	0,3				
Tars and bitumens	A	Establishment	3	-	88	75% over 86 days	0,3	0,025
		Re-application	-	3				
	G	Establishment	3	-	92	70% over 20 days	2,2	0,05
		Re-application	-	1,5				

Notes

Refer to individual site analyses for full data. Summary data not necessarily comparable between sites since traffic types and volumes, wearing course material types and climatic conditions prevailing at time of test are dissimilar. Application technique refers to test site only and may differ between applications. Applications noted (?) - no data available with which to qualify establishment treatments.

All palliatives (with infrequent watering) share one common failing as compared with frequent water-spray systems. Material spillage on roadways was extremely common at all sites and spilled material was subject to re-entrainment. With frequent watering, the spilled material is moistened at approximately hourly intervals, whilst with hygroscopic products, if spillage is not too excessive, some sympathetic transfer of moisture may take place between treated road and the spillage, reducing dustiness. In the case of once-only applications, or those products requiring re-application only over longer intervals, spillage would go untreated for 2-7 weeks and as such generate most of the fugitive dust emissions from the road. Blading the spillage from the road is problematic in that it creates new untreated surfaces (especially in the case of spray-on applications) and, for mix-in applications, may damage the treated layer.

In mines where spillage cannot be effectively controlled (especially prevalent where bottom dump trucks are used), watering, or failing that, the use of a road sweeper/vacuum in combination with a dust palliative may prove to be more effective for dust control. In locations where trackout from an untreated onto a treated road is a problem (ramps to main haul road and tipping point to main haul road especially), watering these untreated sections aggravates the problem with moisture and mud. The use of a palliative in these areas is problematic since it was seen at a number of sites that the palliative, whether mix-in or spray-on high, could not withstand the high lateral shear forces generated by slow speed manoeuvring. In permanent tip areas, the solution may lie in the provision of a concrete cast in-situ pavement which can be swept clean.

From the analyses undertaken, it is clear that a poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative. The haul road wearing course material should ideally meet the minimum specifications presented in Table 3.19. If not, the inherent functional deficiencies of the material will negate any benefit of gained from using dust palliatives. In road surfaces with too much gravel, dust palliatives do not appear to work effectively, more especially where a spray-on technique is used as opposed to a mix-in. The palliatives do not aid compaction of the surface because of the poor size gradation, nor form a new stable surface. New surface area is created from exposed untreated material whilst, with a mix-in application, poor compaction leads to damage and ravelling of the wearing course, traffic inducing breakdown of the material and eventual dust generation. With regard to water-soluble palliatives, rapid leaching may be problematic.

In compact sandy soils, bituminous and tar-based products appear effective whilst leaching of water-soluble products may be problematic. However, in loose medium and fine sands, bearing capacity will not be adequate for the tar/bitumen products to maintain a new surface and degeneration was seen to occur rapidly. In road surfaces with too much silt, it is unlikely that a dust suppression program will be effective. Excessive silt or sand fractions may lead to a slippery road whilst poor bearing capacity leads to rutting and the need for road rehabilitation or maintenance, which destroys most products. Small scale potholing was observed on a number of pavements following spray-on application or re-application, as a result of trafficking lifting fine cohesive material from the road. Again, where no depth of treatment has built up, this will lead to the creation of new untreated surface areas. In summary, no benefit is likely to be gained from applying any class of palliative to a wearing course material that is inadequate in terms of published selection guidelines.

In general, spray-on applications do not appear appropriate for establishment of dust treatments, especially with regard to depth of treatment required. A spray-on re-application may be more appropriate, but only if penetration of the product into the road can be assured, otherwise it will only serve to treat loose material or spillage build-up, which will rapidly breakdown and create new untreated surfaces. A spray-on treatment is however useful to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions from truck induced turbulence.

Good construction practice will aid long term preservation of the asset. Approaches to consider in the construction of haul roads, in addition to appropriate material selection, are;

- Provision of a crown in the base layers to permit a uniform thickness of wearing course to be placed.
- Provide wearing course crown and adequate crossfall for effective drainage from the pavement, without excessive erosion. This will minimise water penetration, potential leaching of palliatives and a reduction in fines erosion.
- Provision of adequate side drains to lead water away from the road

The potential of dust palliatives to improve functionality has been illustrated at most sites, but more particularly those with a wearing course material that complies with the selection parameters for mine haul road wearing course materials. Road roughness also improved slightly at most sites, but this improvement was primarily attributed to a reduction in loose material, especially on roads deficient in binder or poorly graded. In both cases, functionality eventually reduces to a point where maintenance is required. Ideally, a palliative life that matches blading intervals would be ideal; the palliative degenerating over time at a similar rate to functionality, thus when the road is bladed, the maximum economic life has been extracted from the treatment. In the case of a mix-in palliative, spray-on re-applications could be usefully applied (provided that adequate penetration is achieved) to cover the upper 10-25mm of disturbed road surface.

Rainfall was seen to reduce both functionality and the degree of dust palliation achieved, primarily as a result of either poor road construction practices and/or leaching or erosion of the surface treatment. In those products where water penetration into the wearing course is prevented, the improved wet-weather trafficability reduces production downtime and the obviates the necessity for mud blading.

The average degree of palliation achieved can significantly reduce dust emissions from mine haul road, and it has been shown in previous Chapters that the primary impact of these reductions would be improved visibility and safety, and in the case of open-cab trucks, an improvement in the air quality index. The analysis of both degree of palliation and suppression efficiencies is not complete without some indication of the cost efficiency associated with each product over its estimated lifetime. Using the critical measures of performance assigned to the various palliatives analysed, the following chapter presents an economic evaluation model for selection, application and maintenance of dust palliatives on mine haul roads.

CHAPTER 6

EVALUATION OF HAUL TRUCK DRIVER EXPOSURE TO HAUL ROAD RESPIRABLE DUST

6.1 Introduction

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a typical operating cycle. Seven test sites were evaluated in terms of the typical air quality indices (AQI's) that could be expected for a truck driver during a normal working day, linking sources of dust to overall AQI contribution during a typical haul cycle. Using the previously established intervention level and re-application frequencies to generate an average degree of dust palliation, the impact of this reduced dustiness is assessed in the light of expected improvements in the overall AQI.

6.2 Analysis of Air Quality Index

The methodology adopted was based on in-cab sampling of the respirable dust fraction concentration (-10 m/m^3) using the Hund Tyndalometer. Data were recorded for the following general hauling activities;

- Travelling on haul road (unladen)
- Travelling on ramp (unladen)
- Waiting, spotting and loading at loading area
- Travelling on ramp (laden)
- Travelling on haul road (laden)
- Waiting and tipping at dump or tip

Seven test sites were evaluated, covering a range of vehicle and haul road conditions. In each case, the road was evaluated in it's dry base-case (unwatered or untreated) condition. In addition to the dust concentration, the following parameters, which could affect air quality in the haul truck, were also recorded;

- Number of vehicle interactions on the road (either following another vehicle or passing another truck in the opposite direction)
- Sealed (air conditioned) cab or open (windows open) cab
- Average time taken to complete each hauling activity.

To determine the typical AQI's that a haul truck driver would be exposed to during a typical cycle, a calculation procedure as specified in the Guidelines for the Gravimetric Sampling of Airborne Particulates for Risk Assessment in Terms of the Occupational Diseases in Mines and Works Act (78/1973) Parent Document (1994). The sampling methodology did not conform to that outlined in the document since personal gravimetric sampling devices would not allow for intermittent reading and the interrogation of data for each specific activity. The data thus recorded should therefore not be seen as equivalent to that recorded by gravimetric means, primarily because the analysis assumes that the average values obtained over two repeats of the test (of approximately 30-62 minutes duration) and the associated AQI's will apply over a full shift.

Gravimetric personal samplers were used at two sites, located on the haul roads as opposed to in the haul truck cab. Since the data generated from each assessment was more applicable to external conditions rather than those experienced directly by the haul truck operator, the data was not used directly to determine the exposure to respirable dust, but rather for the measurement of ambient dust levels in the vicinity of the test sections, as discussed in Chapter 5.

Data relating to the specific pollutant threshold limit values was obtained from the Guidelines Document (Supporting Document No.2, 1994) for alpha quartz content data relating to samples, either taken on the mine for the same statistical population of which haul truck drivers are members, or from mine data in which similar wearing courses were used (in terms of weathering product). A threshold limit value time-weighted average concentration of 2,0mg/m^3 of the respirable fraction was used where alpha quartz concentrations did not exceed 5%, otherwise a value of 0,1mg/m^3 was adopted (for alpha quartz > 5%). AQI was calculated from the time-averaged dust concentration over the complete cycle of activities, using appropriate threshold limit values as outlined above. A typical set of results is given in Table 6.1.

The AQI was assessed in terms of the recommended good practice, inspection and cessation of work levels of <0,5, >1,0 and >5,0 respectively, for each of the sealed or open cab tests and for the individual components of the haul cycle, and following the approach outlined in the Draft Guidelines for the Compilation of a Mandatory Code of Practice for an Occupational Hygene Program (No.1 Personal Exposure to Airborne Pollutants) (Department of Minerals and Energy, draft ammendment 6 of 1999), in which personal exposure can was specified according to the bands A to D representing exposures greater than the threshold limit value (or occupational exposure level, OEL) to less than 10% of the OEL..

6.3 Results of Air Quality Index Assessments

Figure 6.1 summarises the results of the respirable dust assessments for all seven test sites evaluated. The percentage contribution is shown for each cycle activity, calculated from the time-weighted average concentrations of respirable dust recorded. The percentage source contribution is shown, for both open and sealed cab conditions. When the specific road-related activities of travelling on the haul road and ramps, in both laden and unladen conditions is considered, it is seen that 48% of the total respirable dust emissions are generated from these sources. When the cab is sealed, this figure reduces to 34%. Although it is only a small percentage reduction over the open-cab conditions when analysed on a per source contribution basis, the reductions as a percentage of total respirable dust recorded are significant for the sealed cab for a number of activity cycle components.

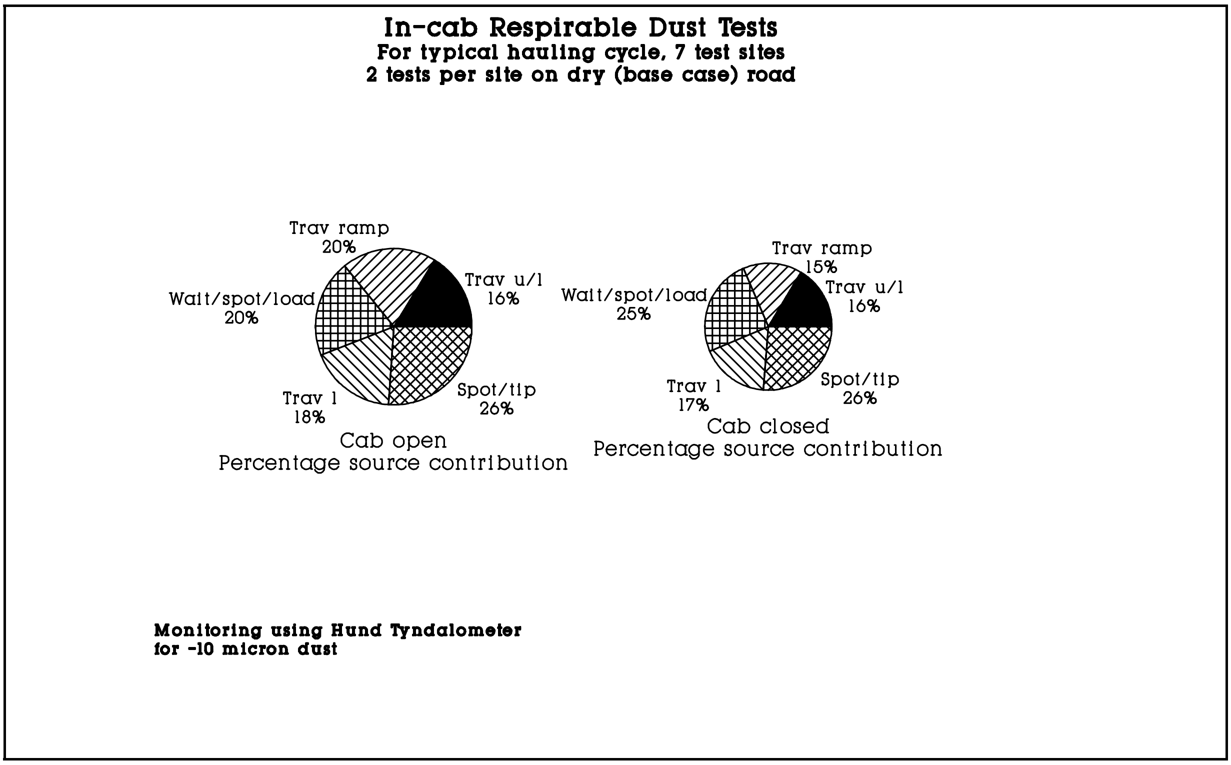


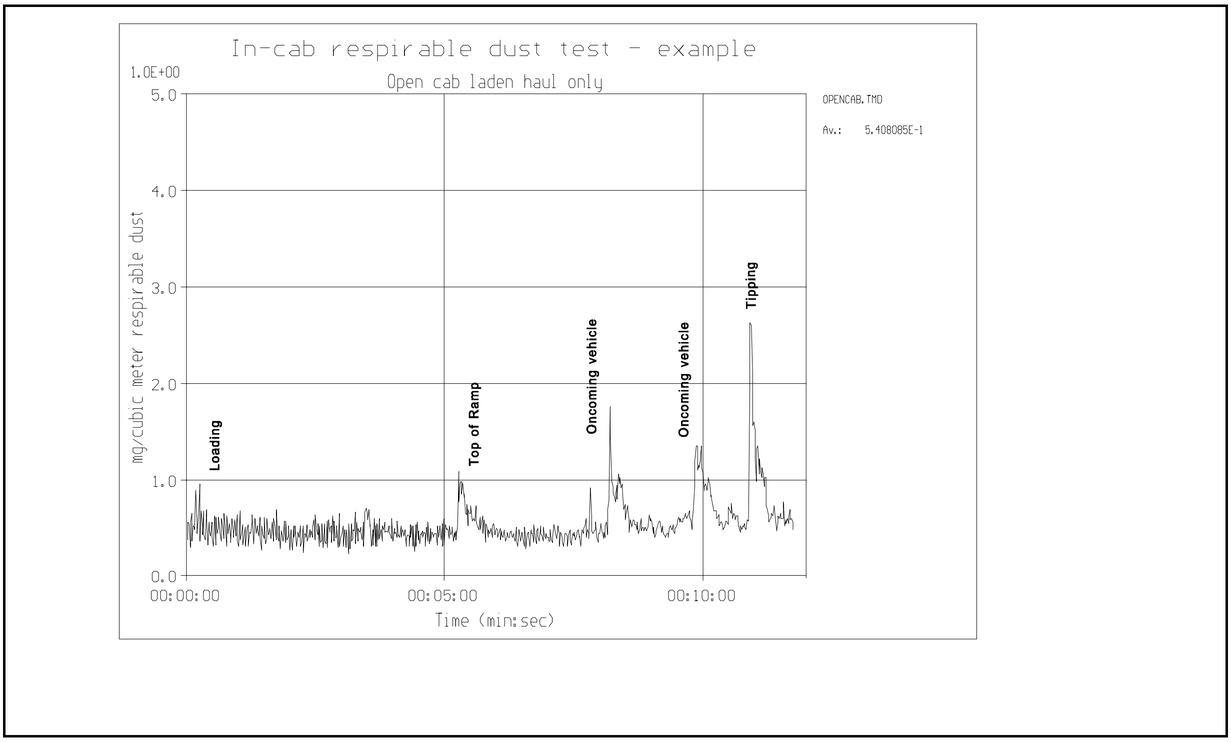
Table 6.1 Typical respirable dust sample test results and calculations

Respirable Dust Tests Site B	Average Respirable Dust Concentration over 2 tests (mg/cubic meter -10 micron fraction)		Average duration of cycle activity (minutes)	AQI for individual cycle components	
	Open cab	Closed cab		Open cab	Closed cab
	Average	Average		AQI	AQI
Travelling unladen on haul road	5,77	2,88	19	3.29	1.64
Travelling unladen on ramp	2,89	1,00	3	1.65	0.57
Wait/spot/load	7,67	6,77	4	4.37	3.86
Travelling laden on ramp	3,01	0,49	5	1.72	0.28
Travelling laden on haul road	4,45	1,14	26	2.54	0.65
Spot/tip	12,55	9,07	5	7.15	5.17
Total cycle time (minutes)			62		
Time weighted average (TWA) conc (mg/m^3)	5,52	2,62			
Quartz content of respirable sample (%)	5.7				
Time weighted average concentration quartz mg/m^3	0.31	0.15			
Threshold limit value (mg/m^3)	0.1				
AQI @ quartz >5%	3.15	1.49			

The data in Figure 6.1 was compiled from the time-weighted exposure averages of all test site activities combined and as such includes considerable variation from dusty wearing course materials and/or specific vehicle types. The exposure time in each in each assessment is also important since lower tonnage operations, employing shorter roads should report lower road-related exposure levels than would a high tonnage operation and longer haul roads. The number of vehicle interactions is an important factor in the analysis since the majority of dust exposure is generated from dust plumes created by other vehicles (except on the slower ascending or descending ramps areas where the truck is typically engulfed in its own plume). Figures 6.2 and 6.3 illustrate a typical dust test data set which shows the open-cab conditions recorded loading, travelling, truck interactions and dumping (Figure 6.2) and the closed-cab conditions for a similar haul, also including two interactions (Figure 6.3). Only the loading, top of ramp (where the haul truck slowed and was engulfed in it's own dust plume) and the dump points are comparable in terms of dust exposure for the open and closed cab conditions.

The tendency of the wearing course itself is also a significant factor in the total dust exposure. With reference to sites A (high tonnage, large truck and long haul distance) and F (low tonnage, small truck, short haul distance), with a cycle time of 32 minutes, site A drivers are subjected to an AQI of between 1,51 and 3,7 at dump and load points whilst the corresponding AQI's at site F are 5,5 to 5,7. For the road component, site A AQI's lie between 0,15 and 0,69 whilst those of site F between 2,56 and 3,34. It was anticipated that the effects of haul road length and fleet size (an indirect measure of tonnage hauled) would cancel out in the analysis, since low tonnage operations operating shorter roads with fewer vehicles would generate a similar number of interactions as a high tonnage operation with longer roads and more vehicles. This was confirmed from the experiment, as only 2 to 3 oncoming vehicle interactions were observed in each test. However, to more reliably interpret the results, a more rigorous experimental design would be required in which the various dependant variables are analysed at different levels.

In each assessment at each site, readings were discarded when the recording vehicle either approached a vehicle ahead, or was overtaken by another vehicle. The decision to discard these readings was taken on the basis of observations of normal operating practice; haul truck drivers tended to space themselves on the road to avoid the worst part of the preceding vehicles dust plume. Table 6.2 illustrates peak respirable dust concentrations recorded following a truck and after passing another truck travelling in the opposite direction. Although high values, the duration of these peaks was relatively short and the overall effect on the average cycle AQI is considered to be small.



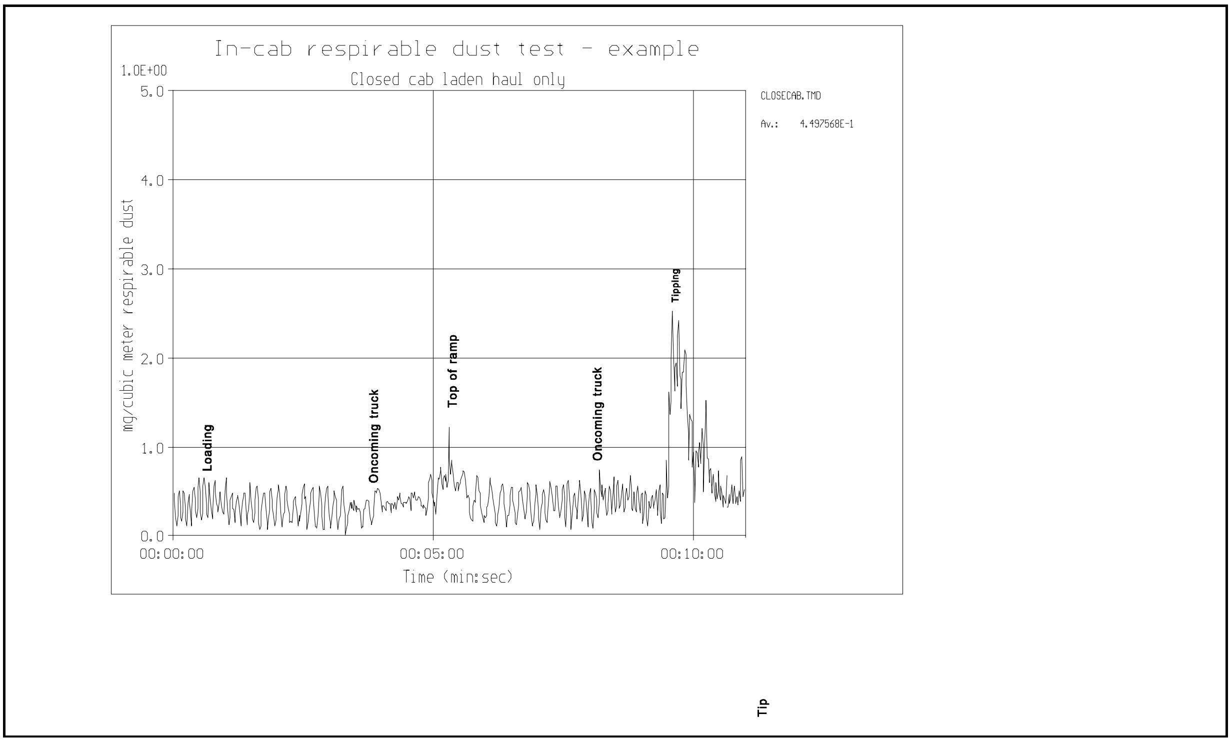


Table 6.2 Typical peak respirable dust concentrations recorded in an open and closed cab

Vehicle interaction	**Peak Respirable Dust Concentration (mg/cubic meter -10 micron fraction)**		**Air Quality Index (for peak values only)***		**Percentage reduction (%)**	**Notes**
	Open cab	**Closed cab**	**Open Cab**	**Closed cab**		
Travelling behind truck	16,011	0,532	8,18	0,27	96,7	At 20-40m following distance
Passing truck in opposite direction	0,768	0,124	0,39	0,06	83,9	Both trucks travelling at 30-35kph

Notes
* Using an alpha-quartz respirable sample content of <5% and Threshold Limit Value of 2,0mg/m^3 applied to the total sample.

Significant reductions are seen as a result of using closed or sealed cabs in both cases. Figures 6.4 and 6.5 show the variation in percentage source contribution for the open and closed cab measurements. From these figures it is evident that the majority of exposure is attributable to loading and dumping activities with the haul roads and ramps themselves accounting for between 10%-15% each of the total exposure (open cab) and 5-10% each (closed cab). Figure 6.6 shows the reduction in dust exposure per cycle activity. A 30%-55% reduction in dust concentrations measured in a sealed cab as compared to an open cab were realised for the haul road related activity cycles, only the wait/spot and load cycle activity demonstrating a smaller percentage reduction, primarily as a result of the operators opening the cab windows to improve rear vision when reversing towards the loader or dump point. These results, although in contrast to Amponsah Da-costa's work (1996) which established that haul road generated dust was the single most significant source of dust on a typical surface strip coal mine, are only related to a specific population's exposure to haul road generated dust and not the total dust generated.

Figure 6.7 summarises the data in terms of the overall AQI for each test site evaluated. In general, haul truck drivers in open cabs were exposed to poorer quality air than their equivalents in sealed or closed cabs. For open cabs, the average AQI over a typical operating cycle was approximately 3,0 which exceeded the correction intervention level of 1,0. For sealed cabs, the average cycle AQI was generally less than 1 but not less than the established good practice level of 0,5. A combination of high traffic volumes, a wearing course material prone to dustiness, high alpha-quartz respirable fraction content and dry loading or dumping conditions resulted in sealed cab AQI's exceeding 1,0. These trends are confirmed in Table 6.3 when the classification band is determined following the Draft Guidelines for the Compilation of a Mandatory Code of Practice for an Occupational Hygene Program (No.1 Personal Exposure to Airborne Pollutants) (Department of Minerals and Energy, draft ammendment 6 of 1999), from which it is seen that those sites operating open-cab trucks in conjunction with respirable alpha-quartz contents of the sample greater than 5% are classified as Category A.

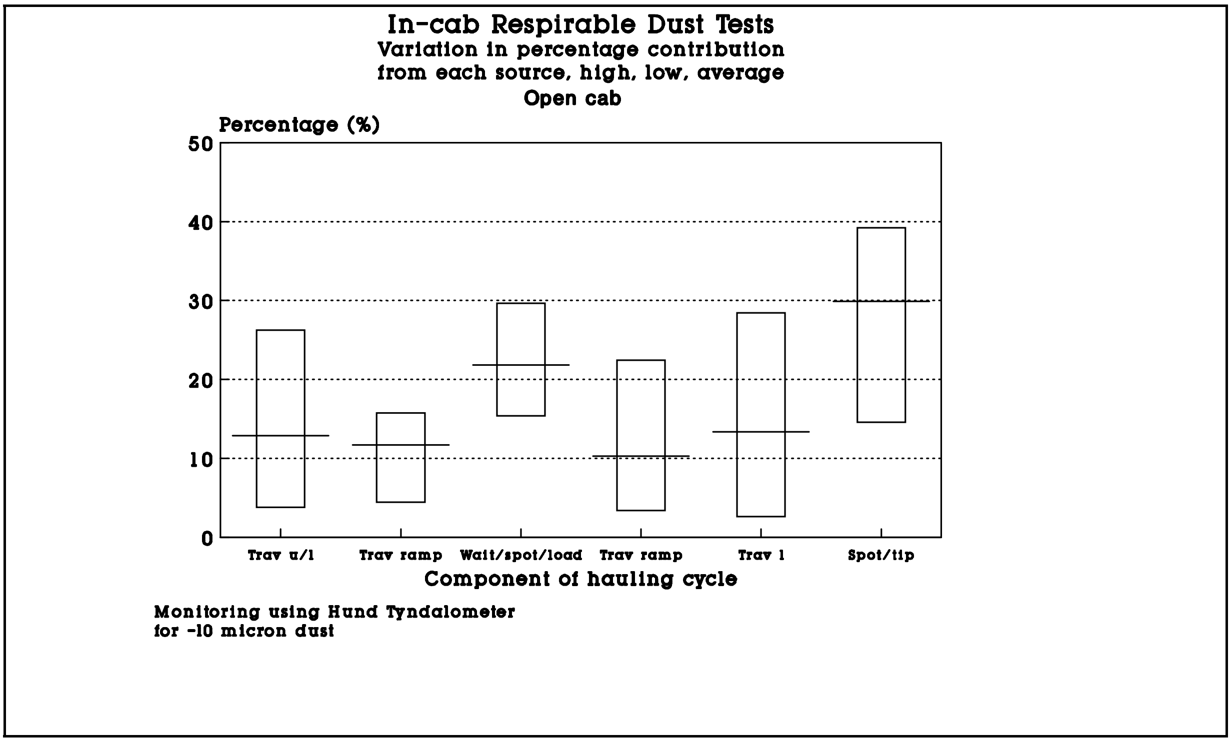
Table 6.3 Classification bands following Department of Minerals and Energy, 1999

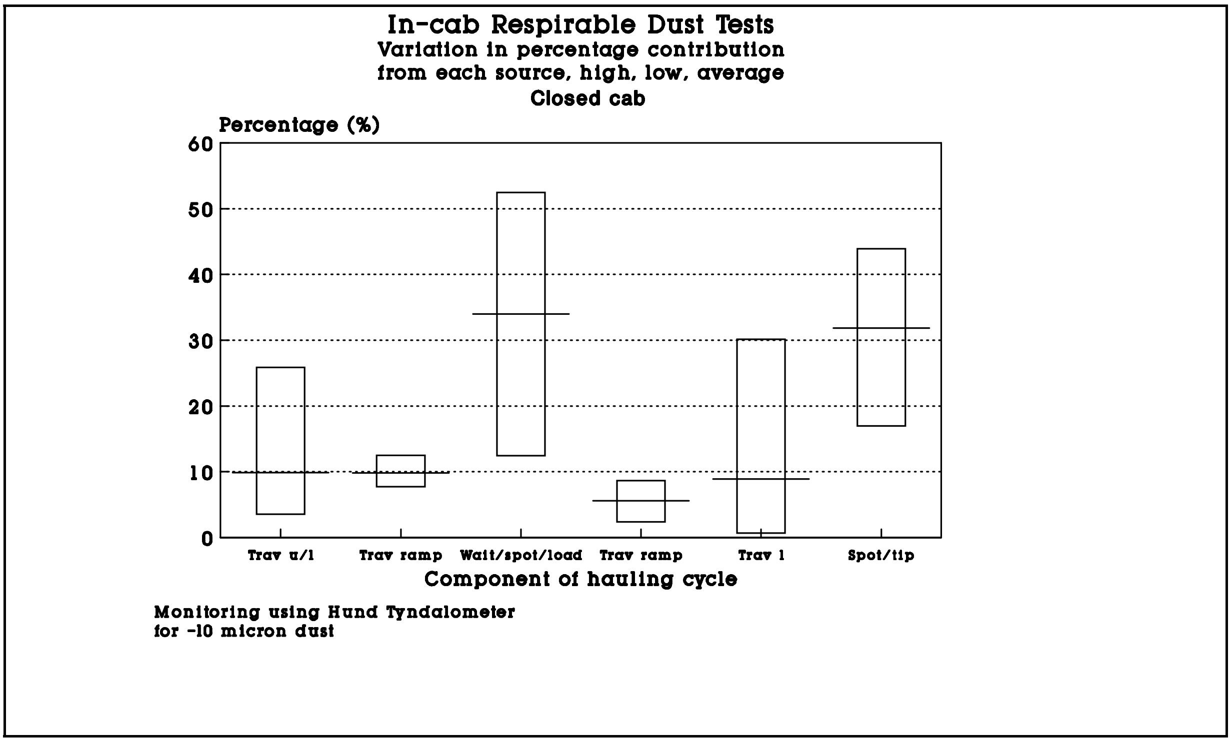
Test site	Open-cab classification band	Closed-cab classification band
A	D	Below threshold 10% OEL[1] value
B	A	A
C	D	No test
D	A	C
F	A	A
G	Below threshold 10% value[1]	Below threshold 10% OEL[1] value
H	D	No test

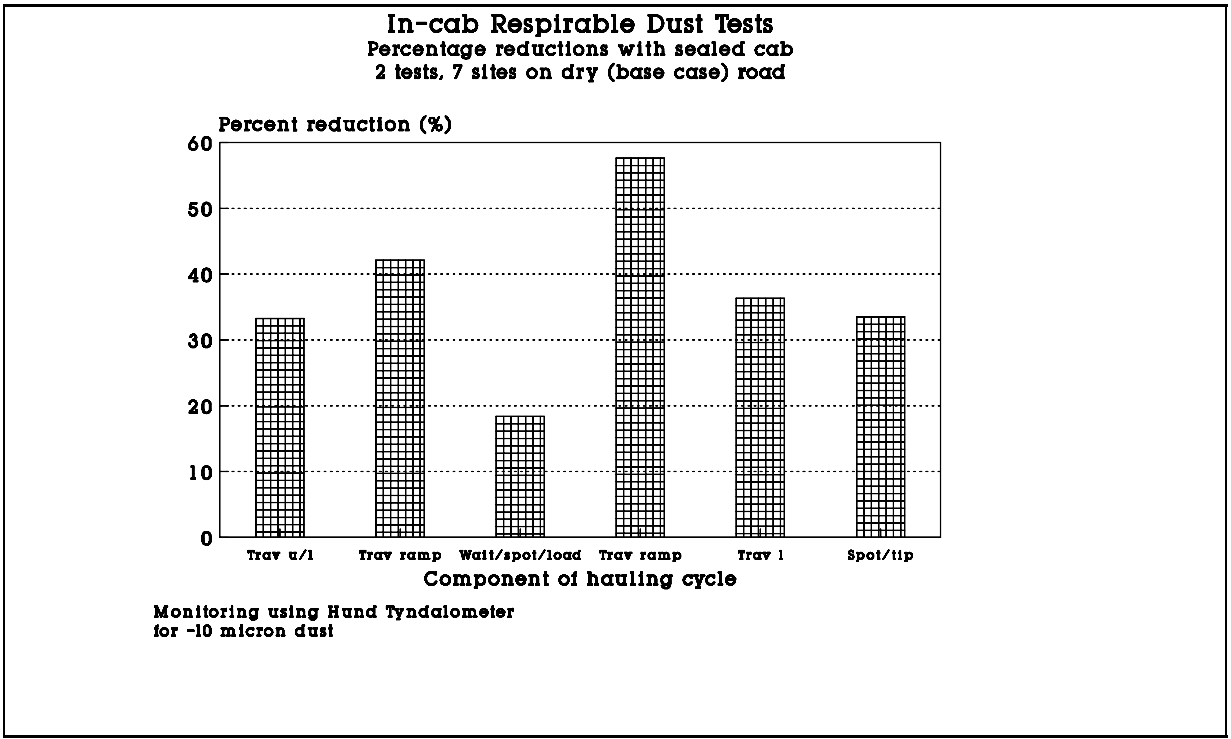
Note

[1] Below specified 10% of Occupational Exposure Limit (equivalent to TLV)

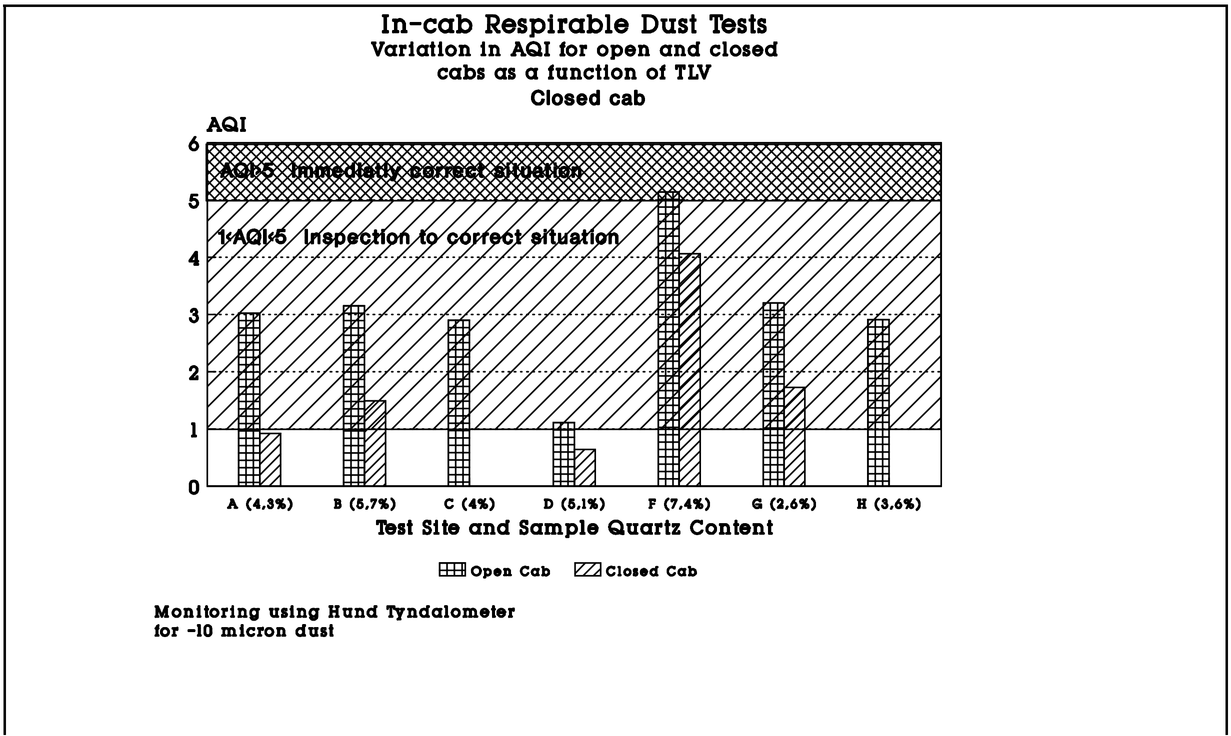
In summarising the evaluation of haul truck driver exposure to haul road respirable dust it is clear that, despite the limited data, basic experimental design and assumptions implicit in the analysis of the data, it is unlikely that haul road generated respirable dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are used. In most large mine haul trucks, a sealed and air conditioned cab is a standard feature. The greatest contribution to dust generation was derived from loading and dumping points, combined with the fact that drivers tended to open cab windows to improve visibility whilst reversing. Further benefit could be gained from the use of wet scrubbers in the air conditioning system where ambient dust levels warrant concern, or where the dust, once inside the sealed cab, needs to be removed quickly.


In-cab Respirable Dust Tests
Variation in percentage contribution
from each source, high, low, average
Open cab
Percentage (%)
50
40
30
20
10
0
Trav u/l
Trav ramp
Wait/spot/load
Trav ramp
Trav l
Spot/tip
Component of hauling cycle
Monitoring using Hund Tyndalometer
for -10 micron dust


In-cab Respirable Dust Tests
Variation in percentage contribution
from each source, high, low, average
Closed cab
Percentage (%)
60
50
40
30
20
10
0
Trav u/l
Trav ramp
Wait/spot/load
Trav ramp
Trav l
Spot/tip
Component of hauling cycle
Monitoring using Hund Tyndalometer
for -10 micron dust



Whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources. Where low capacity open cab trucks are used, typically in low tonnage operations with short haul distances, in conjunction with inherently dusty wearing course materials with high (>5%) respirable alpha-quartz fractions, palliation may significantly improve AQI's, especially if the



benefits of palliation were extended to better dust control at the loading point, since on short haul trips, the time spent loading represents a greater proportion of the overall cycle time. The frequency of re-application of water-based palliation as established in Chapter 4 entails considerable capital and operating expenditure. Coupled with the need to reduce dust from a safety perspective, the use of palliatives can still be motivated where water-spray tankers are re-deployed to reduce dust emissions, especially at the loading area. Excessive water in the loading area is problematic since it may lead to tyre damage where slow speed manoeuvring is required, but a fine mist applied to the loading face as it is exposed would obviate the need for short-term, high volume applications which lead to excessive run-off. Due to the dynamic nature of the loading face, effective suppression can only be realistically achieved by either the use of a dedicated water-car or releasing the water-car from haul-road dust suppression duties. The choice of solution is a function of the cost-effectiveness of the palliatives used compared to other dust suppression alternatives and will be explored in the following Chapter.

CHAPTER 7
ANALYSIS OF DUST PALLIATIVE COST EFFECTIVENESS

7.1 Introduction

The development and evaluation of dust control strategies requires an analysis of the relative costs of alternative palliation options, such that the most cost-efficient option can be determined, together with an indication of the sensitivity of the selection in terms of the primary modelling parameters. A pre-requisite of any cost evaluation is a model that provides a rapid means of making a consistent comparison of the real costs of alternative control measures. Changes in cost of dust control and the reduction in emissions resulting from the introduction of alternative strategies are utilised to evaluate dust control options. This allows the economic implications of the introduction of alternative strategies to be expressed in terms of a base-case cost, in this case water-based spraying.

This Chapter details the development of the cost-effectiveness model, introducing the primary data classes required prior to specifying the individual model components. The data classes are described and component values ascribed, based on current (1999) data and costs. A comparative analysis is then undertaken for each class of palliative previously monitored, using the water-spray efficiency model and required degree of palliation for a maximum specified dust defect as the starting point. The individual palliative cost-effectiveness, compared to a base-case cost of water-spray application and the associated Rand per square meter cost is then discussed.

7.2 Model Development

The development of the model consisted of identification of the key components that affect the overall cost of dust control and their interrelationship and effect on the total cost (R/m^2). The major cost elements for dust control include capital equipment, operation and maintenance costs, together with material cost (palliative cost) and activity-related costs such as surface preparation, dust palliative application, grading and watering and finishing, for either a mix-in or spray-on establishment or re-application. Other cost elements include equipment downtime and vehicle maintenance costs. These parameters are, in turn, influenced by the selected palliative and application methodology and frequency. Costs associated with reduced road maintenance intervals are also important since improvements in functionality were seen in Chapter 5 to be a major benefit of dust palliatives, especially where re-application interval could be made to coincide with blading activities.

The benefits derived from the application of any palliative have been broadly summarised as;

- An air quality improvement, reducing the health risk to workers, less time lost due to sickness and a cleaner (safer) environment.
- Total road-user costs (vehicle and road maintenance) are reduced.
- Improved hauler cycle times.
- Reduced dust control costs (R/m^2 road surface)

These benefits must be completely characterised to fully determine the value of dust suppressants. Portions of the last two can be costed, but the primary benefit - that of improved air quality and road- and driver-safety is problematic. It has been established that a truck driver's exposure to the dust produced, and for how long, is not critical in terms of AQI for the characteristic dust involved, except where a combination of open-cabs and short-hauls or high traffic volumes are found. The safety benefit is more tangible - the current practice of applying water at 60-90 minute intervals is incorrect in view of the preferred levels of dustiness and visibility required to be maintained on a mine haul road. This would imply that by reducing the frequency of watering, through the use of palliatives, this may offset the additional costs of material and construction required for their effective application. Table 7.1 summarises all possible primary data classes recognised in the cost analysis in terms of cost or benefit, highlighting those used in developing the cost model.

The capital costs of a dust suppression system for a haul road are those direct and indirect expenses incurred up to the date when the control system is placed in operation. The capital cost of equipment was regarded in this model as a once-off expense incurred at the start up of a project and is wholly tax deductible. Consideration was therefore only given to the influence of maintenance and operating costs on total costs. However, the model has been constructed to determine any additional equipment requirements (especially in the case of water tankers) and indicates the number of units required to maintain the level of dust control required. In the case of reduced water-car utilisation associated with the use of palliatives, a utilisation figure is calculated for comparison purposes, and the associated operational cost savings are calculated. However, whether these savings are fully realised depends on how the equipment is deployed. Equipment already in inventory could impact on the decision to use

Table 7.1 Summary of cost/benefit analysis for cost model development

BENEFIT	INCLUDED IN MODEL	COST	INCLUDED IN MODEL
Improved safety	X[1]	Surface preparation, palliative establishment application and finishing costs (equipment and material)	✓
Improved health	X[1]	Palliative re-application (equipment and material)	✓
Reduction in grading cost	✓	Remaining grading costs	✓
Reduction in grading frequency	✓	Remaining watering costs	✓
Reduction in watering cost	✓[2]	Reduced safety (cost of accidents)	X[1]
Reduction in vehicle down-time and maintenance	X	Reduced health (cost of exposure to low AQI)	X[1]
Improved hauler cycle times	X[1]	Reduced water-car fleet utilisation	X[2]

Note

1 Not analysed, but if model comparison is based on the cost to achieve a specified level of control efficiency, many of the costs become equal or do not apply. For example, the comparative safety and health benefits from reduced dustiness would become equal, irrespective of control methodology applied (water-spray base-case or palliative).

2 Reduced utilisation of water-car or road maintenance fleet would not necessarily generate savings, except for reduced maintenance, parts and fuel, since vehicle and driver would still be required. However, where the fleet consists of more than 1 vehicle is in use, the reduction in numbers may generate savings.

either water-based or chemical suppression. A chemical-based program could require between 50-90% less grader and water-car capacity even when the same equipment is used for establishment and re-application. If no other use can be found for the grading and water-car spare capacity, the idle equipment should also be considered a cost. In the model, it is assumed that both grader and water-car can be deployed elsewhere. In Chapter 6 it was recommended that spare water-car capacity be used to water the loading and tipping points more regularly since a these areas contributed significantly to the fugitive dust emissions recorded.

Operating costs are considered as labour and those costs of consumables required to operate equipment, such as materials and utilities, whilst maintenance costs are expenses associated with equipment maintenance such as routine servicing and overhauls. These costs are expressed as average hourly operating costs for the various equipment used to establish, maintain and water or re-apply palliative to the road; water-car, grader, offset disc harrow plough and compacter. Estimates are given for each activity of the productivity of the equipment in terms of kilometers per hour bladed, watered, compacted or ploughed. Where equipment is not used in a specific activity then the productivity value reverts to zero and no cost is calculated.

7.3 Primary Data Classes Analysed

The primary data classes analysed in the model are discussed in the following sections and incorporate the following;

1. Water-based spray re-application model, as discussed in Chapter 4
2. Road and climate data specific to area being assessed (for water-based spraying model only)
3. Water-car operating data (for water-based spraying)
4. Water and chemical palliative application rate and cost data
5. Equipment activity productivity and cost data for establishment, application (spray-on or mix-in and spray-on re-application).
6. Road functionality data and required maintenance intervals

7.3.1 Road and Climate Data

Table 7.2 summarises the data required to define the road and climate. Days with more than 5mm rain are excluded from the water-based suppression cost calculations. The hours of dust suppression required per day are used to calculate water-based suppression costs. In the case of chemical suppression, it is assumed that the palliative works 24 hours per day, whether required to or not.

Table 7.2 Cost model road and climate data requirements

Road data	
Segment length (km)	3
Segment width (m)	30
Climate data	
Days with >5mm rain per annum	86
Hours of dust suppression required per day	24

7.3.2 Water-car Operating Data

Table 7.3 summarises the water-car operating data for water-based spraying. Availability is defined as the engineering availability of the units, whilst spraying utilisation is defined as the percentage of total available time the unit spends watering. Given the need both to refill the water-car and travel empty to the filling point, this value does not generally exceed 60-65% (Kotze, 1999), depending on location of watering points, water-car capacity and filling point rate of delivery. The water-based spray re-application rate was calculated form the model described in Chapter 4, based on a coverage of 0,5l/m^2. A maximum allowable dust defect score is specified, from which the maximum allowable and average dustiness is calculated and, according to the wearing course and climate characteristics, the average degree of palliation and water-based re-application frequency determined.

Table 7.3 Cost model water-car data

Equipment data - water car	
Number of units available	2
Capacity (klitres)	50
Average watering speed (km/h)	20
Number of passes required for specified road width	2
Availability (%)	90
Spraying utilisation (%)	60
Water-based spraying re-application rate (minutes)	Calculated from watering model

7.3.3 Water and Chemical Palliative Application Rate and Cost Data

Table 7.4 summarises the water and chemical palliative application rates and cost data. For the chemical palliative, application rates are subdivided into initial (establishment) application and follow-up re-applications at a rate and frequency fixed by the degree of dust palliation required, together with the results of the palliative performance assessment presented in Chapter 5.

The palliative performance results presented in Chapter 5 highlighted the fact that application of any palliative to a sub-standard wearing course will not improve the performance of the

Table 7.4 Cost model water and chemical palliative application rate and cost data

Water data	
Water cost (R/klitre)	0
Application rate (l/sq meter)	0.5
Palliative data	
Product cost (R/litre)	1.6
Establishment litres/sq meter	3
Re-application litres/sq meter	0.125
Re-application frequency (1 per n days)	15
Re-establishment frequency (1 per n years)	11

wearing course over the long term and that poorly designed pavements cannot be remediated through the use of palliatives. The test results incorporated into the model may therefore not represent the optimal performance of the palliative selected. The user can therefore specify alternate establishment and re-application strategies that more closely reflect the anticipated palliative performance, should the need arise. In addition, the testwork conducted did not allow for the build-up of palliative in the road and thus it is possible that the model under-estimates the degree of palliation achieved over a specified time period, especially where multiple re-applications are envisaged.

The re-application frequency was estimated according to the average degree of dust palliation required to maintain the specified dust defect degree and average dustiness. Data in Table 5.12 was analysed and incorporated to produce the site- and analysis-specific model data. The re-establishment frequency accommodates the longer-term performance by allowing a road to be re-established after a certain period - for example where water-soluble products wash-out in the wet season, re-establishment would be necessary the following dry season. A ten year modelling period was chosen since most strip coal mine haul roads are dynamic and have relatively short production lives. Therefore, specifying a re-establishment frequency of 11 years is equivalent to no re-establishment over the life of the road.

7.3.4 Equipment Activity Productivity and Cost Data

Table 7.5 summarises the equipment activity productivity and cost data requirements for the model. The values used can be modified to reflect individual mine operating cost and productivity data, as well as the individual equipment required for the various applications of palliative (establishment mix-in or spray-on, followed by re-application spray-on only). Productivity per kilometer is specified, depending on the road width and equipment types.

7.3.5 Road Functionality Data and Required Maintenance Intervals

Table 7.6 summarises the data requirements in respect of normal road maintenance activities (untreated road, subject to normal water-based spraying) and any additional maintenance required over and above the blading of road prior to the re-application of a chemical palliative. Additional maintenance is an important cost considerations since it was shown in Chapter 5 that ideally, a road should deteriorate at a rate that matches the re-application rate of the palliative. Should this not be the case, additional blading will be required in the intervening period which decreases the overall cost-effectiveness of the treatment. Deterioration rates are a function of wearing course material type and traffic volumes and will vary from site to site. A treated road handling low traffic volumes will generate smaller cost savings than would be the case for higher traffic volumes, since the normal maintenance interval will be longer and approach that associated with the use of chemical palliatives. In this case, the only cost benefit will be derived from the reduced watering frequency.

7.4 Calculation of Annual Costs of Dust Palliation Options

Calculation of total annual cost of controlling dust emissions from unpaved haul roads was accomplished in five steps. The first step was the determination of the times between applications and the application intensity. Application parameters are based either on measured palliative performance, vendor's specifications and recommendations or the water-based spray model, to achieve a specified average degree of dust palliation. Information required at this stage included re-application intensity and frequency. The second step involved calculation of the number of annual applications required in order to determine the cost of product for maintaining the road or re-establishment as the case may be.

Table 7.5 Cost model equipment activity productivity and cost data requirements

Hourly operating costs

Discount rate (%)	6
Water-car operating cost (R/hr)	296
Plough operating cost (R/hr)	140
Grader operating cost (R/hr)	192
Compactor operating cost (R/hr)	140

Equipment productivity

	Establishment Mix-in				Establishment spray-on				Re-application Spray-on		
	Grader	Plough	Water-car	Compacter	Grader	Plough	Water-car	Compacter	Grader	Plough	Watercar
Hours/km											
Surface prep	5	2	0	0	0	0	0	0	1.5	0	0
Application	0	0	3	0	0	0	0	0	0	0	4
Finishing	2	0	1	3	0	0	0	0	0	0	0
Equipment cost/km	1344.00	280.00	1184.00	420.00	0.00	0.00	0.00	0.00	288.00	0.00	1184.00
TOTAL COST PER KM	9684.00				0.00				4416.00		

Table 7.6 Cost model road maintenance and functionality data

Functionality data maintenance interval	
Maintenance interval on road when using water-based suppression (1 per n days)	4
Grader productivity (hr/km bladed) for routine road maintenance at 30m road width	1.80
Extra road maintenance (blading) at intervals (1 per n days) for treated road, NOT coincident with re-application	0

Steps three and four are categorised under road maintenance (watering and grading). The type and frequency of grading, which are based on the condition of the haul road, are determined in order to estimate grading cost. The final step was the calculation of the total annual cost, involving the sum of all the activity-related costs and the cost of the product used for establishment application and subsequent re-applications, on the basis of a total cost per square meter treated and total annual cost.

Tables 7.7 and 7.8 illustrate the results from a modelling exercise, using the data given in the preceding Tables 7.2 to 7.6. Table 7.7 presents the results of the water-based spray palliation method in which re-application is required every 33 minutes to maintain an average degree of palliation of 65%, based on a maximum allowable dust defect score of two. Table 7.8 illustrates the equivalent cost of a chemical-based palliative, applied according to the data presented in Tables 7.3 to 7.6. Figure 7.1 summarises the analysis for all palliatives tested in Chapter 5, using a maximum allowable dust defect score of two, equivalent to an average degree of dust palliation of 65% and watering every 33 minutes. Polymer and tar/bitumen products show a cost benefit over water-based spraying, the polymer emulsion only after establishment in year one (ie. initial costs are higher due to establishment), whilst the tar/bitumen product is also initially cheaper. Palliative cost, establishment and re-application rates and methodologies, together with the average degree of palliative performance acheived are presented in Table 7.9. Use of this data implies that each evaluation took place under optimal conditions, which was not the case. The application of any palliative to a sub-standard wearing course will not improve the performance of the wearing course over the long term and that poorly designed pavements cannot be remediated through the use of palliatives. The test results incorporated into the model may therefore not represent the optimal performance of the palliative selected. Care should be taken when specifying the modelled or alternate establishment and re-application strategies. It is important that the data used closely reflects the anticipated palliative performance.

Table 7.7 Cost model results for example calculation of data in Tables 7.2-7.6, for a dust defect score of two, water-based dust suppression

Water-based spraying cost model results

Litres water per segment per application	45000
Water car capacity factor (%)	90
Time to complete 1 application (minutes)	18
Applications per day	44
Spraying hours required per day	13.1
Spraying hours available	25.9
Water-car fleet utilisation (%)	50.5
Additional water-cars required	0
Cost of water application (R/day)	3875.68

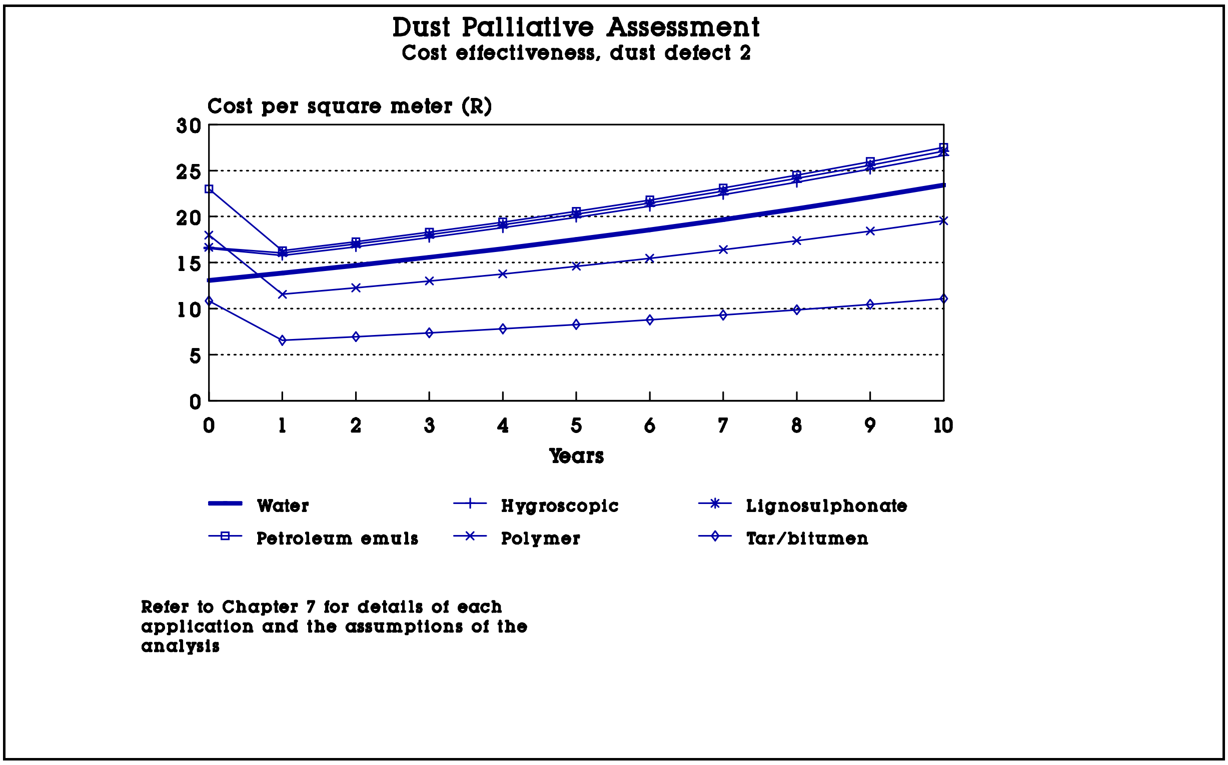
		Years									
		1	2	3	4	5	6	7	8	9	10
Annual cost watering (R)	1082284.21	1147221.27	1216054.54	1289017.82	1366358.89	1448340.42	1535240.84	1627355.29	1724996.61	1828496.41	1938206.19
Annual maintenance cost (R)	94672.80	100353.17	106374.36	112756.82	119522.23	126693.56	134295.18	142352.89	150894.06	159947.70	169544.57
Annual cost R/m^2	13.08	13.86	14.69	15.58	16.51	17.50	18.55	19.66	20.84	22.09	23.42
CUMULATIVE ANNUAL COST (R)	1176957.01	2424531.45	3746960.35	5148734.989	6634616.10	8209650.085	9879186.10	11648894.29	13524784.96	15513229.07	17620979.83

Table 7.8 Cost model results for example calculation of data in Tables 7.2-7.6, for a dust defect score of two, chemical palliative-based dust suppression, using tar/bitumen class of palliative

Palliative treated road cost model results

Establishment (mix-in) equipment	9684.00
Establishment (spray-on) equipment	0.00
Establishment palliative	432000.00
Reapplication (spray-on) equipment	4416.00
Reapplication palliative	18000.00
Reapplications per annum	25
Annual cost of (extra) blading (R)	0.00

		YEARS									
		1	2	3	4	5	6	7	8	9	10
TOTAL ANNUAL COST (R)	976305.60	590459.86	625887.45	663440.69	703247.14	745441.96	790168.48	837578.59	887833.31	941103.30	997569.50
Annual cost R/m^2	**10.85**	**6.56**	**6.95**	**7.37**	**7.81**	**8.28**	**8.78**	**9.31**	**9.86**	**10.46**	**11.08**
CUMULATIVE ANNUAL COST (R)	976305.60	1566765.46	2192652.90	2856093.59	3559340.73	4304782.69	5094951.17	5932529.77	6820363.07	7761466.38	8759035.88



When the dust defect score is increased to three, watering frequencies reduce to 48 minutes and only the polymer and tar/bitumen products show any cost benefit over water-based spraying, and only after establishment, as shown in Figure 7.2. No model was analysed for petroleum resins since no applicable data was determined in Chapter 5. When the allowable dust defect score is increased to four, watering becomes the cheapest dust palliation option as shown in Figure 7.3. Current mine operating practice is typically represented by a dust defect value of between three and four which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, it was established in Chapter 4 that a maximum dust defect score of two was desirable from mine operators point of view and therefore, some form of chemical palliation would be beneficial in the long term, subject to the other cost constraints remaining valid.

Figure 7.4 illustrates the effect of re-establishment on cumulative cost per square meter road treated. If re-establishment is required at certain intervals (in this case every four years), this can significantly affect overall costs and result in the treatment cost approaching the cost of water-based palliation. This is particularly significant for water soluble palliatives which would need annual re-establishment. Similarly with extra road maintenance between palliative re-applications; Figure 7.4 shows how with two extra road bladings over a 15 day period, the chemical control option is more expensive than watering. In this analysis, it is assumed that no palliative is applied during the extra blading activity, but only at the specified re-application interval. This equates to an effective road maintenance interval (including the extra blading) of 5 days which is similar to the frequency associated with water-based palliation only.

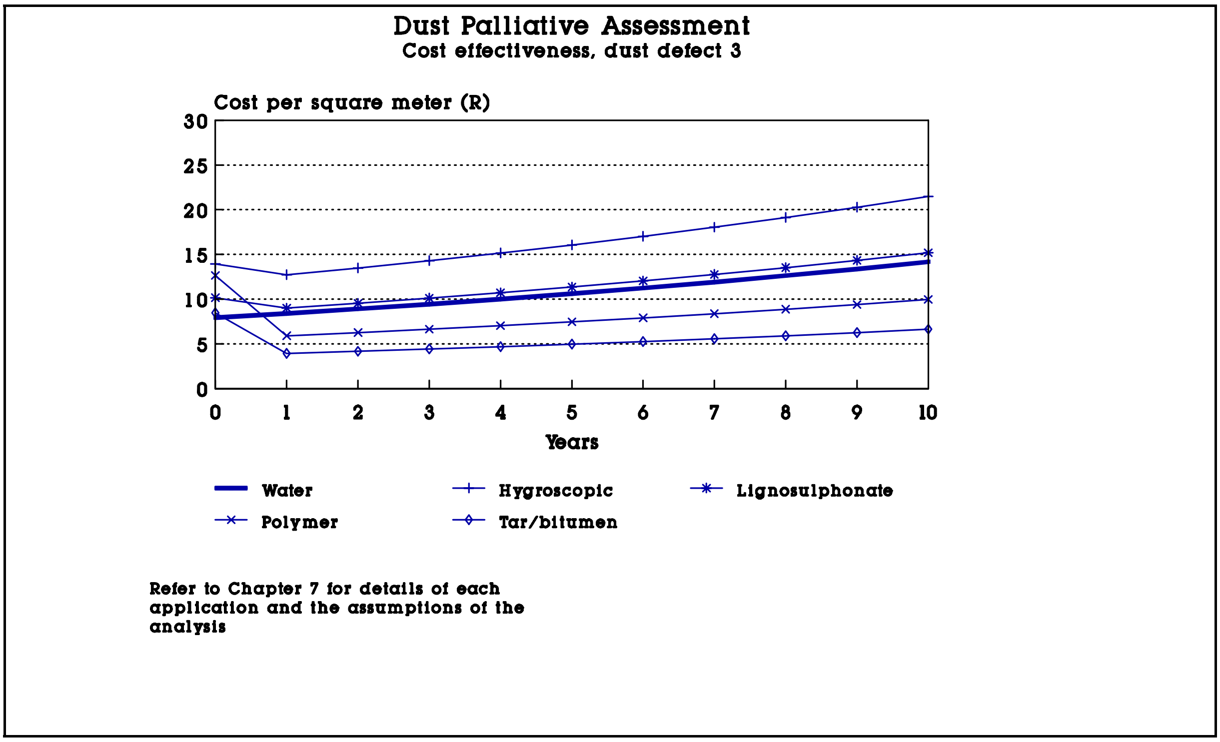
Table 7.9 Summary of chemical palliative performance and cost modelling data

Suppression method and class of palliative	**Product price (R/l)**[1]	**Establishment or Re-application**	**Application methodology (l/m^2 @ interval)**[2] **(S = spray-on M = mix-in)**		
			Dust defect score 2 Average degree of dust palliation 66%	**Spray or mix**	**Dust defect score 3 Average degree of dust palliation 40%**
Watering	No-cost	R	Every 33 mins	S	Every 58 mins
Hygroscopic salts	1,10	E	2l/m^2	S	2l/m^2
		R	0,5l/m^2 every 10 days	S	0,25l/m^2 every 10 days
Lignosulphonate	1,80	E	1l/m^2 ?	M	1l/m^2 ?
		R	0,2l/m^2 every 10 days	S	0,1l/m^2 every 10 days
Petroleum resins	7,00	E	1,2l/m^2	M	Unknown
		R	0,11l/m^2 every 20 days	S	Unknown
Polymer emulsions	7,80	E	0,95l/m^2	M	0,95l/m^2
		R	0,05/m^2 every 15 days	S	0,025/m^2 every 15 days
Tar/bitumen	1,60	E	3l/m^2	M	3l/m^2
		R	0,125l/m^2 over 15 days	S	0,063l/m^2 over 15 days

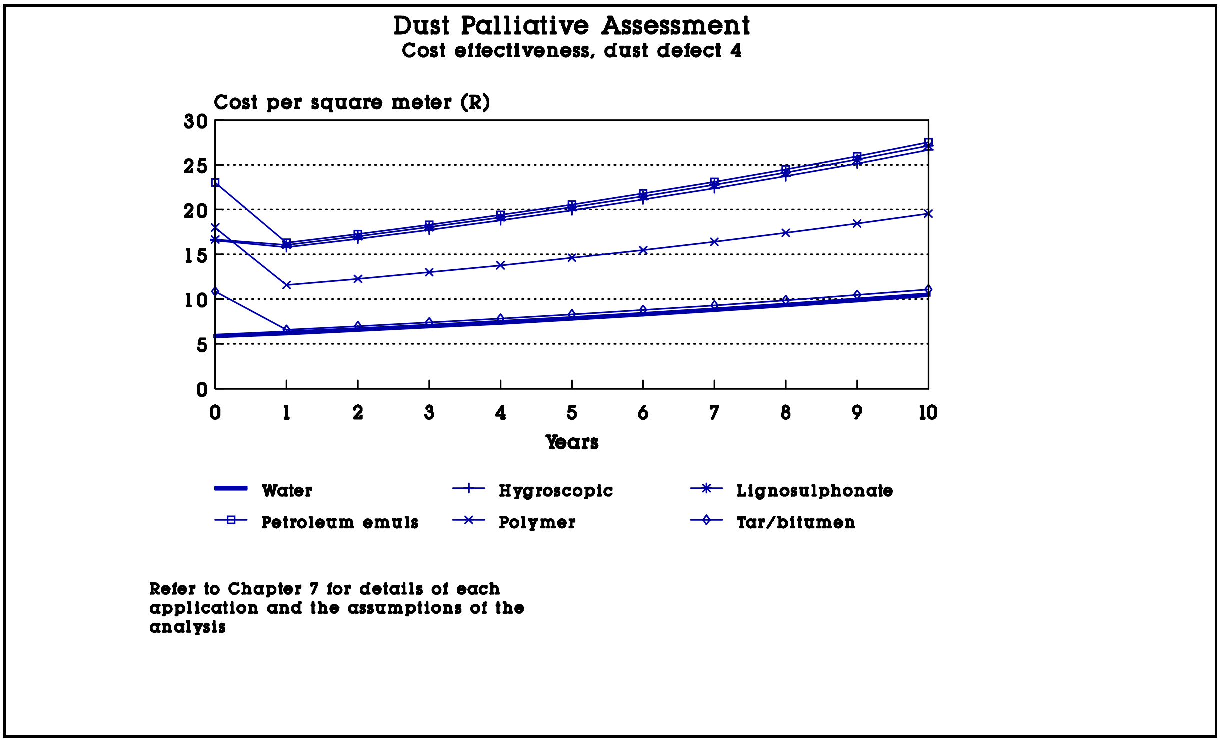
Notes

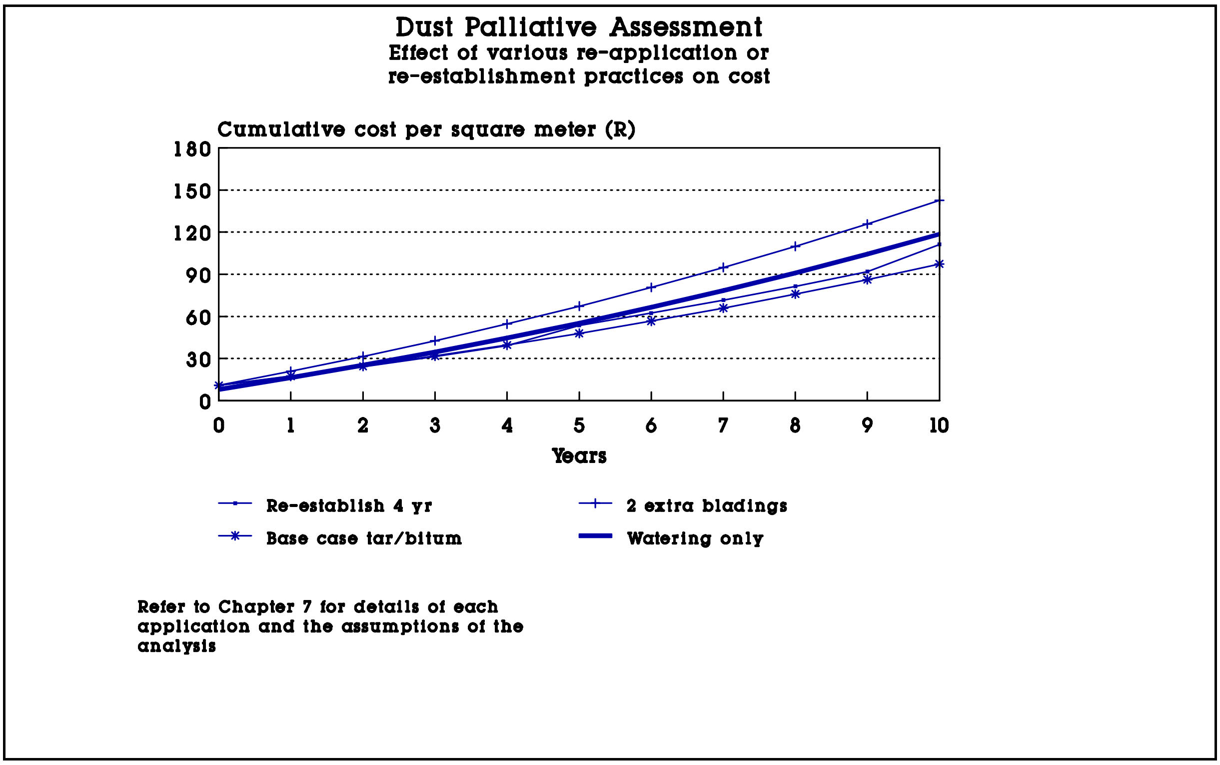
1 Actual price depends on mine and supplier location. Quoted price typical for class of product only, not individual product types. Management fees, etc. NOT INCLUDED in price.

2 The test results incorporated into the model may not represent the optimal performance of the palliative selected. Care should be taken when specifying the modelled or alternate establishment and re-application strategies. It is important that the data used closely reflects the anticipated palliative performance and that wearing course material conforms to selection guidelines.

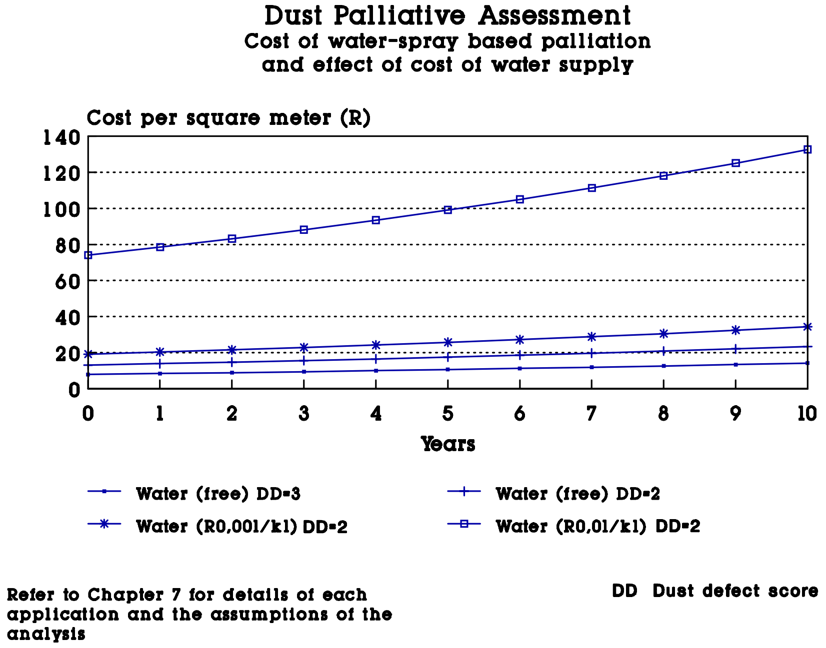


When the duration of dust suppression is considered, water-based spraying exhibits a cost benefit over that of chemical-based methods. In the analysis it is assumed that a palliative once applied, is active for 24 hours per day over its useful life. In the case of a mine, the road may





not be trafficked for 24 hours a day and as such suppression may not be needed. For a 24 hour dust suppression program based on water spraying to maintain a 65% average degree of palliation, the cost per square meter equates to R13,80 for the particular model parameters chosen. If the required watering hours is reduced to 18 hours, costs fall by 17% to R10,07/m^2 and for a 12 hour period, by 49% to R7,00/m^2. Under these circumstances, water-based spraying will be invariably cheaper than any form of chemical-based palliation.


Dust Palliative Assessment
Cost of water-spray based palliation
and effect of cost of water supply

Refer to Chapter 7 for details of each application and the assumptions of the analysis

DD Dust defect score

In Table 7.4, a cost option for water-based suppression was included. Currently, mines regard the water used for dust allaying purposes as a no-cost item since it is derived ex-pit. This assumption is incorrect since there is a cost associated with the provision and maintenance of the water filling points and reticulation system. To illustrate the impact of assigning a cost to the water used for dust allaying on the haul roads, water is assigned a no-cost value for maximum allowable dust defect scores of two and three, then a value of 0,1c/kl and 1c/kl, for a maximum allowable dust defect score of two. When the dust defect score is increased from two to three, the cost per square meter reduces by 39% as shown in Figure 7.5. At a dust defect score of two, when a charge for water is applied, the costs increase by 146% and 566% respectively for 0,1c and 1c per kilolitre. This would therefore significantly enhance the viability (in terms of cost-effectiveness) of using dust palliatives.

7.5 Summary of Palliative Cost Effectiveness Model

For chemical-based dust suppressants, the average degree of dust palliation and the period over which it applied has been shown to be considerably better than that achievable by water-based spraying alone. However, in terms of cost-effectiveness, an evaluation model was required with which to determine the extent of the cost benefits attributable to chemical-based dust suppression, together with an indication of those factors likely to alter the trade-off between water- and chemical-based dust palliation.

The model developed for the analysis consisted of identification of the key components that affect the overall cost of dust control and their interrelationship and effect on the total cost (R/m^2). The major cost elements for dust control include capital equipment, operation and maintenance costs, together with material cost (palliative cost) and activity-related costs such as surface preparation, dust palliative application, grading and watering and finishing, for either a mix-in or spray-on establishment or re-application. Other cost elements include equipment downtime and vehicle maintenance costs. These parameters are, in turn, influenced by the selected palliative and application methodology and frequency. Costs associated with reduced road maintenance intervals are also important since improvements in functionality were seen in Chapter 5 to be a major benefit of dust palliatives, especially where re-application interval could be made to coincide with blading activities.

The palliative performance in the model was based on data presented in Chapter 5, in terms of the product's establishment application rate (l/m^2), establishment method (spray-on or mix-in) and re-application rate (l/m^2 spray-on only) and frequency, to achieve a comparable average degree of dust palliation as to that achieved by water under the same conditions. Use of this data implies that each evaluation took place under optimal conditions, which was not the case. The application of any palliative to a sub-standard wearing course will not improve the performance of the wearing course over the long term and that poorly designed pavements cannot be remediated through the use of palliatives. The test results incorporated into the model may therefore not represent the optimal performance of the palliative selected. Care should be taken when specifying the modelled or alternate establishment and re-application strategies. It is important that the data used closely reflects the anticipated palliative performance. In addition, the testwork conducted did not allow for the build-up of palliative in the road and thus it is possible that the model under-estimates the average degree of palliation achieved over a specified time period, especially where multiple re-applications are envisaged.

For a maximum allowable dust defect score of two, both the tar/bitumen and polymer emulsion classes of product rendered a cheaper overall cost per square meter of treated road than did dust control by water-based spraying, with the tar/bitumen class of product also be significantly cheaper, even during establishment where the higher application rates usually resulted in the first year cost of treatment being in excess of that of water alone. When the allowable dust defect was increased to three, similar results were seen except for initially higher costs in up to year 1. When the allowable dust defect score reached four, due to associated lower average degree of dust palliation required, water-based spraying was the cheaper option. Current mine operating practice is typically represented by a dust defect value of between three and four which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, it was established in Chapter 4 that a maximum dust defect score of two was desirable from mine operators point of view and therefore, some form of chemical palliation would be beneficial in the long term, subject to the other cost constraints remaining valid.

Up to now a non-permanent surfacing was considered as the mines indicated a need to be able to blade spillage from the road. Spillage could be removed by other means, including brooming or vacuuming. Considering the rapid deterioration of the palliatives tested and the need to rejuvenate at regular intervals, a cheap type of permanent surfacing may be an economic option. Chip seals, with bitumen-rubber binder are highly flexible, and may prove to be an economic option, as it is likely that this could be constructed for under R15/m^2. With a life of at least four years and no blading maintenance, this may prove more viable than the most cost effectice chemical palliative thus far analysed. This is an issue that should be fully costed and modelled, but at present falls outside the scope of this report.

The effect of a number of other model variables were analysed, the most significant being any extra blading required, over and above that dictated by the palliative re-application frequency, and the daily duration of dust palliation. For the particular model parameters analysed, additional blading of the road (typically at intervals not dissimilar from the blading frequency associated with water-based dust suppression) resulted in a significant increase in costs such that watering became the cheapest suppression option. From this result it was clear that improvements in road functionality can significantly impact costs per square meter and any palliative applied should ideally contribute to improved functionality. In the case of the daily duration of dust palliation, since chemical-based palliatives act 24 hours per day, irrespective of how the road is trafficked, any non-trafficked periods will also be suppressed whilst with the water-based system, non-trafficked periods do not require watering. Thus it is seen that where a daily duration of trafficking falls below 14-16 hours, watering will invariably represent the cheapest suppression option.

The assumption that water used for dust allaying purposes is a no cost item is incorrect since there is a cost associated with the provision and maintenance of the water filling points and reticulation system. When a charge for water is applied and modelled, the costs per square meter road increase by 146% and 566% respectively for 0,1c and 1c per kilolitre. This would therefore significantly enhance the viability (in terms of cost-effectiveness) of using dust palliatives.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This Chapter presents a summary of the main conclusions of the SIMRAC (SIMCOL) research project COL467 which examined techniques to reduce the safety and health risk associated with the generation of dust on strip coal mine haul roads. The objective of the work was to develop a set of guidelines for the appropriate surface treatment selection, application and maintenance to provide a cost-effective means of reducing the safety and health hazard associated with dust on strip coal mine haul roads. This would be used to identify suitable spray-on or mix-in surface treatments to reduce the generation of dust, within the constraints of cost effectiveness and maintainability, through consideration of wearing course material type, traffic volumes and current road maintenance activities.

The mining industry, specifically surface strip coal mine operators can use the guidelines to optimise the safety and health of surface strip coal mine transport operations, through the reduction of transport related accidents and the structured recognition, evaluation and solution of dust generation problems on mine haul roads, leading to safer mining operations. The objectives were addressed through an assessment of the following enabling activities;

1. A literature study encompassing current state of the art regarding dust suppression techniques, products and measurement and assessment methodologies.
2. The identification of an appropriate experimental design and the establishment and/or characterisation of sites and test sections on participating mines
3. The identification of suitable surface treatments products
4. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites without treatment
5. The quantitative and qualitative evaluation of the dust defect visibility and health risk on sites with treatment, over a full climatic cycle where possible
6. A report offering recommendations and conclusions regarding the optimal wearing course surface treatment and management strategy

The following primary outputs were provided:

- ■ Guidelines to enable mine operators to cost-effectively reduce the safety and health risk of dust generated on strip coal mine haul roads through the optimal selection, application, evaluation, and maintenance of spray-on or mix-in dust palliation treatments.

- A qualitative methodology for evaluating haul road dust hazards and intervention levels adapted from a quantitative measuring system.
- The modelling and prediction of haul road dust hazards from consideration of wearing course material type, traffic volume, climate, maintenance and surface treatment applied to the road.
- The development of acceptability criteria for the haul road dust defect hazard and the dust health risk.

8.1.1 Review of the Current State

The literature study, encompassing both local and overseas sources revealed that scant attention had been paid to aspects of dust and dust control on mine haul roads and what data existed was generally uncoordinated and not comparable from site to site. No work addressed specifically the health aspects of dust generation, although they were alluded to in a number of studies where environmental and safety factors were considered. In the public domain, dust control and the assessment of dust palliatives have received more attention and formed the background to the study, especially in terms of the identification of general factors governing the emission of fugitive dust. Many of the studies undertaken by product manufacturers or road authorities were both uncoordinated and poorly monitored, with minimal information being recorded or published with which to objectively evaluate a product's performance. Many such experiments have failed, both on public roads and mine roads, due to a combination of poor marketing, sub-standard roads or application and construction techniques and no or inappropriate follow-on or re-application maintenance. This resulted in chemical palliatives being viewed with considerable scepticism by the industry.

Seven classes of palliative product were identified and their key performance limitations identified. The selection matrix needed to be extended to mine haul road applications to confirm their applicability under these significantly different operating conditions. Road wearing course material parameters were reviewed in the light of recommended selection parameters and as a precursor to identifying the likely application range of each palliative.

Economic evaluation forms an integral part of the assessment of dust palliative safety and health related performance issues on mine haul roads. A review of previous studies identified the key deficiencies in those analyses and provides the basis for the experimental design and test methodology. When coupled with the current state of dust measurement and dust prediction, it is clear that existing prediction models do not provide data required to assess the impact of haul road dust palliatives on safety and health: Control efficiencies over a longer term are required, coupled with as large a variation in the key performance factors previously identified. In addition, an estimate was required of the exposure to fugitive dust by persons on a mine haul road under the various traffic volume, wearing course and palliative types, using water-based suppression as the base case.

8.1.2 Development of Experimental Design

The primary objective of the study was to determine the most suitable haul road surface treatments which lead to a reduction in the generation of traffic-induced dust, within the constraints of cost effectiveness and maintainability. It was recognised that the extent of dust generation from hauling operations was attributable to a number of factors, namely;

- Wearing course material type
- Traffic volumes
- Road geometrics
- Climate
- Road maintenance activities.
- Type and application of palliative

The approach adopted for the study entailed the analysis of a number of in-service mine roads which covered the fullest range of these factors. Climate as a factor was eliminated from the study since most mines were located in the same physiographical region, as was the road traffic volume factor, primarily since the test site locations did not enable similar materials to be tested under a range of traffic conditions and due to the variable nature of the traffic itself. The class of palliative tested was limited by the selection (previously) made by the particular mine and little control could be exercised over the choice of palliative at each site.

The factor coverage envisaged in the experimental design encompassed various wearing course material weathering groups including pedocretes, argillaceous, acid crystalline, discards, carbonates and mixtures of materials. These material types formed the predominant material types for road construction in the Mpumulanga coalfield region. Twelve test sites were identified, seven of which were used for palliative testing and the generation of dust and watering efficiency models, two sites being used for chemical palliative testing only and three sites for the generation of dust and watering efficiency models only.

The range of chemical palliatives assessed was limited by the particular dust problems encountered and, to a lesser extent, the degree to which the particular product was marketed to the mines. Of the six product categories identified, hygroscopic salts, lignosulphonates, petroleum resins, polymer emulsions and tar/bitumen products were assessed. Modified waxes were not included in the assessment since no sites were identified at which waxes were being used.

8.1.3 Evaluation of Water-based Spray Suppression

Water-spray based dust suppression is the most common means of reducing dustiness on mine haul roads, the combination of a water-car and regular spray applications of water providing a relatively inexpensive, but not necessarily efficient, means of dust suppression. Five test sites were used to develop a water-spray based dust suppression model. The management strategy for water-spray based dust suppression was based on user defined levels of dust defect acceptability, both from a health and safety point of view. Mine operating personnel's opinion was used to attach defect scores to specific dust readings during the monitoring process. In general, the consensus was that a dust defect score of two represented a practical dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

An approximate appreciation of the role of climatic condition, expressed as mean monthly evaporation rates, on the time taken for water-spray based suppression to degenerate to zero was determined from a number of test sites over the range of typical summer and winter evaporation rates. To determine the re-application interval required to maintain dust defect scores at or below two and to therefore eventually model the cost-effectiveness of water-spray based suppression compared with other strategies, the peak and total dustiness of various types of wearing course materials and the effect of traffic speed on dustiness was modelled.

To provide an initial estimate of the dustiness associated with a particular wearing course material, seven test sites were selected from which data was recorded and analysed to model three parameters; the mass of dust as loose material on the road (g/m^2), the total dustiness (from consideration of peak and period of plume) and the total dustiness as a function of vehicle speed and mass of loose material on the road. By combining each of these models with the maximum allowable dust defect score and the associated peak value, the degree of palliation required to maintain this maximum defect score, and the associated re-application time, was determined. Under typical summer conditions, with a large rear-dump truck running at an average speed of 40km/h on a well built and maintained (untreated) haul road, re-watering is required at approximately 30 minute intervals to maintain a dust defect that at no time exceeds a score of two. Under winter conditions, the re-application interval extends to approximately 60 minutes. Current practice on mine haul roads involved re-watering every 60-90 minutes and this correlated, through the model, to a dust defect score of between three and four. It was therefore concluded that re-watering at such intervals was not sufficient to maintain the road-user defined limit of a dust defect score of 2, nor the equivalent average degree of dust palliation over the period analysed.

Whilst the combinations of these models gave an insight into the required watering frequencies for various combinations of vehicle types, speeds, traffic volumes, wearing course material types and evaporation rates, care should be taken to ensure that parameters used for the calculation fall within the sphere of influence of the major independent variables analysed. Further refinement of these models, through the analysis of extra test sites would enable a greater range of variables to be reliably analysed and thereby improve the predictive capability of the models proposed. Nevertheless, the example calculation procedure presented for determining typical water-based spray re-application frequencies can be used as a base case scenario with which to compare other types of dust palliatives.

8.1.4 Evaluation of Chemical-based Suppression

The evaluation of the various classes of palliatives previously identified involved the analysis of application methodology, maximum and average degrees of palliation achieved and the time period, degeneration rates expressed in terms of time from initial establishment and re-application (if appropriate). A degeneration rate expressed as a function of daily traffic volume was also included, but, due to the variability encountered in traffic volumes over the analysis period, the data was found to be misleading: Where traffic is not constant over the test period, or where smaller trucks or a better "quality" wearing course is used, artificially low traffic-induced degeneration rates were seen.

The highest instantaneous control efficiency measured was 92% immediately after application for the tar/bitumen class of palliative. The highest average efficiency measured was 75% over 86 days for tar/bitumen palliatives which was also the longest control period evaluated. Generally, for the palliative applications using spray-on techniques for establishment, the average degree of palliation hovered in the 40% to 60% range for the first two weeks, then decreased rapidly with time, whilst for the classes of palliatives using mix-in techniques for establishment, the average degree of palliation remained in the 60% to 70% range for the first 7 weeks, then decreased at a slower rate with time. In all cases, a longer analysis period and follow-up re-applications would probably increase the degree of palliation achieved and reduce its degeneration rate, due to build-up of residual product in the road. The results may therefore under-estimate the degree of palliation that can be achieved over the long term and therefore over-estimate the cost of a long-term chemical dust suppression program compared to water-spray systems.

All palliatives (with infrequent watering) share one common failing as compared with frequent water-spray systems. Material spillage on roadways was extremely common at all sites and spilled material was subject to re-entrainment. With frequent watering, the spilled material is moistened at approximately hourly intervals, whilst with hygroscopic products, if spillage is not too excessive, some sympathetic transfer of moisture may take place between treated road and the spillage, reducing dustiness. In the case of once-only applications, or those products requiring re-application only over longer intervals, spillage would go untreated for 2-7 weeks and as such generate most of the fugitive dust emissions from the road. In mines where spillage cannot be effectively controlled (especially prevalent where bottom dump trucks are used), watering, or failing that, the use of a road sweeper/vacuum in combination with a dust palliative may prove to be more effective for dust control. In locations where trackout from an untreated onto a treated road is a problem, watering these untreated sections aggravates the problem with moisture and mud. The use of a palliative in these areas is problematic since it was seen at a number of sites that the palliative, whether mix-in or spray-on high, could not withstand the high lateral shear forces generated by slow speed manoeuvring. In permanent tip areas, the solution may lie in the provision of a concrete cast in-situ pavement which can be swept clean.

From the analyses undertaken, it was clear that a poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative. The haul road wearing course material should ideally meet the minimum recommended specifications. If not, the inherent functional deficiencies of the material will negate any benefit of gained from using dust palliatives. In general, spray-on applications do not appear appropriate for establishment of dust treatments, especially with regard to depth of treatment required. A spray-on re-application may be more appropriate, but only if penetration of the product into the road can be assured, otherwise it will only serve to treat loose material or spillage build-up, which will rapidly breakdown and create new untreated surfaces. A spray-on treatment is however useful to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions from truck induced turbulence.

The potential of dust palliatives to improve functionality was illustrated at most sites, but more particularly those with a wearing course material that complies with the selection parameters for mine haul road wearing course materials. Road roughness also improved slightly at most sites, but this improvement was primarily attributed to a reduction in loose material, especially on roads deficient in binder or poorly graded. In both cases, functionality eventually reduces to a point where maintenance is required. Ideally, a palliative life that matches blading intervals would be ideal; the palliative degenerating over time at a similar rate to functionality, thus when the road is bladed, the maximum economic life has been extracted from the treatment. In the case of a mix-in palliative, spray-on re-applications could be usefully applied (provided that adequate penetration is achieved) to cover the upper 10-25mm of disturbed road surface.

Rainfall was seen to reduce both functionality and the degree of dust palliation achieved, primarily as a result of either poor road construction practices and/or leaching or erosion of the surface treatment. In those products where water penetration into the wearing course is prevented, the improved wet-weather trafficability reduces production downtime and this obviates the necessity for mud blading.

8.1.5 Evaluation of Haul Truck Driver Exposure to Respirable Dust

The health risk associated with exposure to fugitive dust emissions from mine haul roads was assessed through a number of sampling exercises undertaken in mine haul truck cabs, over a typical operating cycle. Seven test sites were evaluated in terms of the typical air quality indices (AQI's) that could be expected for a truck driver during a normal working day, linking sources of dust to overall AQI contribution during a typical haul cycle. Using the previously established intervention level and re-application frequencies to generate an average degree of dust palliation, the impact of this reduced dustiness was assessed in the light of expected improvements in the overall AQI.

In general, haul truck drivers in open cabs were exposed to poorer quality air than their equivalents in sealed or closed cabs. For open cabs, the average AQI over a typical operating cycle was approximately 3,0 which exceeded the correction intervention level of 1,0. For sealed cabs, the average cycle AQI was generally less than 1 but not less than the established good practice level of 0,5. A combination of high traffic volumes, a wearing course material prone to dustiness, high alpha-quartz respirable fraction content and dry loading or dumping conditions resulted in sealed cab AQI's exceeding 1,0. In summarising the evaluation of haul truck driver exposure to haul road respirable dust it is clear that, despite the limited data, basic experimental design and assumptions implicit in the analysis of the data, it is unlikely that haul road generated respirable dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are used. In most large mine haul trucks, a sealed and air conditioned cab is a standard feature. The greatest contribution to dust generation was derived from loading and dumping points, combined with the fact that drivers tended to open cab windows to improve visibility whilst reversing. Improved rear vision should be considered to reduce the entry of dust into a closed cab. Further benefit could be gained from the use of wet scrubbers in the air conditioning system where ambient dust levels warrant concern, or where the dust, once inside the sealed cab, needs to be removed quickly.

Whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources and the associated safety benefits. Where low capacity open cab trucks are used, typically in low tonnage operations with short haul distances, in conjunction with inherently dusty wearing course materials with high (>5%) respirable alpha-quartz fractions, palliation may significantly improve AQI's, especially if the benefits of palliation were extended to better dust control at the loading point, since on short haul trips, the time spent loading represents a greater proportion of the overall cycle time. The recommended frequency of re-application of water-based palliation entails considerable capital and operating expenditure. Coupled with the need to reduce dust from a safety perspective, the use of palliatives can still be motivated where water-spray tankers are re-deployed to reduce dust emissions, especially at the loading area.

8.1.6 Evaluation of Palliative Cost-effectiveness

For chemical-based dust suppressants, the average degree of dust palliation and the period over which it applied was shown to be considerably better than that achievable by water-based spraying alone. However, in terms of cost-effectiveness, an evaluation model was required with which to determine the extent of the cost benefits attributable to chemical-based dust suppression, together with an indication of those factors likely to alter the trade-off between water- and chemical-based dust palliation.

The model developed for the analysis consisted of identification of the key components that affect the overall cost of dust control and their interrelationship and effect on the total cost (R/m^2). The major cost elements for dust control include capital equipment, operation and maintenance costs, together with material cost (palliative cost) and activity-related costs such as surface preparation, dust palliative application, grading and watering and finishing, for either a mix-in or spray-on establishment or re-application. Other cost elements include equipment downtime and vehicle maintenance costs. These parameters were, in turn, influenced by the selected palliative and application methodology and frequency. Costs associated with reduced road maintenance intervals were also important since improvements in functionality were seen to be a major benefit of dust palliatives, especially where re-application interval could be made to coincide with blading activities.

The palliative performance in the model was based on the product's establishment application rate (l/m^2), establishment method (spray-on or mix-in) and re-application rate (l/m^2 spray-on only) and frequency, to achieve a comparable average degree of dust palliation as to that achieved by water under the same conditions. Use of the data implied that each evaluation took place under optimal conditions, which was not the case. The application of any palliative to a sub-standard wearing course will not improve the performance of the wearing course over the long term and that poorly designed pavements cannot be remediated through the use of palliatives. The test results incorporated into the model may therefore not represent the optimal performance of the palliative selected. Care should be taken when specifying the modelled or alternate establishment and re-application strategies. It is important that the data used closely reflects the anticipated palliative performance. In addition, the testwork conducted did not allow for the build-up of palliative in the road and thus it is possible that the model under-estimates the average degree of palliation achieved over a specified time period, especially where multiple re-applications are envisaged.

For a maximum allowable dust defect score of two, both the tar/bitumen and polymer emulsion classes of product rendered a cheaper overall cost per square meter of treated road than did dust control by water-based spraying, with the tar/bitumen class of product also be significantly cheaper, even during establishment where the higher application rates usually resulted in the first year cost of treatment being in excess of that of water alone. When the allowable dust defect was increased to three, similar results were seen except for initially higher costs in the first year. When the allowable dust defect score reached four, due to associated lower average degree of dust palliation required, water-based spraying was the cheaper option. Current mine operating practice is typically represented by a dust defect value of between three and four which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, using a road-user defined maximum dust defect score of two, some form of chemical palliation would be beneficial in the long term, subject to the other cost constraints remaining valid.

The effect of a number of other model variables were analysed, the most significant being any extra blading required, over and above that dictated by the palliative re-application frequency, and the daily duration of dust palliation. For the particular model parameters analysed, additional blading of the road (typically at intervals not dissimilar from the blading frequency associated with water-based dust suppression) resulted in a significant increase in costs such that watering became the cheapest suppression option. From this result it was clear that improvements in road functionality significantly impact costs per square meter and any palliative applied should ideally contribute to improved functionality. In the case of the daily duration of dust palliation, since chemical-based palliatives act 24 hours per day, irrespective of how the road is trafficked, any non-trafficked periods will also be suppressed whilst with the water-based system, non-trafficked periods do not require watering. Thus it is seen that where a daily duration of trafficking falls below 14-16 hours, watering will invariably represent the cheapest suppression option.

The assumption that water used for dust allaying purposes is a no-cost item is incorrect since there is a cost associated with the provision and maintenance of the water filling points and reticulation system. When a charge for water is applied and modelled, the costs per square meter road increase by 146% and 566% respectively for 0,1c and 1c per kilolitre. This would therefore significantly enhance the viability (in terms of cost-effectiveness) of using dust palliatives. Chip seals, with bitumen-rubber binder are highly flexible surfacings and may prove to be an economic option, as it is likely that this could be constructed for under R15/m^2. With a life of at least four years and no blading maintenance, this may prove more viable than the most cost effectice chemical palliative thus far analysed. This is an issue that should be fully costed and modelled, but at present falls outside the scope of this report.

8.2 Recommendations

The following recommendations are made in the light of the findings outlined above;

1 From a mining perspective, the following parameters define an acceptable dust palliative;

- ■ Mix-in establishment applications with minimal site preparation (rip, mix-in and recompact) and spray-on maintenance re-applications, or (less preferable), spray-on establishment applications with deep penetration into the compacted wearing course, followed by spray-on maintenance re-applications.
- ■ Straight-forward applications requiring minimal supervision, not sensitive nor requiring excessive maintenance or closely controlled re-applications.
- ■ Trafficable within a maximum of 24 hours (short product curing period).
- ■ Availability in sufficient quantity at reasonable prices.
- ■ Adequate proven or guaranteed durability, efficiency and resistance to deterioration by leaching, evaporation, ultra-violet light and chemical reaction with wearing course or spillage on road, to provide a high degree of dust palliation over a period commensurate with the functional deterioration profile of the road.
- ■ Effective over both wet and dry seasons.
- ■ Safe to handle, non-inflammable, non-corrosive, non-toxic, neither in its pre- nor post application (leached constituents) state and environmentally acceptable. Evaluated against local and international standards.

2 The management strategy recommended for water-spray based dust suppression should be based on user defined levels of dust defect acceptability. In general, the consensus of road-users was that a dust defect score of two represented a practical dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

3 Since the evaluation of haul truck driver exposure to haul road respirable dust concluded that it is unlikely that such dust poses a significant threat to average air quality in the driver's cab, especially where sealed cabs are used, it is recommended that where low capacity open cab trucks are used in conjunction with inherently dusty wearing course materials with high (>5%) respirable alpha-quartz fractions, palliation should be considered to improve AQI's, especially if the benefits of palliation were extended to better dust control at the loading and tipping points. Consideration should also be given

providing improved rear vision facilities to prevent dust entering closed cabs.

4 Whilst the data would motivate against the use of dust palliatives purely on the grounds of improvements to air quality, the results should be viewed holistically with regard to the overall mine dust palliation strategy, more particularly, the control of the various dust sources and the associated safety benefits. Coupled with the need to reduce dust from a safety perspective, the use of palliatives can still be motivated where water-spray tankers are re-deployed to reduce dust emissions, especially at loading or tipping areas.

5 Under typical summer conditions, for a water-based spray suppression system with a large rear-dump truck running on a well built and maintained haul road, re-watering is required at approximately 30 minute intervals to maintain a dust defect that at no time exceeds a score of two. Under winter conditions, the re-application interval extends to approximately 50 minutes.

6 The watering model should be used to determine individual mine watering frequencies for the characteristic site parameter combinations. Further refinement of the model is recommended to enable a greater range of variables to be reliably analysed and thereby improve the predictive capability.

7 The average degree of palliation achieved using chemical palliatives can significantly reduce dust emissions from a mine haul road, and the primary impact of these reductions would be improved visibility and safety, and in the case of open-cab trucks, an improvement in the air quality index. It is recommended that palliatives be considered as a dust suppression system, subject to the limitations described.

8 A mix-in establishment is recommended for a mine haul road, irrespective of palliative type, followed by spray-on maintenance re-applications. A poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative and it is recommended that the haul road wearing course material should at least satisfy the minimum material selection specifications. If not, the inherent functional deficiencies of the material will negate any benefit gained from using dust palliatives.

9 A spray-on treatment is recommended to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically

being uncompacted, would provide some depth of penetration and a reduction in dust emissions generated from truck induced turbulence.

10 All palliatives (with infrequent watering) share one common failing as compared with frequent water-spray systems. Material spillage on roadways was extremely common at all sites and spilled material was subject to re-entrainment. In mines where spillage cannot be effectively controlled, watering, or failing that, the use of a road sweeper/vacuum in combination with a dust palliative may prove to be more effective for dust control.

11 The use of a palliative in dumping and tipping areas is not recommended due to the high lateral shear forces generated by slow speed manoeuvring. In permanent tip areas, the solution may lie in the provision of a concrete cast in-situ pavement which can be swept clean.

12 Road functionality can be significantly improved through the use of dust palliatives. A palliative application frequency is recommended which matches road blading intervals; the palliative degenerating over time at a similar rate to functionality, thus when the road is bladed, the maximum economic life has been extracted from the treatment.

13 The model developed for the analysis of palliative comparative cost-effectiveness should be used as a basis for the identification and costing of the key components that affect the overall cost of dust control. Care should be taken when specifying the modelled or alternate establishment and re-application strategies and it is important that the data used closely reflects the anticipated palliative performance. Since the testwork conducted did not allow for the build-up of palliative in the road it is possible that the model under-estimates the average degree of palliation achieved over a specified time period, especially where multiple re-applications are envisaged.

14 For a maximum allowable dust defect score between two and three, several classes of product rendered a cheaper overall cost per square meter of treated road than did dust control by water-based spraying. When the allowable dust defect score reached four, due to associated lower average degree of dust palliation required, water-based spraying was the cheaper option. Current mine operating practice is typically represented by a dust defect value of between three and four which would indicate that in some circumstances, watering is the cheapest form of dust palliation. However, using a road-

user defined maximum dust defect score of two, some form of chemical palliation would be beneficial in the long term, subject to mine cost constraints and assumed palliative performance models.

15 Additional blading of the road (typically at intervals not dissimilar from the blading frequency associated with water-based dust suppression) should be avoided since this resulted in a significant increase in costs, making watering the cheapest suppression option. Improvements in road functionality significantly impact costs per square meter and any palliative applied should ideally contribute to improved functionality.

16 Where the road is required to handle traffic over short period of time per day, typically below 14-16 hours, watering will invariably represent the cheapest suppression option under these circumstances, subject to individual mine cost and road performance constraints.

17 The assumption that water used for dust allaying purposes is a no cost item is incorrect and should be re-evaluated by mines since there is a cost associated with the provision and maintenance of the water filling points and reticulation system. Subject to the actual cost of water being determined, this could significantly enhance the viability (in terms of cost-effectiveness) of using dust palliatives and may even warrant the assessment of flexible bitumen-rubber bound chip seals.

8.3 Recommendations for Further Research

Whilst the conclusions and recommendations presented fulfil the objectives of the research project, several areas were identified which, albeit outside the scope of the current work, may be beneficial in reducing dust emissions and/or more fully defining certain key aspects of the original problem. The following recommendations for further research are made;

1 A longer evaluation period for individual chemical palliatives. To overcome the problem of small, expensive trials which may fail in the short term, likely palliatives can be initially selected according to their potential cost-effectiveness compared to watering and these specific palliatives analysed.

2 The watering model could be improved by extending the data to cover a greater climatic

region, with the inclusion of wind speed and humidity data over shorter time periods to enable daily water-based dust management strategies to be defined. The current model broadly represents seasonal watering practices but does not accommodate optimisation and management on a daily basis. The cost model indicates that by tailoring the watering model to daily re-application interval, significant cost savings and improved efficiencies can be realised.

3 Dust control methods and options need to be further investigated at pit loading and tipping points since the greater proportion of a driver's exposure to dust was generated from these two sources. The chemical palliation options analysed here are not appropriate in controlling this fugitive dust source.

4 More permanent surfacing needs to be investigated, both from a cost effectiveness and suppression efficiency point of view. Bitumen-rubber chip seals may prove to be a tractable and affordable option in conjunction with brooming or vacuuming, obviating the need for blading maintenance and providing a relatively cheap all weather surface.

REFERENCES

ADDO, J.Q. AND SANDERS, T.G. (1995). Effectiveness and Environmental Impact of Road Dust Suppressants. MPC Report 94-28A, Mountain Plains Consortium: Fargo, North Dakota, USA.

AMPONSAH-DACOSTA, F. (1997). Cost-effective strategies for dust control in an opencast coal mine. MSc Project Report, University of the Witwatersrand, Johannesburg, South Africa.

ARRB. (1996). Road Dust Control Techniques, Evaluation of Chemical Dust Suppressants' Performance. Special Report 54, Victoria, Australia.

BISHOP, T. (1999). Personal communication. Revertex Chemicals (Pty) Ltd, Jacobs, South Africa.

BOYD, K.R & VON CAAUWENBERGHE, R. (1980). Evaluation of lignosulphonate as a dust palliative. Research report 80-2, report 1, Department of Highways and transportation, Materials Research Division, Winnipeg, Manitoba, Canada.

BURROWS, J (ed). (1989). Environmental Engineering in South African Mines. 1st Edition, MVSA, South Africa.

COPPIN, N. & ARMSTRONG, A. (1996). Dust - understanding the solutions. Quarry Management, 23(3), Institute of Quarrying, Nottingham, UK, pp29-35.

COMMITTEE OF STATE ROAD AUTHORITIES. (1985). Technical recommendations for highways (TRH14): Road construction materials. CSRA TRH14, Pretoria, RSA.

COMMITTEE OF STATE ROAD AUTHORITIES. (1990). The structural design, construction and maintenance of unpaved roads. Draft CSRA TRH20, Pretoria, RSA.

COMMITTEE OF STATE ROAD AUTHORITIES. (1990a). Pavement management systems: Standard visual assessment manual. Draft TMH9, Pretoria, RSA.

COWHERD, C, (Jr). (1986). Fugitive Dust Emissions, Midwest Research Institute, Kansas City

Missouri, USA.

DAVIES, C.N. (1947). The Sedimentation of Small Suspended Partaicles. Sympoium on Particle Size Analysis. Trans. Instn. Chem. Eng., Vol 25, 1947, supple. p25-39.

DEPARTMENT OF MINERALS AND ENERGY. (1994). Guidelines for the gravimetric sampling of airborne particulates for risk assessment in terms of the ODMW Act 78 of 1973. Department of Minerals and Energy, GME 16/2/3/2/3, Pretoria, South Africa.

DEPARTMENT OF MINERALS AND ENERGY. (1996). Mine Health and Safety Act, 1996. Act No 29 of 1996, Department of Minerals and Energy, Pretoria, South Africa.

DEPARTMENT OF MINERALS AND ENERGY. (1999). Draft Guidelines for the Compilation of a Mandatory Code of Practice for an Occupational Hygene Program (No.1 Personal Exposure to Airborne Pollutants). Department of Minerals and Energy, draft ammendment 6 of 1999, Pretoria, South Africa.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY. (1998). National Water Act, 1998. Act No 36 of 1998, Department of Water Affairs and Forestry, Pretoria, South Africa.

GARDINER, L.R & SCHROEDER, H.H.E. (1982). The deposition of airborne particulates in the respiratory tract. Air Pollution Division, Industrial Hygiene Branch, COM Research Report, Johannesburg, South Africa.

HUND GMBH. (1991). Environmental Monitoring. Helmut Hund Gmbh. Wetzlar, Germany.

JONES, D. (1996). The inpacts and control of dust on mine haul roads. Proceedings of the South African Institute of Mining and Metallurgy Conference on Surface Mining, Glen H.W. ed., 30 September - 4 October 1996, Sandton, South Africa, pp. 351-355

JONES, D. (1996a). The impacts and control of dust generated from unsealed roads. Proceedings of the South African Institute of Civil Engineers, Second National Conference on Environmental Management Technology and Development, Indaba Conference Centre, Johannesburg, South Africa.

JONES, D. (1997) Synthesis Report on Dust and Dust Control Research in South Africa.

Contract Report CR- 97/075, Division of Roads and Transport Technology, CSIR, Pretoria, South Africa.

JONES, D. (1998). The Devlopment of a Dust Prediction Model for Prioritising Dust Control on Unsealed Roads. Proc., 19th ARRB TR Conference, Sydney, Australia.

JONES, D. (1999). Holistic Approach To Research into Dust and Dust Control on Unsealed Roads. Division of Roads and Transport Technology, Council For Scientific and Industrial Research, Pretoria, South Africa.

JONES, T.E. (1984). Dust Emission From Unpaved Roads in Kenya. TRRL Laboratory Report 1110, (Transport and Road Research Laboratory), Crowthorne, UK.

KOTZE, W. (1999). An Evaluation of Haul Road Dust Suppression At New Vaal Colliery. Project Report Mining Engineering, Faculty of Engineering, University of Pretoria, Pretoria, South Africa.

MULHOLLAND, R.W. (1982). Evaluation of dust palliatives of secondary highways. technical Report 18, Saskatchewan Department of Highways, Regina, Canada.

NATIONAL INSTITUTE FOR TRANSPORTATION AND ROAD RESEARCH. (1986). Standard methods of testing road construction materials. Technical methods for highways No. 1 (TMH1), CSIR, Pretoria, RSA.

NETTERBERG, F. (1985). Wearing courses for unpaved roads. NITRR technical noteTS/33/85, CSIR, Pretoria, RSA.

PAIGE-GREEN, P. & NETTERBERG, F. (1987). Requirements and properties of wearing course materials for unpaved roads in relation to their performance. Fourth International Conference on Low-volume Roads, Transportation Research Record 1106, vol 1, National Research Council, Washington, USA, pp208-214.

PAIGE-GREEN, P. (1989). The influence of geotechnical properties on the performance of gravel wearing course materials. PhD Thesis, University of Pretoria, South Africa.

REICHERT, J. (1987). Results of an enquiry concerning the maintenance of unpaved roads in developing countries. OECD working group, Paris, France.

SIMPSON, G.C, RUSHWORTH, A.M, VON GLEHN, F.H. AND LOMAS, R.H. (1996). Investigation into the causes of transport and tramming accidents on mines other than coal, gold and platinum. Safety in Mines Research Advisory Committee, Other Mines Sub-committee final project report OTH202, Department of Minerals and Energy, Pretoria, South Africa.

THOMPSON, R.J. (1996). The Design and Management of Surface Mine Haul Roads. PhD Thesis, Faculty of Engineering, University of Pretoria, Pretoria, South Africa.

THOMPSON, R.J. & VISSER, A.T. (1997). An Integrated approach to the design of surface mine haul roads in South Africa. International Journal of Storing, Handling and Transporting in Bulk; Bulk Solids Handling, vol 17, n3.

THOMPSON, R.J, VISSER, A.T, SMITH, R.A.F AND FOURIE. G.A.F. (1997). Final report for project SIMOT 308, Safety in Mines Research Advisory Committee, Other Mines Sub-committee, Department of Minerals and Energy, South Africa

THOMPSON, R.J AND VISSER, A.T. (1999). The management of unpaved road networks on opencast mines. Transportation Research Record (TRR) 1652 vol 2, Transportation Research Board, National Academy Press, Washington, D.C., USA, pp 217-224.

UMA ENGINEERING LTD. (1987). Guidelines for the cost effective use and application of dust palliatives. Roads and Transportation Association of Canada, Ottawa, Canada.

USBM. (1983). Cost-effectiveness of dust controls used on unpaved mine haul roads. United States Bureau of Mines Report, by Pedco Environmental Inc., JO218021, Minneapolis, Minesota, USA.

USDA. (1993). What the forest service does. United States Department of Agriculture, Forestry Service.

USEPA. (1987). User's Guide: Emision Control Strategies and Emission Factors for Unpaved Road Fugitive Emissions. United States EPA, EPA/625/5-87/022, Research Triangle Park, North Carolina, USA.

USEPA. (1988). Control of open fugitive dust sources. Office of Air Quality Planning and Standards, United States 68-02-4395, MRI project 8985-14, Research Triangle Park, North Carolina, United States.

USEPA. (1995). National Air Pollution Emission Trends, 1990-1995. Office of Air Quality Planning and Standards, United States EPA/454/R-96-007, Research Triangle Park, North Carolina, United States.

VISSER, A.T. (1981). An evaluation of unpaved road performance and maintenance. PhD Thesis, University of Texas at Austin, USA.

WEINERT, H.H. (1980). The natural road construction materials of Southern Africa, H and R Academia, Cape Town, South Africa.