Prediction of Skid Resistance Performance of Chipseal Roads in New Zealand

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Executive Summary

Introduction

A four-year programme of research was undertaken in New Zealand (from 2000 to 2003) to determine how aggregate size, shape and spacing (i.e. macrotexture) impacts on the provision of low- and high-speed wet coefficients of tyre-road friction. This research programme involved a combination of field, laboratory-based and statistical modelling studies.

Emphasis was placed on the in-service skid resistance performance of straight and level sections of state highway where horizontal tyre forces will be at their lowest and least variable. This eliminated any confounding effects brought about by vehicle manoeuvres that generate higher but more variable tyre forces, such as when accelerating from rest, braking, cornering, and hill climbing.

The primary aim of the research was the development of a model, validated for conditions found on the New Zealand State Highway network, that allows reliable prediction of in-service skid resistance performance of chipseal surfaces from readily determined surface and traffic characteristics. The intended uses of the model are to guide design; allow more effective safety management of road networks through the ability to forecast the need for skid resistance restoration treatments; and to identify aggregate properties that have the greatest influence on skid resistance so that laboratory test procedures utilised for prequalifying surface course aggregates on the basis of their long-term skid resistance can be improved.

Secondary aims were to:

- determine relationships between common skid resistance measures employed in New Zealand and the friction coefficient of car tyres as derived from emergency braking tests;
- gain an improved understanding of contamination mechanisms, notably tracked binder film and detritus build-up over dry spells and their adverse effect on skid resistance; and
- quantify the contribution of macrotexture to low-speed and high-speed wet coefficients of braking friction.

The following conclusions and recommendations have been derived within the scope and limitations of the research programme.

Field Study – Emergency Braking Tests

Emergency braking tests, involving both four-wheel locked braking and ABS (independent anti-lock braking system on all four wheels) were performed on six test sites to obtain accurate measurement of wet and dry stopping distances and associated average coefficients of friction. These sites comprised 4 chipseal and 2 asphaltic concrete surfaces, and covered a wide range of microtexture and texture depth levels so that the various aggregate contributions to tyre–road friction could be assessed. The limited emergency braking tests provided evidence that:

1. The reported influence of road surface texture depth on low and high speed friction is negated by vehicles fitted with anti-lock braking systems (ABS) and tyres with adequate tread depth (i.e. ≥ 1.5 mm). Under such operating conditions, wet tyre–road friction appears to be insensitive both to speed over a 25 to 100 km/h range and to texture depth.
2. Under locked-wheel braking initiated at typical urban speeds (i.e. ≤ 50 km/h), wet tyre–road friction reduces with increasing speed but not at the rate predicted by International Friction Index (IFI).
3. Skid testers in common use in New Zealand display differing sensitivities to microtexture and macrotexture properties of road surfaces. However, their measurements of skid resistance showed significant correlations ($r^2 \geq 0.8$) with both dry and wet tyre–road coefficients of friction derived from locked-wheel emergency braking. Generally, SCRIM (Sideway-force Coefficient Routine Investigation Machine) measurements were shown to provide the most reliable estimates.

Recommendation

- Improved understanding of the inter-relationships between wet tyre–road friction, volumetric texture depths of tyres and road surfaces, vehicle speed, and water film depth is required before models for the reliable prediction of friction under different wet operating conditions can be developed. In the interim, IFI modelling of wet friction–speed dependencies appears adequate if the volumetric texture depth of the tyre is incorporated in the calculation of the speed number Sp.

Field Study – Time Series GripTester Measurements

GripTester surveys were undertaken on public roads to monitor the variation of skid resistance of road surfaces over a prolonged period of time. These surveys established that skid resistance is highest soon after a period of rain and then reduces with time if there is a prolonged dry spell. The results highlight the need to take care when interpreting skid resistance measurements to distinguish what is the inherent skid resistance of a road surface and what is the influence of previous rainfall history.

Recommendation

- Some evidence suggests that the rate at which skid resistance decays, as a function of days since rain, will differ with aggregate type (i.e. greywacke, basalt, andesite, etc.). Therefore, further investigation is required to quantify the rate the skid resistance of a road surface reduces with the length of time since rain as a function of skid tester device, aggregate rock type, sealing chip size, and aggregate microtexture depth. The findings will be useful for interpreting and normalising skid resistance survey results and in the selection of sealing chips to achieve a specified level of skid resistance.

Laboratory-Based Study – Bitumen Contamination

British Pendulum Tester (BPT) measurements were performed on pavement core and laboratory-made chipseal samples successively coated with thicker films of bitumen. This allowed the relative contributions of aggregate microtexture and surface texture profile to be quantified in terms of British Pendulum Number (BPN). These measurements showed that:

1. Aggregate microtexture contributes between 8 BPN (worn surface) and 28 BPN (new surface) to the overall skid resistance of the road surface sample, corresponding to 13% and 30% respectively.

2. The contribution of macrotexture to overall skid resistance is comparable to that of aggregate microtexture. This was an unexpected result and suggests that for chipseal surfaces, the hysteresis and adhesion components of friction are similar in magnitude.
3. The relative contribution of aggregate microtexture to the skid resistance provided by a road surface increases as the macrotexture of the surface decreases.
4. The presence of bitumen film on chipseal road surfaces can result in reductions of skid resistance of between 20% and 30% in situations where the contamination is severe (i.e. bitumen film thickness of the order of 0.1 mm). However, the resulting level of skid resistance is still significantly greater (at least three times) than that provided by a smooth, bitumen-only surface. This suggests that chipseal surfaces in a flushed condition pose a greater safety hazard to motorists in wet conditions than chipseal surfaces that have been blackened by tracked bitumen.

Recommendations

- To assist the formulation of skid resistance models, and to identify any significant anomalies, the relative contributions of aggregate microtexture and macrotexture to overall skid resistance should be investigated for alluvial-sourced and hard rock-sourced aggregates of the rock types commonly used in New Zealand as sealing chips.
- Safety management of road networks should target the elimination of flushed sections of chipseal surfaces wherever they occur at locations of high friction demand, such as mid-curve, and wherever the continuous length of flushed surface in a wheelpath is 20 m or greater, to prevent potentially hazardous braking manoeuvres.

Statistical Modelling Studies – Aggregate Characteristics and Skid Resistance

A regression analysis was performed to investigate the sensitivity of in-service skid resistance performance of chipseal-surfaced sections of state highway to aggregate and texture characteristics under different traffic loading. This regression analysis was performed on a specially assembled database that comprised SCRIM-based skid resistance data from annual network surveys undertaken since 1998 and 18 different standard measures of surface texture derived from stationary laser profiler measurements made on 47 straight and level test sites located on state highways.

The regression analysis revealed that:

1. The model for relating skid resistance, aggregate PSV, and HCV traffic contained in Transit New Zealand's TNZ T/10 specification gave predictions of skid resistance that correlated poorly ($r^2 = 0.08$) with the measured in-service skid resistance of the 47 test sites. This model tended to overestimate the level of skid resistance, which is a concern. The predicted mean summer SCRIM coefficient (MSSC) values agreed to ±0.04 of that observed for about 55% of the test sites (26 out of 47).

2. The critical determinants of in-service skid resistance performance of straight, chipseal-surfaced road sections were identified through unconstrained stepwise regression analysis to be:
   - cumulative heavy commercial vehicle (HCV) passes; and
   - the mean spacing between tips of the aggregates (the smaller the spacing, the higher the skid resistance).

3. A threshold value of cumulative HCV passes exists which, when reached, results in no further reduction in skid resistance over time due to traffic-induced wear. This threshold value is 1 million HCV passes.

4. When the stepwise regression was forced to include aggregate PSV as a model input, the following surface texture variables became important predictors of skid resistance:

   Rsk = the skewness of the road profile about the mean line;
   delq = the root-mean-square (rms) slope of the road surface profile;
   Rvm = the mean maximum depth of the road profile from the mean line.

5. In practice, the combined contribution of the surface texture variables Rsk, delq, and Rvm to overall skid resistance was found to range between –0.07 MSSC and 0.03 MSSC with a mean value of –0.03 MSSC. This result suggests that the potential for optimising aggregates with regard to shape and distribution within the surface to maximise skid resistance may be limited.

6. The regression model that displayed the best compromise between ease of application and accuracy was as follows:

$$MSSC_{av} = 0.0013 \times PSV + 0.10 \times e^{-CHCV} - 0.007 \times ALD + 0.44$$

   where:
   $MSSC_{av}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
   PSV = polished stone value
   CHCV = cumulative heavy commercial vehicle traffic per lane in millions
   = commercial vehicle traffic > 3.5 tonnes /lane/day × surface age (years) × operational days per year (=300)/10^6
   = 0.0003 × HCV × AGE
   ALD = the average least dimension of the sealing chip (mm)

7. This regression model represents a significant improvement over the skid resistance model incorporated in Transit New Zealand's T/10 specification, achieving fit statistics of $r^2 = 0.35$, and standard error of estimation (SE) = 0.04.

8. The average HCV exposure of two-lane rural state highways is 129 HCV/lane/day. The expected rate of change in skid resistance due to the polishing action from this volume of HCV traffic is estimated from the regression model to average out at about –0.003 MSSC/year over the expected service life of a chipseal surface. This can be regarded as being negligible, when compared to short-term variations in skid resistance brought about by spells of dry and wet weather.

9. A critical value of cumulative HCV passes exists, above which it is very difficult to satisfy investigatory levels for skid resistance specified in Transit New Zealand's T/10 specification for the high demand site categories (i.e. 1, 2 and 3) using natural aggregates.

10. Evidence suggests that the skid resistance deterioration mechanism for alluvial aggregates is quite different to that of aggregates quarried from hard rock.

11. By grouping the 47 test sites in terms of alluvial- and hard rock-sourced aggregates and performing a separate regression analysis on each grouping, an indication of the size of differences in MSSC sensitivities to the key variables of PSV, cumulative HCV passes and aggregate size, was able to be obtained for these two aggregate types.

12. The preliminary indications are that:
    - selection of "rounded" alluvial aggregates for skid resistant surfaces should be predicated on PSV as is current practice; and
    - selection of "angular/sharp-edged" hard rock aggregates should be predicated on size (the smaller the better) and ability to withstand tip- and edge-wear caused by HCV traffic.

Recommendations

- The statistical modelling has shown that, for a given speed, the more often there is contact between the tyre and road, the higher the skid resistance. For the vehicle speeds expected on rural state highways, a mean spacing of 5 mm to 15 mm between tips of aggregates is considered necessary to satisfy both hysteresis and drainage requirements. In comparison, the tip spacing measured in the field ranged between 8 mm and 25 mm, reflecting the dominant use of Grade 2 to Grade 5 sealing chips.

  A move to confine the construction of chipseal surfaces to Grade 3 to Grade 6 sealing chips is therefore seen as being desirable for efficient provision of skid resistant roads.

- Aggregates need to be tested for their ability to maintain their shape under the wearing action of HCV traffic. A possible candidate test is the aggregate abrasion value (AAV), which provides a measure of resistance of the aggregate to surface wear by abrasion.

- Measuring more surface texture variables than mean profile depth (MPD) during annual high speed condition surveys of the state highway network should be considered so that additional information on amplitude, spacing and shape characteristics of the road surface profile can be provided. This will lead to an improved knowledge as to how the macrotexture of a road surface wears as a result of both seasonal effects and exposure to traffic. This improved knowledge, in turn, can be used to improve design processes and laboratory test procedures utilised for prequalifying surface course aggregates on the basis of their long-term skid resistance.

- Continued investigation in the following two areas is required to refine the regression model to the stage that it can be incorporated in Transit New Zealand's T/10 specification:
  - Effect of aggregate microtexture depth and abrasion/wear resistance to establish whether or not separate models will be needed for different types of sealing chip, i.e. for hard or soft alluvial or quarried rock.
  - Effect of horizontal tyre forces to establish whether or not the rate of skid resistance decay with cumulative HCV passes increases and/or the equilibrium value of skid resistance reduces as a function of increasing horizontal tyre forces.

- If the proposed regression based skid resistance model is to be used for seal design purposes, the constant term should be reduced by 0.08 to 0.36 to account for both short-term weather effects and the model's precision. This will yield conservative estimates of skid resistance for straight road sections.

- The PSV test allows roading aggregates to be ranked according to their ability to resist polishing under standard conditions. However, at the present time, it has not been established whether or not the polishing action of HCV traffic is more or less abrasive than the polishing action of the PSV test, yet in modelling skid resistance, aggregate PSV is still assumed to correspond to the situation of terminal microtexture.

- As depth of microtexture has been shown to be a strong contributor to the variation of skid resistance, the development of microtexture decay relationships for different natural aggregate sources is necessary to advance skid resistance modelling, and to allow selection of aggregates on the basis of exposure to cumulative HCV passes over the expected service life of the road surface.
- There is a need to better understand how the microtexture characteristics of roading aggregates change with respect to cumulative HCV passes and how this can be reliably simulated through laboratory testing.

Abstract

This report presents the results of a 4-year research programme (from 2000 to 2003) involving a combination of field, laboratory-based, and statistical modelling studies undertaken to identify critical aggregate properties from the perspective of in-service skid resistance performance of chipseal surfaces. Emphasis was placed on straight and level road sections to minimise confounding effects brought about by braking, cornering, and traction manoeuvres.

The principal finding of the research was that the critical determinants of in-service skid resistance performance of chipseal surfaces were:
- cumulative heavy commercial vehicle (HCV) passes; and
- the mean spacing between tips of aggregates.

As a result, a rational model was formulated that provides 95% certainty that the predicted value of skid resistance will be within ±0.08 MSSC of observed values. The model inputs are limited to PSV, HCV traffic, seal age and aggregate average least dimension (ALD). However, significant inter-relationships between aggregate microtexture and macrotexture were also identified, which require additional investigation given their implication to current seal design practice.

The preliminary indications are that:
- selection of "rounded" alluvial aggregates for skid resistant surfaces should be predicated on PSV as is current practice; and
- selection of "angular/sharp-edged" hard rock aggregates should be predicated on size (the smaller the better) and ability to withstand tip- and edge-wear caused by HCV traffic.

Nomenclature

As abbreviations, acronyms and symbols are fully defined when they first appear in the report, only those more commonly used are listed below for ready reference.

AAV = aggregate abrasion value
ABS = anti-lock braking system
AGD = the average greatest dimension of the sealing chip (mm)
ALD = the average least dimension of the sealing chip (mm)
ASME = American Society of Mechanical Engineers
BPN = British Pendulum Number
BPT = British Pendulum Tester
CHCV = cumulative heavy commercial vehicle traffic per lane in millions
CS = average sealing chip size (mm)
CVD = number of HCVs/lane/day ≥ 3.5 tonnes
delq = the root-mean-square (rms) slope of the road surface profile
EBP = emergency braking performance
ESC = Equilibrium SCRIM Coefficient
F(S) = wet coefficient of friction at a skidding speed of S km/h
GCW = Gross Combined Weight
GN = GripNumber
HCV = heavy commercial vehicle
IFI = International Friction Index
ISO = International Standards Organisation
MPD = Mean Profile Depth (mm)
MSSC = Mean Summer SCRIM Coefficient
NAASRA = National Association of Australian State Road Authorities
Pc = peak count density
PSV = polished stone value
RAMM = Road Assessment and Maintenance Management
r = coefficient of correlation
r^2 = coefficient of determination
RS = Reference Station
Rsk = the skewness of the road profile about the mean line
Rvm = the mean maximum depth of the road profile from the mean line (m)
SC = SCRIM Coefficient
SCRIM = Sideway-force Coefficient Routine Investigation Machine
SCRIM$^+$ = SCRIM fitted out to measure road condition (roughness, rutting & texture) and road geometry in addition to wheelpath skid resistance
SE = Standard Error of Estimation
SFC = Side-Force Coefficient
Sp = speed number (km/h)
SLP = stationary laser profiler
μ = coefficient of friction

1. Introduction

Road surfaces must provide adequate skid resistance for maintaining safe vehicle operation over their service lives. However, road surfaces deteriorate with time and exposure to traffic, not only structurally, but also in their ability to provide adequate skid resistance when wet. Over the longer term, skid resistance gradually decreases because of the polishing action of traffic and eventually levels off at an equilibrium value, which will be determined largely by the aggregate. Therefore, a primary consideration in the design of road surfaces is the polishing properties of aggregates.

To ensure that a proposed mix design is capable of providing a long-term skid resistant surface, Transit New Zealand has specified a functional relationship in its TNZ T/10 specification (TNZ 2002a) that allows the required Polished Stone Value (PSV) of an aggregate to achieve a target skid resistance level to be computed. This relationship, derived from Szatkowski & Hosking (1972), equates PSV to the required level of skid resistance and volume of commercial vehicle traffic as follows:

$$PSV = 100 \times SR + 0.00663 \times CVD + 2.6 \qquad \text{Equation 1.1}$$

where:

SR = T/10 investigatory level value for the site of interest in units of Side Force Coefficient (SFC)

CVD = number of heavy commercial vehicles (HCV) per lane per day having a weight of 3.5 tonnes or greater

Subsequent research has demonstrated that different aggregates with the same PSV provide a range of skid resistance levels in practice and even aggregates from the same source can deliver a range of skid resistance levels for the same volume of commercial vehicle traffic (Catt 1983; Roe & Hartshorne 1998). Therefore, this highlights the need to view Equation 1.1 above as only a guide to in-service performance rather than a definitive guarantee of performance.

In the New Zealand context, recent research found Equation 1.1 to give poor correlation ($r^2 = 0.28$) with skid resistance measurements conducted on 24 specially selected chipseal sites located on State Highways 2 and 50 (Cenek et al. 1998). However, this poor correlation was attributed to:

- the restricted range of aggregate PSV;
- some skid resistance readings possibly being affected by road film contamination; and
- failure of Equation 1.1 to account for size and shape characteristics of the aggregate.

Given the importance of a reliable predictive model for the implementation of Transit New Zealand's skid resistance policy as outlined in their T/10 specification, a programme of research was formulated to investigate whether or not Equation 1.1 could be modified to improve the level of agreement between experimental and observed in-service skid resistance performance of road surfaces, and to address issues arising from the application of Equation 1.1. Specifically, the research considered:

- Relationships between common skid resistance measures employed in New Zealand for the safety management of road networks and the friction coefficient of car tyres, as obtained from emergency braking tests. This is to ensure that any predictive model derived for estimating skid resistance correctly mirrors actual car-tyre sensitivities to road surface characteristics, rather than those of the measuring tyre of the skid tester used in acquiring the skid resistance data.
- An improved understanding of contamination mechanisms, notably tracked binder film and detritus build-up over dry spells, and their adverse effect on skid resistance.
- Quantification of the contribution of road surface texture depth to low-speed and high-speed skid resistance.

This report details the research tasks undertaken to address the knowledge gaps listed above and the associated principal findings.

2. Terminology

The terms "road surface friction" and "skid resistance" are often used interchangeably by those involved with the management and maintenance of road networks. However, there is a subtle and important difference between the two variables.

Road surface friction refers to the resistive force that is developed between a specific tyre and a specific road surface under particular conditions. As the frictional force provided by the tyre–road combination is proportional to the load applied, it is normalised by the load to give a coefficient of friction.

The *coefficient of friction* is affected by a large number of variables including road surface, tyre and vehicle characteristics; vehicle speed; ambient temperature; and presence of contaminants. In general terms, when a road surface is dry, the coefficient of friction is normally high and adequate for most normal vehicle manoeuvres. However, when the road surface is wet, the coefficient of friction decreases significantly and is more dependent on the condition of the tyre and road surface.

Skid resistance is the term used to describe the contribution that the road makes to the development of tyre–road friction. It is essentially a measurement of the coefficient of friction obtained under standardised conditions in which various variables are controlled so that the effects of the road surface characteristics can be isolated. Skid resistance is also high in dry conditions and so the term skid resistance is almost always used in the context of wet road surfaces.

3. Experimental Design

3.1 Contracted Research Tasks

The contracted research tasks were conducted in three consecutive stages as follows:

- Stage 1, relationship between skid tester measurements and emergency braking performance;
- Stage 2, contamination effects; and
- Stage 3, predictive model for estimating skid resistance from seal characteristics.

Each of these three stages is expanded on below.

3.1.1 Stage 1

In Stage 1, the degree of correlation between the output from the different skid testers available in New Zealand and the straight-line braking performance of a representative passenger car was determined for a range of road surfaces. The intent of Stage 1 was to guide the selection of the most appropriate skid tester for subsequent use in Stages 2 and 3.

Controlled braking tests were performed on a sufficiently diverse sample of sealed road sections so that the derived coefficient of friction values adequately accounted for the range of friction likely to be encountered by the travelling public. A total of six straight and level sites of comparable roughness and low cross-slope were selected that included chipseals, which ranged in texture depth from 1 mm to 3 mm, and asphaltic concrete surfaces. One of the chipseal sites displayed a high level of flushing. The microtexture and texture depth characteristics of each of the test sites were quantified by wheel path measurements made respectively with a British Pendulum Tester (BPT), shown in Figure 1.1, and Transit New Zealand's stationary laser profiler (SLP), which is described in Cenek et al. (1997) and shown in Figure 1.2.

The test vehicle, a 1994 Holden Commodore Acclaim, was instrumented to accurately measure braking distance via a fifth wheel, and braking forces via body mounted accelerometers. These transducers were interfaced to a computer-based data acquisition system to allow flexibility in the way the logged data was processed. The testing programme included dry and wet road surface anti-lock braking system (ABS) and locked-wheel (non-ABS) emergency braking initiated at 25 and 50 km/h, and additional wet road surface ABS braking initiated at 75 and 100 km/h. A water truck was employed to provide an even, consistent amount of water over the test sites for the wet road surface emergency braking tests. The estimated water film depth for these wet road surface tests was approximately 1 mm.

Besides the BPT measurements, skid resistance surveys of the test sites were made with three mobile skid testers: the Sideway-Force Coefficient Routine Investigation Machine (SCRIM); the GripTester; and the Norsemeter ROAR. These mobile skid

Machine (SCRIM); the GripTester; and the Norsemeter ROAR. These mobile skid testers are in common use in New Zealand and provide an example of a side force, fixed-slip and variable-slip skid-testing device respectively (PIARC 1995). All the skid testers, including the BPT, were operated in accordance with the manufacturers' instructions. The water film depths utilised were 1 mm for SCRIM, 0.25 mm for the GripTester, and 0.5 mm for the Norsemeter ROAR.

The mobile skid tester surveys of the test sites were conducted at three different speeds: 25, 50 and 75 km/h. These differences in speed allowed any dynamic influences to be identified, as well as evaluation of the effectiveness of the International Friction Index (IFI) in converting skid resistance measurements produced by the different testers, or by the same tester at different speeds, to a common scale (PIARC 1995).

Regression analysis was applied to the acquired data to establish significant correlations between (1) the various skid testers, (2) the skid testers' output and braking distance, (3) low and high speed skid resistance, and (4) braking distance and texture depth.

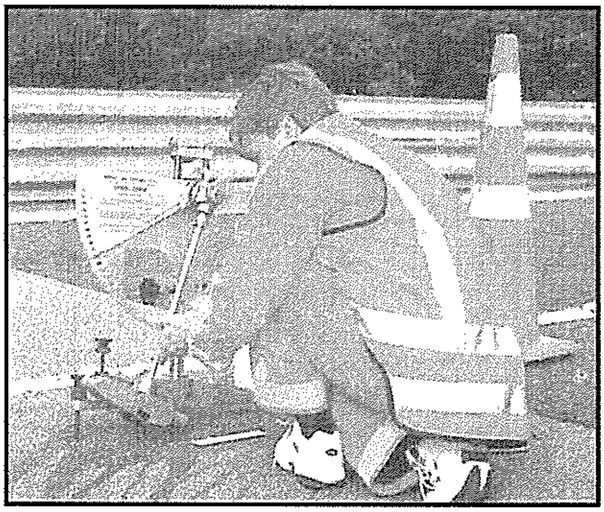


Figure 3.1 Skid resistance being measured with British Pendulum Tester.

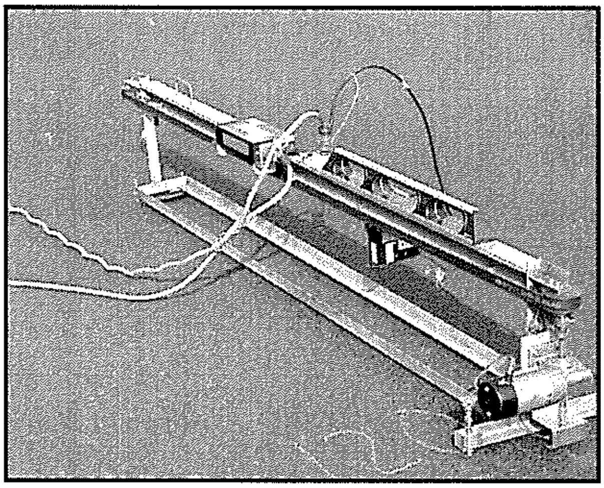


Figure 3.2 Transit New Zealand's stationary laser profiler used for obtaining texture profiles.

3.1.2 Stage 2

Stage 2 was concerned with quantifying short-term variations in skid resistance caused by environmental factors so that these variations could be appropriately accounted for in any subsequent statistical modelling. The removal of environmentally related short-term variations is desirable as it allows the contribution of road surface characteristics to observed long-term skid resistance performance to be better highlighted. The two causes of short-term variations in skid resistance selected for investigation were:

- bitumen binder contamination; and
- occurrence of rain.

3.1.2.1 Sensitivity to Binder Film

New Zealand surfacings sometimes have a layer of binder coating the surface of the aggregate and masking the microtexture. This coating occurs either on newly laid asphalt surfacings, or as a pre-coating for chipseal surfacings, or as a result of binder tracked from "bleeding" road sections during hot weather spells. This coating is gradually worn away by traffic until the aggregate is exposed and the normal polishing process begins. It is likely that different friction generating mechanisms apply when the aggregates are in this "blackened" state because of the reduced influence of microtexture. Therefore, the skid resistance characteristics will depend more on the shape characteristics of the aggregate, which helps promote hysteretic friction and also the adhesive or viscous properties of the binder.

In order to quantify the loss of skid resistance caused by binder film, both dry and wet emergency braking tests and skid tester measurements were planned to be performed on two chipseal-surfaced road sections in a blackened state caused either by pre-coating or tracked binder. One of these test sections was to have a coarse texture while the other medium to fine texture so that the influence of aggregate size and shape could be investigated. Comparative measurements were also to be performed on comparable "non-blackened" road sections to establish the degree of skid resistance loss related to binder film. The skid tester measurements were also to be repeated after a period of about a month to establish whether or not the skid resistance is restored as the binder is worn away by traffic with the "non-blackened" surfaces being employed as controls.

3.1.2.2 Sensitivity to Rainfall

During long dry spells a fine film of oil and rubber builds up on road surfaces, especially of heavily trafficked highways. This is normally washed off by regular rain, but after a two- to three-week dry spell, a shower of rain can create a very slippery surface, known in the tyre industry as "summer ice". Although the occurrence of rainfall is generally accepted as the reason for short-term variations in skid resistance, the mechanism by which the variations are produced is not sufficiently well understood to permit reliable modelling. For example, is a cloudburst of say an hour's duration during daylight less effective in restoring skid resistance than light rain through the night when traffic is light and the evaporation rate is low.

To address this knowledge gap, a measurement programme was undertaken over a six-month period to acquire skid resistance time histories of a road section with a skid tester before, during and after rainfalls of varying levels and durations. Standard skid tester measurements were obtained on the test road section at approximately two-weekly intervals to monitor variation in the measured skid resistance over a prolonged time period. In addition, the skid resistance measurements made during periods of rain were both standard (a controlled jet of water applied immediately in front of the measuring wheel of the skid tester) and non-standard (no water applied in front of the measuring wheel of the skid tester). This facilitated the generation of scale factors relating skid resistance in dry weather to skid resistance in steady rain, and the progressive reduction in skid resistance during a spell of dry weather.

3.1.3 Stage 3

A previous analysis of state highway skid resistance data (Cenek et al. 1998) showed that, if the aggregate PSV was factored out, the size and shape characteristics of the road aggregate made a significant contribution to the in-service skid resistance performance of road surfaces. Accordingly, this stage involved carrying out a multiple regression analysis using aggregate variables that are capable of being determined in the laboratory, such as PSV and aggregate shape, or derived from digital profiles of the road surface obtained with stylus, light sectioning or laser-based profilers (PIARC 1995).

The intent of the multiple regression analysis was to evaluate the significance of various aggregate variables on the in-service skid resistance performance of chipseal surfaces under different traffic loading, and their possible incorporation in the TNZ T/10 functional relationship (Equation 1.1), in order to obtain more reliable estimates of expected equilibrium skid resistance values. A feature of Stage 3, therefore, was the need to make surface profile measurements with Transit New Zealand's SLP at a considerable number of test sites located on the State Highway network.

The dependent variable in the multiple regression analysis was to be the average skid resistance over the test site as measured by the skid tester identified from Stage 1 as best agreeing with actual emergency braking performance, and corrected for contamination effects using findings from Stage 2.

In order to achieve a successful outcome, particular care had to be taken in the selection of the test sites to ensure that the dependent and independent variables of interest covered as wide a range as possible. These variables included in-service skid resistance, total traffic and heavy commercial vehicle (HCV) traffic, PSV, rock type, chip size, and extraction method (alluvial or hard rock quarry).

3.2 Variations

As a result of findings from Stage 1, changes to the experimental design of Stages 2 and 3 were proposed and approved. These changes were as follows.

3.2.1 Stage 2, Sensitivity to Binder Film

The unpredictable nature of bleeding, the very limited application of pre-coated chip and requirements for safe execution of locked-wheel braking on public roads all combined to make the original experimental design logistically problematic. To obviate the need to wait for two suitable road sections to be exposed to tracked bitumen, laboratory-based investigations were substituted for on-road testing. An added incentive to change the experimental design was that a greater range of binder film depths could be investigated for the same cost and, more importantly, the investigations being laboratory- rather than on-road based, enabled better control and quantification of the binder film depths. A better understanding as to how binder film affects the skid resistance of New Zealand chipseal surfaces would, therefore, result.

The laboratory testing under controlled conditions employed a number of portable road surface samples as follows:

- a smooth surface of a standard hard 40/50 bitumen
- a smooth surface of a soft 180/200 bitumen
- a smooth surface of a polymer-modified bitumen (PMB)
- sample road surfaces including:
    - basalt chips of 2 different grades (grade 4 and 6)
    - greywacke chips of 2 different grades (grade 3 and 5)
    - calcined bauxite.

For each of the test road surface samples, the surface of the chips were progressively coated with thin layers of the standard bitumen. The associated effect on the skid resistance was measured after each of the progressive layers of bitumen had been applied. The thickness of the bitumen applied to the test road surface samples was determined by means of weighing.

A British Pendulum Tester (BPT) was used to measure the skid resistance of the test samples.

The three bitumen-only test surfaces were employed to provide a baseline level of skid resistance so that the degrading effect of thickening bitumen film on the test road surface samples could be placed in context.

3.2.2 Stage 3, Data Acquisition for Regression Analysis

To adequately consider all the variables of interest, a statistical experimental design established that the number of state highway test sites where texture profile and skid resistance data was to be acquired, had to increase from the contracted 24 to a minimum of 36. Therefore, to accommodate the increased number of test sites within the research budget available, it was decided to forgo the on-road skid resistance measurements and to utilise skid resistance data already held in Transit New Zealand's Road Assessment and Maintenance Management (RAMM) database. This skid resistance data is acquired with SCRIM$^+$ as part of annual condition surveys of the entire State Highway network and goes back to 1995.

$SCRIM^+$ differs from SCRIM in that simultaneous measurements of the road condition parameters roughness, rutting and texture depth, and road geometry parameters of gradient, horizontal curvature, and crossfall are made in addition to wheel path skid resistance.

The change in the experimental design to use $SCRIM^+$ survey data was considered advantageous because:

- well developed and independently validated procedures are utilised for converting the skid resistance measurements for speed, temperature and seasonal (within year) weather effects;
- skid resistance measurements for the entire sealed State Highway network, amounting to some 22,000 lane-km, are available for every year since 1998 allowing reliable estimates of equilibrium skid resistance to be calculated for those road sections whose surface was two years old or more or had been exposed to one million standard axle passes by taking the mean of Mean Summer SCRIM Coefficients (MSSC) over three or more consecutive years;
- it permitted a significant increase in the number of test sites at which surface profile measurements could be made; and
- the dependent variable of the resulting regression model, MSSC, is the same as used in the skid resistance management of the State Highway network, and so the predictive accuracy of the model will be enhanced by eliminating the need for conversion between different measures of skid resistance.

4. Skid Resistance – Coefficient of Friction Relationships

4.1 Overview of On-Road Test Programme

The aim of the test programme was to establish relationships between maximum all-wheel ABS braking decelerations, all wheels locked slide-to-stop decelerations, and various standard skid tester measures, including IFI. This resulted in emergency braking tests with a specially instrumented vehicle and skid tester surveys being performed on 6 straight and level road sections of comparable roughness and low cross-slope but with a range of microtexture and texture depths.

In general, the microtexture of a road surface determines the frictional capability of a dry road, while texture depth (macrotexture) determines the drainage ability and therefore how effective the microtexture will be when the road is wet. Accordingly, microtexture and texture depth characteristics of the six test sites were quantified by wheelpath measurements made with a British Pendulum Tester (BPT) and Transit New Zealand's stationary laser profiler (SLP) respectively.

Table 4.1 provides location details of the six test sites along with associated site-averaged BPT and texture depth readings in terms of mean profile depth (refer ISO 13473-1:1997). Although the report is concerned with skid resistance performance of chipseal surfaces, the two asphaltic concrete sites were included to allow evaluation of skid tester performance on very low textured, homogeneous, road surfaces.

Table 4.1 Details of emergency braking test sites.

Site No.	Location	Surface	Microtexture in terms of BPT reading	Texture depth in terms of Mean Profile Depth (mm)
1	SH53 RP0/7.69–7.49	Chipseal	73	3.35
2	Alexander Road	Chipseal	77	2.40
3	Camp Road	Chipseal	65	2.14
4	SH53 RP0/12.1–12.3	Flushed Chipseal	54	1.00
5	Manfeild Autocourse, Straight 1	Asphaltic Concrete	63	0.53
6	Manfeild Autocourse, Straight 2	Asphaltic Concrete	71	0.46

The test vehicle was an ABS-equipped 1994 Holden Commodore Acclaim, which was driven by a police-trained driver. It was fitted with a fifth wheel to measure vehicle speed and braking distance, and body-mounted accelerometers to measure deceleration-time histories. Having two independent measuring systems provided the redundancy and crosschecking necessary to give confidence in the derived values of average coefficient of friction. Figure 4.1 shows an emergency braking test in progress.

In addition to the BPT, skid resistance surveys were made over the entire length of each of the test sites tabulated in Table 4.1 with Sideway-force Coefficient Routine

Investigation Machine (SCRIM) (Figure 4.2), GripTester (Figure 4.3) and Norsemeter ROAR (Figure 4.4).

Figure 4.1 Instrumented test vehicle performing a dry surface emergency braking test.

The skid resistance and texture depth measurements allowed calculation of the International Friction Index (IFI) from which the wet locked-wheel braking performance expected of a vehicle with treadless tyres can be predicted for emergency braking initiated at any speed. Direct comparisons between the theoretically derived average coefficients of tyre–road friction during a braking manoeuvre and those experimentally obtained, were possible therefore.

Figure 4.2 SCRIM$^+$, an example of a side force skid tester.

Figure 4.3 GripTester, an example of a fixed slip skid tester.

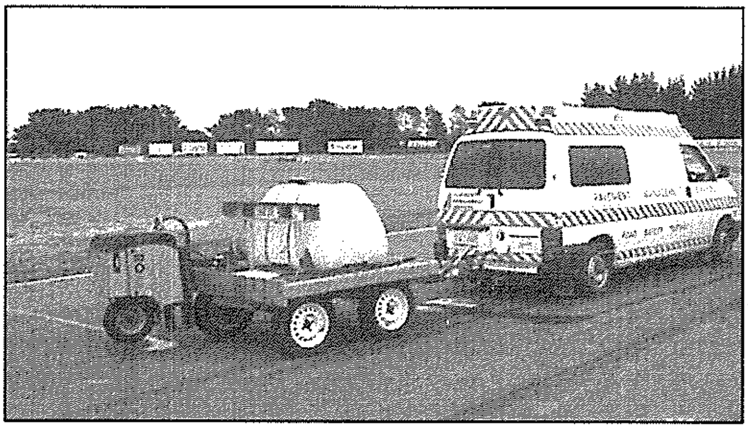


Figure 4.4 Norsemeter ROAR, an example of a variable slip skid tester.

4.2 Results

4.2.1 Relationships Between Emergency Braking Derived Dry and Wet Road Coefficients of Friction

Figures 4.5 and 4.6 show the variation of coefficient of friction with speed for a moderately textured chipseal surface (site 3 in Table 4.1) and a finely textured asphaltic concrete surface (site 6 in Table 4.1) respectively. The coefficients of friction plotted are the average of six repeat measurements. The repeat measurements had a coefficient of variation of between 2 and 6%.

With reference to Figures 4.5 and 4.6, the following observations can be made:

- Dry road, locked-wheel braking coefficients of friction are independent of speed. At an initial braking speed of 50 km/h, dry ABS and non-ABS derived braking coefficients are almost identical. However, at very low speeds (≅ 25 km/h) dry road, ABS braking on the moderately textured surface produces a coefficient of friction that is about 10% less than for non-ABS braking. This effect was also observed at site 2. However, on fine textured asphaltic concrete (site 6), no differences between ABS and non-ABS dry road braking coefficients of friction were observed.
- At urban speeds (≤50 km/h), wet road, locked-wheel braking coefficients of friction decrease with speed at a rate of about –0.002/km/h, irrespective of the road surface texture depth. Additional research is required to establish whether or not this rate applies to higher speeds and is affected by tyre tread depth and water film depth.
- Wet road, ABS braking coefficients of friction show minimal speed dependency. In addition, the wet road, ABS values of braking coefficient of friction are comparable to the wet road, locked-wheel braking coefficient of friction derived from braking initiated at 25 km/h.

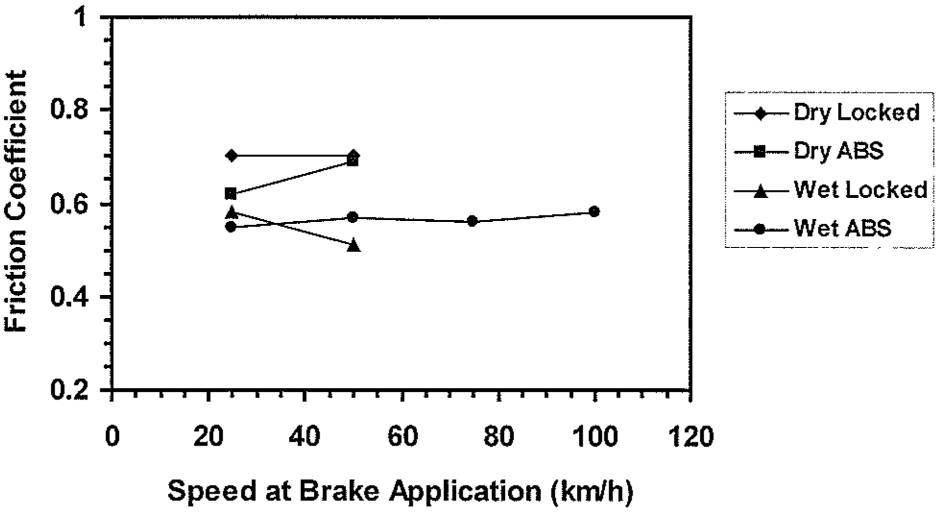


Figure 4.5 Variation in friction with speed observed on a moderately textured chipseal surface.

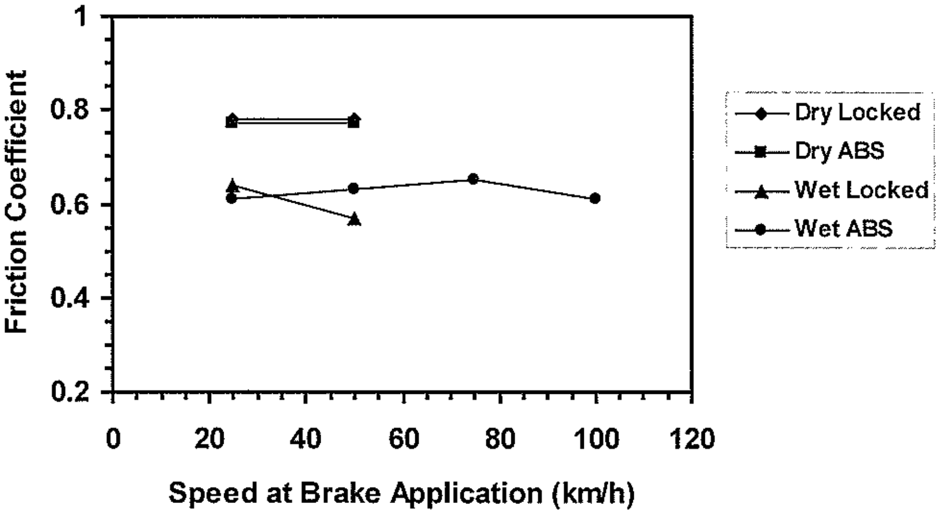


Figure 4.6 Variation in friction with speed observed on a finely textured asphaltic concrete surface.

- The ratio of wet road, ABS braking coefficient of friction to dry road, locked-wheel braking coefficient of friction, these being invariant measures of friction, is about 0.8.

The other test sites tabulated in Table 4.1 displayed the same trends as listed above.

4.2.2 Correlations Between Skid Tester Measures and Emergency Braking Performance

Linear correlations obtained by regressing skid tester measures of wet skid resistance against braking distances and average coefficients of friction acquired from the emergency braking performance (EBP) tests are tabulated in Tables 4.2 to 4.9. The correlation is in terms of coefficient of determination (r^2). This represents the ratio of the explained variation to the total variation. Therefore, if the total variation in the EBP test results can be all explained by the skid tester measures, the ratio is one.

For the purposes of this report, a significant correlation has been arbitrarily defined as $r^2 \geq 0.8$, since such a r^2 value generally guarantees that the standard error in estimated values will be small enough for most engineering applications. Therefore, values of $r^2 \geq 0.8$ have been highlighted in the summary tables of coefficient of determination presented in the following sub-sections.

With reference to Tables 4.2 to 4.9, the speed, in km/h, at which braking was initiated is denoted as the subscript in column headings pertaining to braking distance (d) and coefficient of friction (μ). For example, d_{25} and μ_{25} refer to braking distance and coefficient of friction respectively, measured during braking manoeuvres initiated at 25 km/h. No correlations with dry road ABS braking have been tabulated because differences between ABS and non-ABS dry EBP are minimal over a 25-50 km/h speed range.

4.2.2.1 British Pendulum Tester (BPT)

Under dry conditions, correlations between the BPT and locked-wheel braking distance and coefficient of friction are not significant except for the coefficient of friction for 50 km/h.

Under wet conditions, correlations with locked-wheel and ABS braking test results tend to improve with increasing brake initiation speed.

Table 4.2 Correlations between BPT results and braking distance.

Coefficients of Determination (r^2)	Braking Distance (d)							
	Locked-wheel				ABS			
BPT	Dry		Wet		Wet			
	d_{25}	d_{50}	d_{25}	d_{50}	d_{25}	d_{50}	d_{75}	d_{100}
	0.49	0.07	0.24	0.88	0.57	0.84	0.97	0.76

(subscripted number = speed (km/h) braking is initiated)

Table 4.3 Correlations between BPT results and coefficient of friction.

Coefficients of Determination (r^2)	Coefficient of Friction (μ)							
	Locked-wheel				ABS			
BPT	Dry		Wet		Wet			
	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{75}	μ_{100}
	0.44	0.84	0.97	0.80	0.48	0.57	0.81	0.88

(subscripted number = speed (km/h) at which braking is initiated)

4.2.2.2 SCRIM

Significant correlations between SCRIM and emergency braking tests were identified for dry locked-wheel braking initiated at a slow speed (25 km/h), and wet ABS and non-ABS braking initiated at speeds of 50 km/h or greater. In contrast to the GripTester and Norsemeter, the degree of correlation improves with decreasing survey speed, with the best correlations obtained at a survey speed of 25 km/h rather than the standard survey speed of 50 km/h.

Table 4.4 Correlations between SCRIM and braking distance.

Coefficients of Determination (r^2)	**Braking Distance (d)**							
	Locked-wheel				**ABS**			
SCRIM	Dry		Wet		Wet			
	d_{25}	d_{50}	d_{25}	d_{50}	d_{25}	d_{50}	d_{75}	d_{100}
25km/h	0.81	0.51	0.01	0.61	0.69	0.83	0.78	0.73
50km/h	0.80	0.43	0.00	0.68	0.63	0.83	0.80	0.73
75km/h	0.78	0.49	0.02	0.57	0.48	0.73	0.65	0.66

(subscripted number = speed (km/h) at which braking is initiated)

Table 4.5 Correlations between SCRIM and coefficient of friction.

Coefficients of Determination (r^2)	**Coefficient of Friction (μ)**							
	Locked-wheel				**ABS**			
SCRIM	Dry		Wet		Wet			
	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{75}	μ_{100}
25km/h	0.94	0.74	0.63	0.97	0.84	0.92	0.93	0.81
50km/h	0.91	0.68	0.52	0.97	0.73	0.87	0.87	0.74
75km/h	0.94	0.76	0.35	0.84	0.67	0.84	0.74	0.82

(subscripted number = speed (km/h) at which braking is initiated)

4.2.2.3 GripTester

No significant correlations between dry road emergency braking tests and the GripTester were identified apart from dry coefficient of friction at slow speed (25km/h). However, the agreement between the GripTester and wet road emergency braking tests tends to improve as the GripTester's survey speed is increased.

Table 4.6 Correlations between GripTester and braking distance.

Coefficients of Determination (r^2)	**Braking Distance (d)**							
	Locked-wheel				**ABS**			
GripTester	Dry		Wet		Wet			
	d_{25}	d_{50}	d_{25}	d_{50}	d_{25}	d_{50}	d_{75}	d_{100}
25km/h	0.19	0.33	0.01	0.20	0.18	0.71	0.43	0.34
50km/h	0.42	0.32	0.00	0.53	0.34	0.74	0.75	0.56
75km/h	0.60	0.20	0.00	0.81	0.43	0.83	0.85	0.70

(subscripted number = speed (km/h) at which braking is initiated)

Table 4.7 Correlations between GripTester and coefficient of friction.

Coefficients of Determination (r^2)	Coefficient of Friction (μ)							
	Locked-wheel				ABS			
GripTester	Dry		Wet		Wet			
	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{75}	μ_{100}
25km/h	0.60	0.56	0.58	0.68	0.79	0.65	0.76	0.41
50km/h	0.83	0.64	0.60	0.91	0.51	0.92	0.87	0.68
75km/h	0.73	0.45	0.40	0.85	0.84	0.87	0.69	0.81

(subscripted number = speed (km/h) at which braking is initiated)

4.2.2.4 Norsemeter ROAR

Better correlations between the Norsemeter ROAR and the emergency braking tests were obtained when the Norsemeter ROAR was operated at a fixed slip ratio of 20%, rather than the 34% fixed slip ratio normally used to provide equivalency with the sliding action of SCRIM's yawed measuring tyre. As with the GripTester, the correlations tend to improve as the survey speed of the Norsemeter ROAR increases.

Table 4.8 Correlations between Norsemeter ROAR and braking distance.

Coefficients of Determination (r^2)		Braking Distance (d)							
		Locked-wheel				ABS			
Norsemeter ROAR		Dry		Wet		Wet			
		d_{25}	d_{50}	d_{25}	d_{50}	d_{25}	d_{50}	d_{75}	d_{100}
25km/h	(1)	0.25	0.34	0.31	0.14	0.05	0.18	0.19	0.14
	(2)	0.42	0.32	0.18	0.36	0.18	0.37	0.39	0.32
50km/h	(1)	0.14	0.25	0.51	0.06	0.00	0.07	0.07	0.06
	(2)	0.47	0.44	0.06	0.38	0.30	0.45	0.49	0.36
75km/h	(1)	0.42	0.08	0.05	0.58	0.19	0.42	0.47	0.40
	(2)	0.67	0.36	0.00	0.60	0.49	0.66	0.65	0.60

(1) 34% fixed slip, (2) 20% fixed slip

Table 4.9 Correlations between Norsemeter ROAR and coefficient of friction.

Coefficients of Determination (r^2)		Coefficient of Friction (μ)							
		Locked-wheel				ABS			
Norsemeter ROAR		Dry		Wet		Wet			
		μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{25}	μ_{50}	μ_{75}	μ_{100}
25km/h	(1)	0.62	0.62	0.04	0.34	0.30	0.37	0.24	0.18
	(2)	0.74	0.66	0.14	0.52	0.39	0.50	0.41	0.38
50km/h	(1)	0.45	0.48	0.00	0.18	0.14	0.22	0.10	0.08
	(2)	0.88	0.82	0.35	0.89	0.63	0.64	0.59	0.45
75km/h	(1)	0.44	0.25	0.06	0.44	0.16	0.34	0.32	0.47
	(2)	0.83	0.66	0.41	0.76	0.60	0.72	0.69	0.67

(1) 34% fixed slip, (2) 20% fixed slip

At a survey speed of 50 km/h and 20% fixed slip ratio, the output from the Norsemeter ROAR displayed significant correlation with the dry road locked-wheel braking coefficients of friction. Overall, the Norsemeter ROAR's measure of skid resistance does not provide as good an agreement with wet road emergency braking test results as the other two mobile skid testers, i.e. SCRIM and GripTester.

4.2.2.5 Regression Equations

In New Zealand the mobile skid testers are generally operated at a survey speed of 50 km/h. Figure 4.7 graphically shows the degree of correlation achieved between wet road coefficients of friction derived from locked-wheel braking initiated at 50 km/h (y-axis) and the standard skid resistance measures generated by the four skid testers that were evaluated (x-axis). The resulting best linear fit line is also plotted in Figure 4.7 for each skid tester and the corresponding equation constants tabulated in Table 4.10.

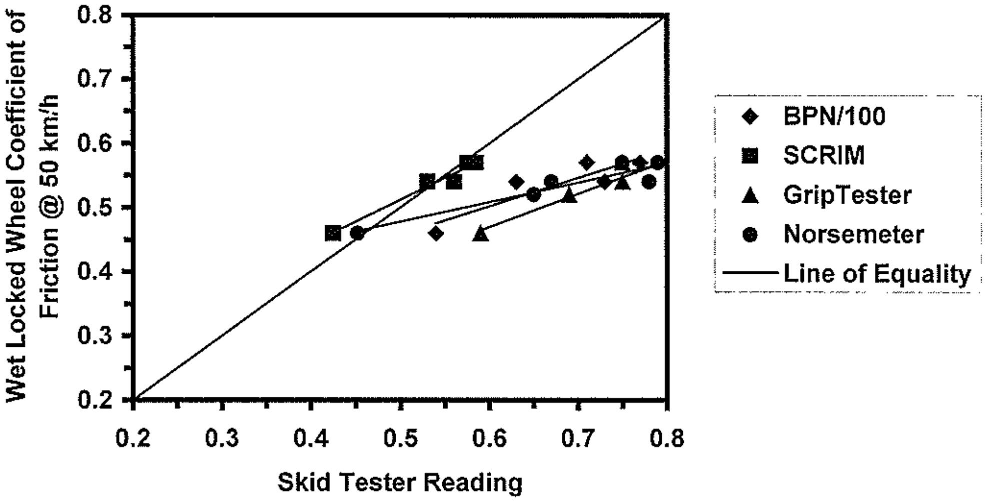


Figure 4.7 Relationship between standard skid tester measures and wet road coefficient of friction.

Standard skid resistance measures imply that the values of skid resistance were normalised according to the procedures adopted in New Zealand by the providers of skid testing services. Therefore, in the case of the BPT measurements, the British Pendulum Number (BPN) values are corrected to a temperature of 20°C, whereas for SCRIM, the side force coefficient (SFC) values are corrected to a survey speed of 50 km/h and temperature of 20°C. The SCRIM SFC values are in turn multiplied by a factor of 0.78 (the index of SFC) to give the derived value, SCRIM Coefficient (SC). New Zealand and the UK are possibly alone in applying the 0.78 factor, and this is done to ensure compatibility with skid resistance values obtained between 1963 and 1972 with earlier SCRIMs that have been used in setting investigatory levels of skid resistance for different road categories (Department of Transport UK, 1999). No corrections have been applied to the GripTester and Norsemeter ROAR measures of skid resistance.

Figure 4.7 shows that SCRIM provides measures of wet friction that are of comparable value to those from 50 km/h locked-wheel braking tests, whereas the other testers generate significantly higher values. This result is attributed primarily to the application of "the index of SFC", which reduces the frictional force measured by SCRIM by 22%.

Table 4.10 Linear regression equations for converting skid tester measures to $F50_{locked,wet}$ (Regression model form: $y = mx + b$)

Skid Tester	Slope (m)	Constant (b)	Standard Error of Estimation	r^2
British Pendulum Tester	0.0044	0.23	0.020	0.80
SCRIM	0.68	0.17	0.009	0.97
GripTester	0.52	0.16	0.013	0.91
Norsemeter ROAR (20% slip)	0.30	0.33	0.015	0.89

All coefficients of determination (r^2) listed in Table 4.10 are highly significant. However, the best agreement between observed on-road wet braking performance and skid tester measure is with SCRIM. This result, in part, provides justification for Transit New Zealand's continued use of SCRIM for annual skid resistance surveys of New Zealand's entire State Highway network, which commenced in 1995. The differences in the coefficients of determination are attributed to the differing degrees to which skid testers are sensitive to texture properties of road surfaces.

With reference to Table 4.10, the very low values of standard error of estimation suggest that application of the above regression equations should result in prediction of average, wet road, braking coefficients of friction that are within ± 0.03 of the measured values obtained with the test vehicle.

4.2.3 Evaluation of the International Friction Index (IFI)

The International Friction Index (IFI) is a common scale for quantifying wet friction from combined skid resistance and texture measurements (PIARC 1995). It consists of two parameters: F60 and Sp.

- F60 is the harmonised estimate of wet friction at 60 km/h skidding speed. F60 approximates the average wet coefficient of friction experienced by a car with four treadless tyres in a 60 km/h locked-wheel skid.
- Sp is the speed number, which provides a measure of how strongly the wet friction depends on skidding speed of a car tyre.

When F60 and Sp are known, the wet friction level at any other skidding speed, S', can be calculated using the equation:

$$F(S') = F60 \times \exp[(60 - S')/Sp] \qquad \text{Equation 4.1}$$

As the BPT, SCRIM and GripTester participated in the international PIARC experiment from which IFI was formulated, the following equations to calculate F60 are available:

BPT:

$$F60 = 0.0436 + 0.0095 \times BPN \times \exp[-50/Sp] \quad \text{Equation 4.2}$$

SCRIM:

$$F60 = 0.0326 + 0.8717 \times SFC \times \exp[(0.34 \times S - 60)/Sp] \quad \text{Equation 4.3}$$

$$F60 = 0.0326 + 1.1176 \times SC \times \exp[-43/Sp] \quad \text{Equation 4.4}$$

GripTester:

$$F60 = 0.0821 + 0.9104 \times GN \times \exp[(0.15 \times S - 60)/Sp] \quad \text{Equation 4.5}$$

where:

BPN is the British Pendulum Number,
SFC is the side force coefficient,
SC is the SCRIM Coefficient,
GN is the Grip Number and
S is the survey speed in km/h

Sp is calculated directly from the measure of mean profile depth (MPD) obtained with Transit New Zealand's SLP through the following relationship:

$$Sp(km/h) = 9.74 + 104.71 \times MPD(mm) \quad \text{Equation 4.6}$$

Data acquired as part of the EBP tests, therefore, was used to assess:

- the effectiveness of the IFI harmonisation; and
- the reliability of the predicted sensitivity of wet road coefficient of friction to skidding speed.

4.2.3.1 F60 Harmonisation

F60 values derived from the standard skid resistance measure generated by the BPT, SCRIM, and GripTester are shown graphically in Figure 4.8 for each site. Typically, the spread in F60 values is 0.06 but can be as large as 0.11. For crash analysis, the tolerable uncertainty in the derived friction value is ±5%. However, the observed uncertainty in F60 is almost double this.

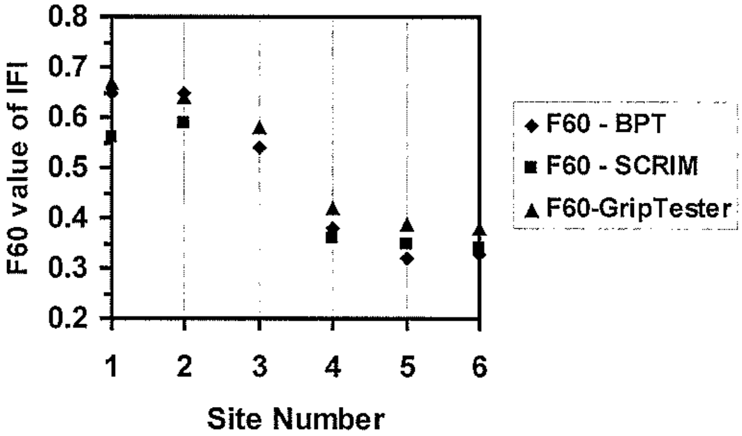


Figure 4.8 Degree of variability in site F60 values.

Such a result suggests that IFI transformation expressions need to be derived specifically for New Zealand road surfaces, chipseals in particular, to reduce the observed degree of variability.

4.2.3.2 Predicted Versus Observed Speed Sensitivities

Observed versus predicted changes in wet road, locked-wheel coefficient of friction as a function of speed is plotted in Figure 4.9 for site 6, by way of example. Site 6 was chosen because it displayed the lowest road surface texture depth and so speed and tyre tread effects were expected to be more pronounced. (SCRIM results were used to derive the IFI measures plotted in Figure 4.9.)

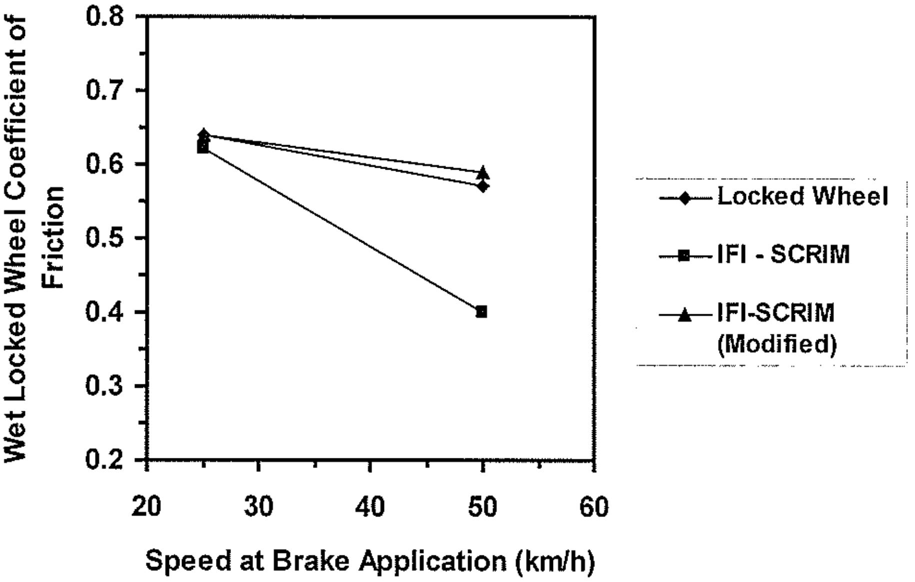


Figure 4.9 Wet braking coefficient of friction versus speed.

Figure 4.9 shows that the treadless tyre assumption implicit in IFI, results in a predicted rate of decrease that is about 3 times greater than actually observed. However, if the tread pattern of the tyre is treated as similar to additional texture on the road, almost perfect agreement is obtained. This result indicates that, although IFI's F60 parameter is for treadless tyres, treaded tyres can be accommodated simply by adding the average volumetric texture depth of the tyre to the mean profile depth of the road surface prior to calculating Sp. (Volumetric texture depth of the tyre is simply the total volume of the grooves within the contact patch divided by the contact patch area.)

Important issues highlighted by this analysis are:

- The influence of tyre tread depth on wet friction even at moderate speeds.
- The IFI speed transformation expression appears valid.
- The need to better understand combined effects of tread depth, speed, and water depth on the emergency braking performance on New Zealand road surfaces.

4.2.3.3 Reliability of F25 and F50 Measures

Figures 4.10 and 4.11 graphically show the level of agreement achieved between wet road coefficient of friction derived from locked-wheel braking initiated at 25 and 50 km/h respectively (y-axis) and the corresponding F25 and F50 values (x-axis) calculated using the IFI transformation expressions applied to the BPT, SCRIM, and GripTester standard skid resistance measures. Plots of the best linear fit lines for each skid tester have been superimposed. In applying the IFI transformation expressions, the value of texture used in the Sp calculation was the sum of the road surface MPD and volumetric texture depth of the tyre. Figure 4.11 can be directly compared with Figure 4.7.

Generally, the IFI transformation to F50 results in correlations with observed F50 that are comparable to just using standard skid resistance measures for SCRIM and the GripTester ($r^2 = 0.95$), but significantly worse for the BPT ($r^2 = 0.66$).

The correlations between predicted and measured coefficients of friction for 25 km/h locked-wheel skid (F25) at $r^2 \cong 0.60$ are less than obtained for 50 km/h locked-wheel skid (F50). However, the 25 km/h correlation results were very much influenced by a large discrepancy between predicted and measured F25 values for site 5. This site can be considered atypical as it displayed lower friction at 25km/h than 50 km/h. Removing this site improved the F25 correlations so that they approached those for F50.

Again, SCRIM derived F25 and F50 values are of comparable magnitude to the measured F25 and F50 values, whereas for the GripTester and BPT they are considerably greater.

Table 4.11 summarises the linear regression equations derived for correcting IFI-derived friction values so that they better match the measured tyre–road friction values. These equations apply equally to F25 and F50 measures, lending weight to the need for the IFI transformation expression to be refined for New Zealand conditions.

Applying the linear correction equations results in the predicted values of F25 and F50 agreeing to better than ±0.04 with the measured values.

Table 4.11 Linear regression equations for correcting IFI predictions of friction.

Skid Tester	Slope (m)	Constant (b)	Standard Error of Estimation	r^2
British Pendulum Tester	0.42	0.27	0.027	0.65
SCRIM	0.65	0.16	0.011	0.95
GripTester	0.64	0.10	0.013	0.92

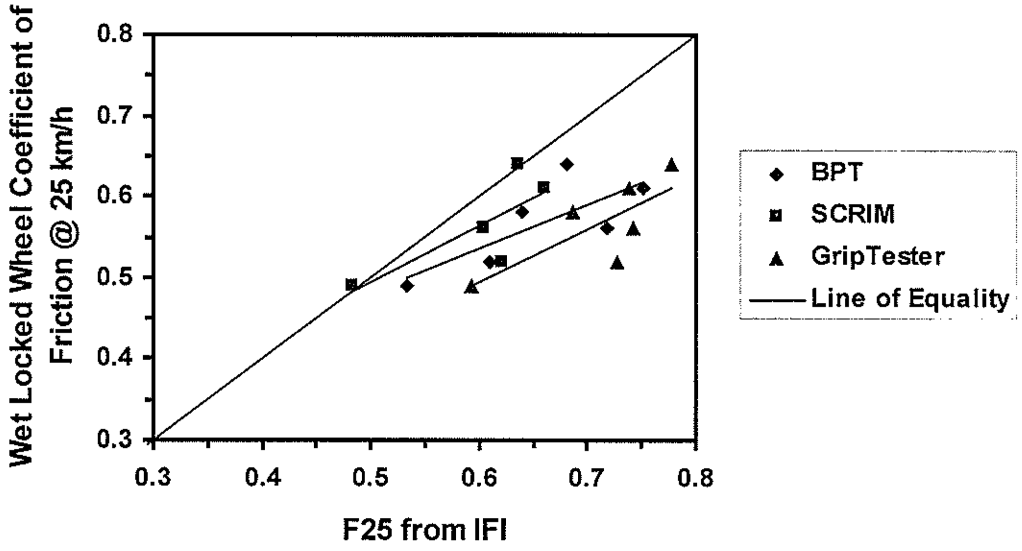


Figure 4.10 Relationships between predicted and measured F25 values.

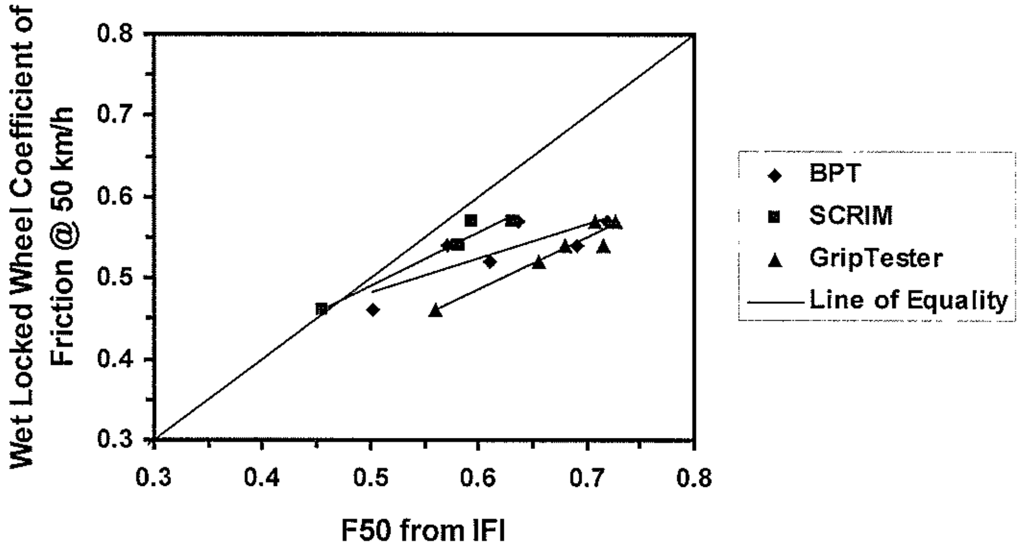


Figure 4.11 Relationships between predicted and measured F50 values.

4.3 Summary of Findings

The principal findings of this investigation into the relationships between measures used for skid resistance management of road networks and emergency braking performance of a representative passenger car are as follows:

- Skid testers in common use in New Zealand show differing sensitivities to microtexture and macrotexture properties of road surfaces. However, their measurements of skid resistance showed significant correlations ($r^2 \geq 0.8$) with both dry and wet road coefficients of friction.

Generally, SCRIM measurements were shown to provide the most reliable estimates. This finding was the catalyst for the changes to the experimental design of Stages 2 and 3 of the research programme as detailed in Section 3.2 of this report.

- The International Friction Index (IFI) F60 harmonisation expressions need to be refined for New Zealand conditions before they can be used with confidence for maintenance management purposes as inter-device variations are too great. This is consistent with latest PIARC findings (Bennis & de Wit 2003).

- Improved understanding of the inter-relationships between wet friction, volumetric texture depths of tyres and road surfaces, vehicle speed, and water film depth is required before models for the reliable prediction of friction under different wet operating conditions can be developed.

  In the interim, IFI modelling of wet friction-speed dependencies appears adequate if the volumetric texture depth of the tyre is incorporated in the calculation of the speed number, Sp.

- Coefficients of friction could possibly be derived for locked-wheel skidding from ABS braking tests. However, the performance of an ABS braking system over a range of operational conditions is peculiar to a particular car make and model. Therefore, the derivation of resulting relationships will be vehicle-specific.

5. Influence of Bitumen Film on Skid Resistance

5.1 Methodology

The aim of the research was to quantify the effect of increasing bitumen film on the skid resistance of a chipseal road surface. The research has been conducted under laboratory conditions, using portable road surface samples covering different aggregate size and type. Skid resistance has been quantified using the standard British Pendulum Tester (BPT) method.

5.1.1 Road Surface Samples

Six chipseal road surface samples selected for investigation are detailed in Table 5.1.

Table 5.1 Descriptions of the road surface samples.

Sample No.	MPD (mm)*	Description
1	3.0	Worn Grade 3 greywacke chipseal from a pavement core
2	1.6	Worn Grade 5 greywacke chipseal from a pavement core
3	3.3	New Grade 4 greywacke chipseal, laboratory-made surface
4	3.5	New Grade 4 basalt chipseal, laboratory-made surface
5	2.2	New Grade 6 basalt chipseal, laboratory-made surface
6	2.8	New calcined bauxite, laboratory-made surface

* Mean profile depth (MPD) is a measure of the macrotexture of the surface, and was measured with Transit New Zealand's stationary laser profiler (SLP).

The 6 samples listed in Table 5.1 have progressively increasing levels of skid resistance in terms of British Pendulum Number (BPN) (see Table 5.3), with sample 1 having the lowest skid resistance (BPN=61) and sample 6 having the highest skid resistance (BPN=100).

The BPN measure of skid resistance is assumed to be closely related to the microtexture of the aggregate. This is because the sliding speed of the BPT's rubber slider is about 10 km/h, which allows sufficient time for any surface water on a textured road surface to drain away, irrespective of the texture depth. Therefore, there is direct contact between the rubber slider and the microtexture of the wetted road surface.

The characteristics of these various samples are as follows:

- The worn samples have relatively smooth chip surfaces with reduced microtexture, and consequently reduced skid resistance. The new samples feel more abrasive, and have greater microtexture.
- The worn samples have had the chips rotated in their bitumen base by progressive traffic action, so that chip corners typically do not protrude. This reduces the MPD of the surface. On the laboratory-made samples, the chips remain as they are initially laid, so that the chip corners often do protrude.

- The greywacke was quarried in the Wellington region. In New Zealand, greywacke is the aggregate type most commonly used for chipseal surfacings.
- The basalt has greater microtexture and a more abrasive feel than the greywacke, and consequently has greater friction. It was quarried in the Auckland region. Basalt is less commonly used for chipseal surfacings than greywacke.
- The calcined bauxite is a specialist high friction surface. The aggregate is manufactured as granules, which are smaller in size than natural aggregate sealing chips.

The binder base on which the chipseals were set did not come into contact with the BPT rubber slider, and therefore had no effect on the results. No binder was visible on the surface of the chipseals in their initial condition.

5.1.2 Bitumen Coatings

Four successive layers of bitumen film were applied to the road surface samples, consisting of coatings of progressively increasing thickness. For the first three of these coatings, the applied bitumen was a standard hard 40/50 bitumen. The film was applied by spraying a solution of 5% bitumen dissolved in cyclohexane solvent. The cyclohexane was allowed to evaporate overnight before BPT measurements were performed. A hard bitumen was used in preference to soft bitumen, which is more commonly used in sealing, to minimise tackiness in the coated road surface samples.

For the fourth coating, a thick bitumen film was desired that would be sufficient to mask most of the microtexture of the aggregate. This could not be achieved using the sprayed solution method. Accordingly, a painted coating of soft 180/200 bitumen emulsion was applied.

Table 5.2 gives details of the four bitumen coatings applied to each road surface sample and corresponding photographic records are provided in Appendix A.1 for visual reference.

Table 5.2 Details of bitumen coatings applied to road surface samples.

Bitumen Coating Identifier	Total Bitumen Film Thickness (microns)	Qualitative Description
A	1	Light stain.
B	4	Medium stain.
C	13	Heavy stain: the chips feel smoother but the microtexture is still clearly discernible.
D	110	Severe contamination. Heavy glossy black bitumen. Most of the microtexture is obscured. Some macrotexture also obscured, especially on sample 2.

The thickness of bitumen applied in each film was measured by weighing paper surfaces, which had been sprayed with the same spray density. However, this method of measuring the film thickness was found to overestimate the film thickness on the chips, as the sprayed solution tended to drain off the chip surfaces and collect in the spaces between the chips. Therefore, in calculating the film thickness, it has been assumed that the film thickness on the chips is half of the film thickness on the paper surfaces. The film thickness listed in Table 5.2 includes the thickness of the previous coating. By way of comparison, a single coating of household paint typically has a thickness of 30-40 microns. Coating A is therefore extremely thin, while coating D is equivalent to about 3 coats of paint.

5.2 Test Results

The BPN measurements of skid resistance were obtained in the laboratory under controlled conditions at a temperature of 16°C. The BPN value presented is the average of measurements for 4 separate test patches distributed on each road surface sample. To eliminate any directionality effects, the road surface sample was rotated through 90° after the BPN measurements were completed on a patch.

All BPN measurements were made according to standard test procedures detailed in Road Note 27 (TRRL 1969).

5.2.1 Road Surface Samples – Unweathered Condition

Only bitumen coatings A, B and C plus the original surfaces were tested in a clean unweathered condition. The coated surfaces were tested on the day after the bitumen had been applied. Satisfactory BPN measurements for coating D could not be obtained when it was only 1 day old because initial tests showed that the BPN measurement changed with successive swings of the pendulum. This outcome was attributed to the soft, tacky bitumen cover being smeared by the action of the rubber slider, thereby exposing the microtexture of the aggregate.

The testing of the bitumen coatings yielded the following general trends:

Coating A

The skid resistance was measured for all the samples after they had been left to dry overnight. Sample 1 showed a significant increase in BPN, but sample 6 showed a significant reduction, and samples 2-5 showed little change in BPN.

Coating B

Again the skid resistance was measured for all the samples after they had been left to dry overnight. Little change was recorded from the results for coating A, and no consistent trend. The reduction in BPN for sample 6 that was noted for coating A was partially reversed for coating B.

Coating C

Only samples 1 and 6 were tested after they had been left to dry overnight. There was little difference from the results for coating B. At this point, testing of coating C was suspended.

A complete listing of the associated BPN results for the unweathered road surface samples is given in Table 5.3.

Table 5.3 British Pendulum measurements for unweathered road surface samples.

Coat	Coat thickness (microns)	British Pendulum Number (BPN)							
		Sample No.						Average	Reduction
		1	2	3	4	5	6		
Original	0	61	70	81	94	93	100	83	-
A	1	68	69	81	91	92	94	83	0
B	4	70	69	83	90	88	98	83	0
C	13	73	-	-	-	-	96	-	-

All the measurements of bitumen coatings in Table 5.3 are for 1-day-old, unweathered samples. Little additional change in BPN was apparent with additional coatings of bitumen film.

The effect of these coatings was to reduce the differences in BPN between the different samples, as evidenced by the following outcomes:

- BPN for sample 1, which had the lowest original skid resistance, was increased by the bitumen coatings.
- BPN for sample 6, which had the highest original friction, was reduced a little by the bitumen coatings.
- The other samples were only slightly changed.

Overall, the different road surface samples appeared to be converging towards a single value of friction for a textured 1-day-old bitumen surface. The 1-day-old bitumen had a tacky feel, which would clearly influence the measurements of BPN.

The method of applying the bitumen film possibly had some influence on the degree that the bitumen remained tacky after 1 day, and therefore on the skid resistance measurements.

5.2.2 Road Surface Samples – Weathered Condition

After application of coatings C and D, the road surface samples were left outside to weather in the sun and rain for 4 days (11 to 14 June 2002) in an exposed area. During this period, the air temperature ranged between 9°C and 17°C, with scattered clouds on days 1 and 2 and occasional showers on days 3 and 4. Winds were moderate to high, with gusts varying between 50 and 100 km/h. Table 5.4 gives the results for the weathered coatings, plus the original surfaces.

For the weathered samples, the bitumen coatings produced a strong effect of reducing the measured skid resistance as the coating thickness increased. Specifically:

- For coating C, the average reduction in BPN was –9 (11%) compared with the original surfaces.
- For coating D, the average reduction in BPN was –16 (19%) compared with the original surfaces.

The reduction in skid resistance was generally greater for the surfaces displaying the highest original skid resistance, but there was some unexplained variation for the different surfaces. For example, the lowest BPN was measured for sample 2 with coating C, but the skid resistance for this sample was increased again with coating D.

Table 5.4 British Pendulum measurements for weathered road surface samples.

Coat	Coat thickness (microns)	British Pendulum Number (BPN)							
		Sample No.						Average	Reduction
		1	2	3	4	5	6		
Original	0	61	70	81	94	93	100	83	-
C	13	58	51	79	89	80	89	74	-9
D	110	53	55	67	80	65	81	67	-16

5.2.3 Discussion of Road Surface Sample BPN Measurements

- The measured skid resistance was influenced by several factors. These factors included the thickness of the bitumen film, weathering of the bitumen film, and the initial road surface. Generalised comments about the influence of any one of these factors may be misleading.
- A recently applied (1-day-old) thin film (about 1 micron thick) of bitumen reduced the difference in BPN between the high and low friction surfaces. (BPN for the low skid resistance road surface sample increased by 8, BPN for the high skid resistance road surface sample reduced by 4) The average effect of the bitumen film for the six different surfaces was zero.
- Second and third additional, progressively thicker, coatings of recently applied bitumen had little additional effect on the measured BPN.
- After application of the third coating, the thickness of bitumen on the chips was about 13 microns, which is about a third of the thickness of a typical single coat of household paint. At this stage, the road surface looked heavily stained. The chips felt somewhat smoother, but the microtexture of the chips was still visible.
- The surfaces were then allowed to weather for 4 days. Weathering reduced the BPN by an average of –9 for all the samples. Individual reductions in BPN related to weathering ranged from –2 to –19. An explanation for the large variation in the influence of weathering could not be found. For example, there was no clear relationship between the effect of weathering and the BPN before weathering.
- A fourth, substantially thicker bitumen coating was then applied. The contamination of the road surface was now severe. The resulting film thickness was about 110 microns, equivalent to about 3 coats of paint. The road surface looked black and glossy, and most of the chip microtexture was obscured.
- The surfaces were then again allowed to weather, and then tested. The average BPN was reduced by –16 compared to the measurements for the original surfaces (and by –7 compared to the measurements for the previous weathered film). The reductions for individual surfaces, compared to the original measurements, ranged from –8 to –28.

- Again, the effect of the most recent coating was not consistent. For example the surface that had the greatest reduction in BPN after the third coating was found to have increased its BPN after the fourth coating.
- The worn Grade 3 chipseal (Sample 1) was the surface with the lowest BPN in this final test, measuring 53 BPN, reduced from 61 BPN in its original condition. This was the road surface sample displaying the lowest skid resistance in its original condition.
- The calcined bauxite (Sample 6) was the surface with the highest BPN in this final test, measuring 81 BPN, reduced from 100 BPN in its original condition. This was the road surface sample displaying the highest skid resistance in its original condition.
- Tyre–road friction consists of two components: adhesion and hysteresis (Anderson & Henry 1979). Adhesion, commonly referred to as grip, is caused by shear forces developed at the tyre–aggregate interface and its magnitude is determined by tyre speed, nature of the tyre, contact pressure between the tyre and the aggregate, and the microtexture of the roading aggregate. The adhesion component of friction decreases as vehicle speed increases.

  Hysteresis is caused by the deformation of the tyre and its development depends primarily on the presence of macrotexture in the road surface. The hysteresis component increases with increasing tyre speed. Therefore, as the hysteresis component of friction will be less for fine textured road surfaces, it can be expected that such surfaces will display a greater sensitivity to any reduction in microtexture brought about by bitumen film build-up.

  When comparisons are made between worn fine and coarse textured road surface samples (i.e. samples 1 and 2) and laboratory-made fine and coarse textured road surface samples (i.e. samples 3-6), the fine textured surfaces in both cases demonstrate significantly more sensitivity to the presence of a thick bitumen film. The resulting reduction in BPN between original and final test conditions was double that observed for the coarse textured surfaces.

5.2.4 Tests on Flush Bitumen Surfaces

In addition to the 6 road surface samples, BPT measurements of skid resistance were performed on 3 samples of bitumen of different grades poured molten onto flat plates and allowed to cool. These samples simulated an extreme flushed road surface as they had no stone chips, and no initial texture. Table 5.5 tabulates details of the bitumen properties along with average BPN values before and after weathering.

The bitumen-only samples were left to weather with the road surface samples in an exposed area for a period of 4 days (11 to 14 June 2002).

On the day after the flush bitumen surface samples were produced, the appearance of the bitumen was highly glossy. As a consequence, the measured BPN was extremely low with a consistent value of 18. Such a low value was expected because there was no visible texture on the glossy surfaces.

After weathering, these surfaces became matt and slightly textured, with an attendant increase in BPN value. Weathering increased skid resistance most for sample 8, for which the weathered BPN was 35. It is conjectured that skid resistance increased most for sample 8, which was a soft 180/200 bitumen, because this sample became pitted by the action of the sun and rain, and therefore developed the most surface texture.

Comparing the BPN values given in Table 5.5 with those in Table 5.4 shows that the skid resistance of a bitumen-coated worn chipseal surface is 1.5 to 2.5 times greater than that of a flush bitumen surface. Because the microtexture is identical in both instances, this significant difference is again attributed to the hysteresis effect, which is more pronounced on coarser textured surfaces.

Table 5.5 British Pendulum measurements for flush bitumen surfaces.

Sample No.	Bitumen Properties	BPN Skid Resistance	
		Unweathered	Weathered
7	A standard hard 40/50 bitumen	17	21
8	A soft 180/200 bitumen	18	35
9	A polymer modified bitumen consisting of 180/200 bitumen with 5% rubber polymer	18	24

5.3 Summary of Findings

From a road safety management perspective, the principal findings of this study, which has been performed to demonstrate the influence of a surface film of bitumen on BPT measures of skid resistance on chipseal surfaces, are as follows.

- The skid resistance of fine textured road surfaces is more affected by the presence of bitumen film than it is for coarse textured surfaces. This is because the relative contribution of aggregate microtexture to the skid resistance provided by a road surface increases as the macrotexture of the surface decreases. As a consequence, fine textured road surfaces display a greater sensitivity to reductions in microtexture brought about by the masking action of bitumen film.

- Although the presence of bitumen film on chipseal road surfaces can result in reductions of skid resistance of between 20% and 30% in situations where the contamination is severe (i.e. bitumen film thickness of the order of 100 microns), the resulting level of skid resistance is still significantly greater (at least three times) than that provided by a smooth bitumen-only surface.

  This finding suggests that chipseal surfaces in a flushed condition pose a greater safety hazard to motorists in wet conditions than chipseal surfaces that have been blackened by tracked bitumen.

- A smooth bitumen-only surface provides skid resistance of between 20 to 35 BPN. This is comparable to the level of skid resistance provided by chipseal surfaces exposed to medium to heavy icing (Dravitzki & Wood 2001).

- An estimate of the contribution of macrotexture to skid resistance was able to be determined by comparing BPN results for the bitumen-only samples and actual and laboratory-made road surface samples, covered with the 100 microns thick bitumen film, as in all cases aggregate microtexture effects can be discounted. For the chipseal surfaces investigated, the profile of the macrotexture appears to be a significant determinant of skid resistance as measured by the BPT, contributing to between 10 and 30 BPN.

6. Influence of Previous Rainfall History on Skid Resistance

6.1 Background

During prolonged spells of dry weather, a fine film of contamination builds up on road surfaces, especially heavily trafficked highways. The contamination consists of a mixture of rubber particles, road aggregate and bitumen particles, soil, dust and other detritus. The contamination is washed off by regular rain, but after a two- to three-week dry spell a shower of rain can create a very slippery road surface, known in the tyre industry as "summer ice".

Vehicle drivers report that the road is most slippery when it first gets wet. If the rainfall continues, it seems that the friction provided by the road surface increases during the first hour or two of rain, and then reaches a steady value when the film of contamination has been washed away. A study specifically designed to investigate this phenomenon was carried out in early 2002 as part of the research programme detailed in this report. In addition, a previous study by Opus Central Laboratories in early 2001 appeared to show evidence of this phenomenon (Jamieson & Patrick 2001). Therefore the 2001 data has been re-analysed as part of the current study. The Central Laboratories GripTester was the device used to obtain all the skid resistance measurements.

Cenek et al. (1999) reported, in Transfund New Zealand Report No. 139, that although the occurrence of rainfall is generally accepted as the reason for short-term variations in skid resistance, the mechanism by which the variations are produced is not yet sufficiently well understood to permit reliable modelling. The recommendations from that Transfund report led to the current study.

While the view outlined above regarding rainfall as a contributory cause of short-term variations in skid resistance is generally accepted as being correct, this view has not always been supported in the research literature. For example, research conducted by the Australian Road Research Board (ARRB) in the 1980s (Oliver et al. 1988) indicated that periodic washing away by rainfall of vehicle oil droppings and tyre detritus deposited on road surfaces could be ruled out as a cause of the variation observed in skid resistance measurements.

6.2 2001 Study

During March to June 2001 Opus Central Laboratories undertook a study on behalf of Transit New Zealand, to obtain GripTester measurements on a number of roads over a period of time, to measure the variation of GripNumber with time (Jamieson & Patrick 2001). Six test sites were monitored over a period of 10 weeks. The study was not intended to specifically focus on the effects of recent rainfall on skid resistance.

In all cases, the skid resistance data consisted of standard GripTester measurements. Such measurements are carried out on a dry road, with the GripTester applying water at a rate of 10.42 ℓ/min directly in front of the test wheel. At the target survey speed of 50 km/h, this flow rate corresponds to a water film depth of 0.25 mm.

The report for this study concluded that considerable variation in skid resistance occurred over the monitoring period. This variation was attributed largely to contaminants reducing the skid resistance, and rainfall combined with traffic action increasing the skid resistance through cleaning.

Figure 6.1 shows a plot using data from the 2001 study. The data has been re-analysed to isolate the influence of rainfall from the other variables that were measured in that study (such as the differences between sites, and variations in road surfaces at each site). This was achieved by averaging measurements from the 6 sites. The plot includes data from 24 separate GripTester tests (i.e. 6 sites, each measured on four separate days). Each test included data from two different surface types. Each test site was about 500 m long, and a single test consisted of three consecutive runs along the test site. Therefore a single data point in Figure 6.1 is the average GripNumber measured over about 9 km of road.

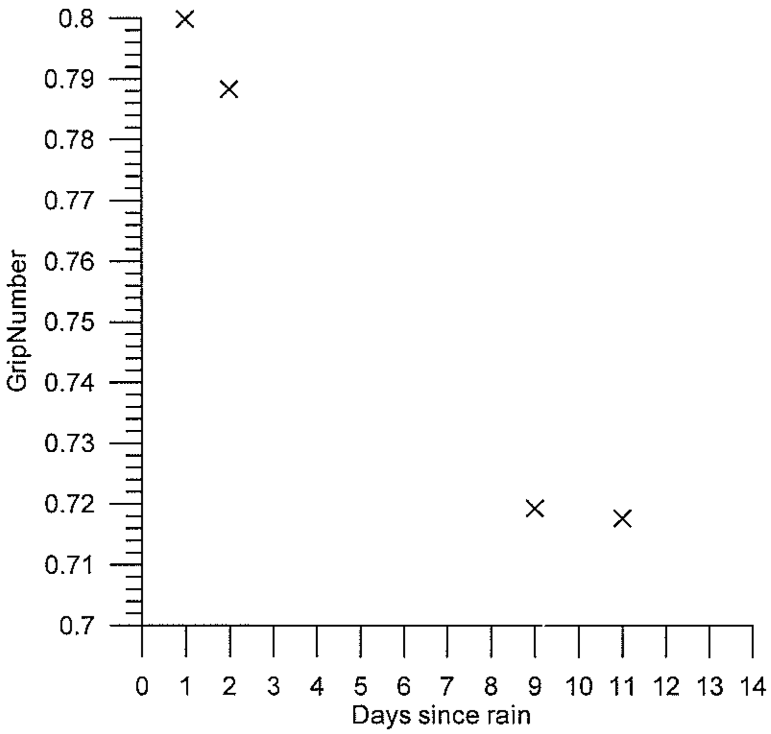


Figure 6.1 Plot of GripNumber against days since rain.

Figure 6.1 indicates that the measured GripNumber is highest (i.e. indicates high skid resistance) soon after a period of rain, and then reduces over the next two weeks or so. A reduction in GripNumber of 0.08 over a period of 10 days was measured against an average GripNumber of 0.76 measured for the whole study. Therefore the measured variation, which was apparently related to the effects of rainfall, was about 10%.

No measurements were obtained more than 11 days after a significant fall of rain. Experience and commonsense indicates that the GripNumber cannot continue to decrease at the same rate indefinitely if there is a prolonged period without rain. The rate of reduction in GripNumber is likely to be greatest within the first 2 weeks after rain, and the data in Figure 6.1 supports this view with some indication that the rate of reduction of GripNumber decreases as time goes on. Therefore, a reasonable hypothesis might be that the rate of reduction in GripNumber is logarithmic. For example, a 10% reduction in skid resistance occurs after 10 days, whereas a 20% reduction occurs after 100 days.

In conclusion, the 2001 study does show a clear effect on skid resistance caused by previous rainfall history. However, the magnitude and form of this effect is not proven.

6.3 2002 Study

6.3.1 Description of the 2002 Study

This study was carried out over period of 6 months from December 2001 to May 2002. It was specifically designed to investigate the effect on skid resistance caused by previous rainfall history.

Standard GripTester measurements were obtained on the test road at approximately two-weekly intervals. This was done to monitor variation in the measured skid resistance with time, as was also the case with the 2001 study. Standard GripTester measurements are carried out on a dry road, with the GripTester applying a film of water directly in front of the test wheel.

In addition to the standard GripTester measurements, which involved wetting the road surface immediately in front of the test wheel with a jet of water, it was desired to measure the change in skid resistance that occurred during a period of rain. Therefore, a range of non-standard GripTester measurements was also obtained on different occasions. These included:

1. Measurements on a wet road, with the GripTester water supply switched OFF.
2. Measurements on a wet road, with the GripTester water supply switched ON.
3. Measurements on a dry or partially dry road, with the GripTester water supply switched OFF.

The test road which we selected was Randwick Road in Lower Hutt. This is a 2-lane urban arterial road with a 50 km/h speed limit. The estimated average daily traffic is 16,000 vehicles for both lanes combined. The road surface is a mixture of chipseal and hot mix of various ages.

The GripTester survey circuit started at the south end of the road, with measurements performed along the northbound lane and continuing around the roundabout at the north end of the road and the return to the starting point along the southbound lane. The total length of a single test run amounted to 2.5 km.

The survey circuit was divided into three sections, the centre section including the bridge over the railway and the roundabout. However, the results for the centre section were found to be more variable than the other sections because of:

- slow traffic on the roundabout;
- occasional queues on the roundabout approach; and
- extensive resealing on the section half way through the study.

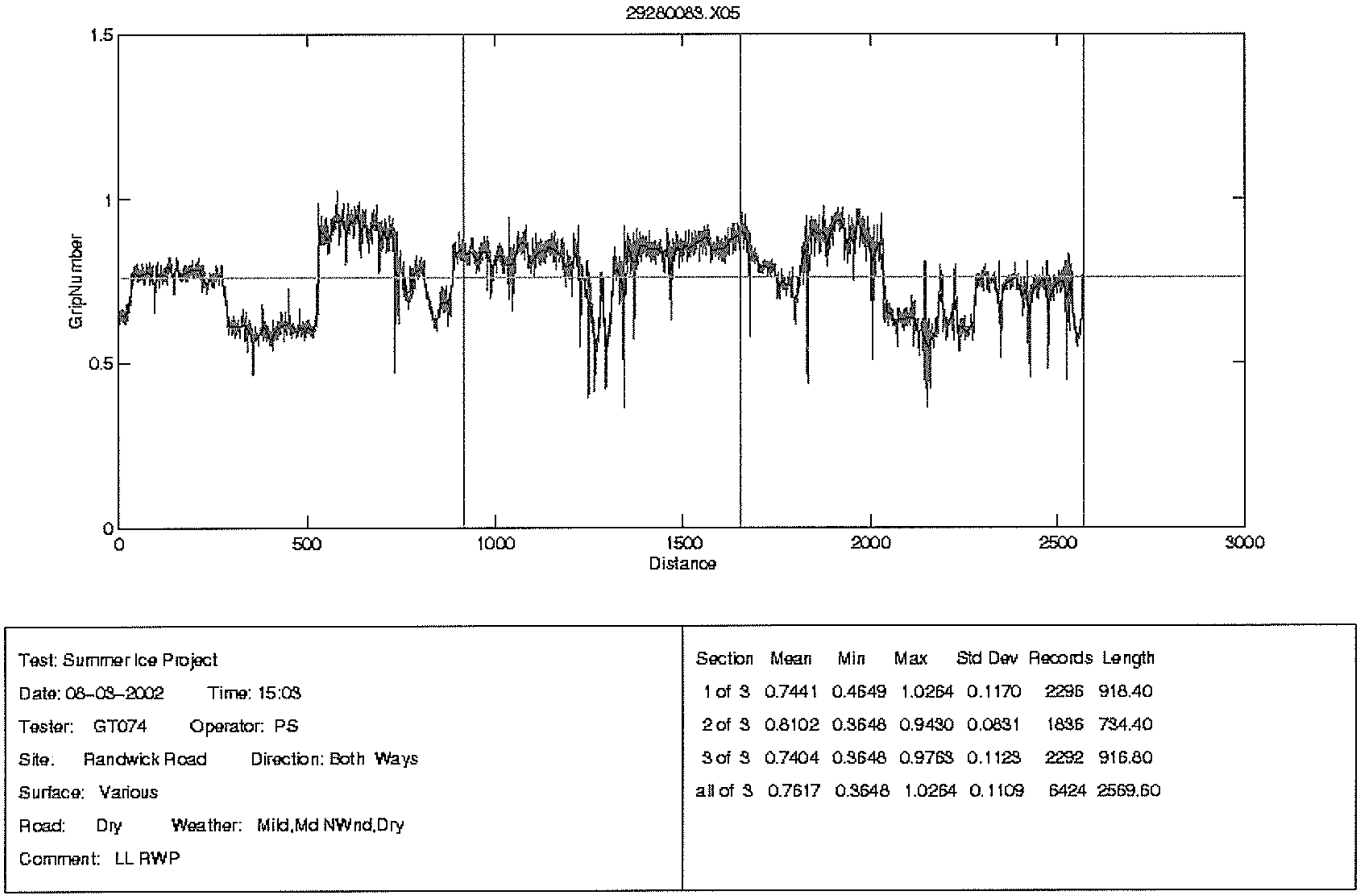
As a consequence, only data from sections 1 and 3 has been analysed for this study. Sections 1 and 3 are each 0.9 km long and so the total length of analysed data for each test run is 1.8 km. Sections 1 and 3 were also partially resealed part way through the study. Fortunately, the new chipseal, and the old hot mix it replaced, both had very similar GripNumber values. Therefore, the effect of the resealing on the mean GripNumber results for each section was negligible.

In summary, the GripTester measurements consisted of:

- 113 test runs done on 12 separate days over a period of 6 months.
- All measurements were made in the right hand wheelpath.
- All measurements were performed at 40 km/h instead of the usual 50 km/h in order to reduce speed variation caused by other traffic. This difference in speed has negligible effect on the resulting GripNumber measurements as the slip speed of the test wheel is reduced from the usual 7.5 km/h to 6 km/h.
- GripNumber was measured at 0.4 m intervals.
- Each set of tests was preceded by a circuit of a different road, in order to bring the GripTester's measuring wheel to operating temperature and stabilise the electronics.
- Typically, unless otherwise stated, the listed GripNumber measurement for a single test is the mean of sections 1 and 3 averaged over 4 consecutive test runs. Therefore, a single test measurement is usually the mean GripNumber measured over 7.2 km of road surface.
- Typically, 5 consecutive test runs were done at 10 minute intervals, with the first test run being treated as an extra. A little more variation was observed in the first test run than in the other 4.

Figure 6.2 shows an example of a plot of the GripTester data from a single standard test run, measured on 8 March 2002.

The weather during the study period was characterised by frequent rain days. At the nearest rain gauge monitored by NIWA, rain was recorded on 78 days during the study period, which is approaching 1 day in 2. Consequently, the longest period since rain for a test was only 9 days. This was less time than had been planned for investigating the effects of sustained dry periods.



Test: Summer Ice Project
Date: 08-03-2002 Time: 15:03
Tester: GT074 Operator: PS
Site: Randwick Road Direction: Both Ways
Surface: Various
Road: Dry Weather: Mild,Md NWnd,Dry
Comment: LL RWP

Section	Mean	Min	Max	Std Dev	Records	Length
1 of 3	0.7441	0.4649	1.0264	0.1170	2296	918.40
2 of 3	0.8102	0.3648	0.9430	0.0831	1836	734.40
3 of 3	0.7404	0.3648	0.9763	0.1123	2292	916.80
all of 3	0.7617	0.3648	1.0264	0.1109	6424	2569.60

Figure 6.2 Measurements from a standard GripTester run along Randwick Road, Lower Hutt.

6.3.2 Results of Standard GripTester Measurements

1. During the 6 months, 10 standard GripTester tests were made. The mean of the standard tests was 0.77.
2. The highest GripNumber measured for a standard test was 0.79. The lowest was 0.74. Therefore the measured GripNumber for the standard tests remained fairly steady over the 6 months monitoring period.
3. Figure 6.3 shows a plot of GripNumber plotted against number of days since the first standard test. Figure 6.4 shows a plot of GripNumber plotted against the number of days since rain, using the same data. Only days with rainfall greater than 1 mm have been considered when counting the days since rain.

   Both plots apparently show a significant trend. It is conjectured that there is a significant trend related to the number of days since rain, and that this is real. The apparent reduction in GripNumber with time is probably coincidental, and is not real.
4. Figure 6.4 shows a reduction in GripNumber at a rate of 0.04 during the first 10 dry days.
5. The highest GripNumber for a single standard run was 0.80. The lowest GripNumber for a single standard run was 0.71. (NB A standard test is the average of 4 standard runs.)
6. The greatest range within the 4 runs of a single standard test was 0.06. Therefore there was about as much variation between the 4 runs of a single test as there was variation between separate tests.
7. Looking at this more closely, the difference between consecutive runs was 0.03 or less for all but two of the runs. However on two occasions the measured GripNumber changed by 0.06 between consecutive runs for no readily apparent reason. The fact that these relatively large changes can occur indicates that time histories of consecutive runs should be considered with some caution.

6.3.3 GripTester Measurements on Dry Roads

The GripNumber for a dry road with water supply switched OFF was measured twice. The average dry GripNumber was 1.19. Therefore, the standard GripNumber was about 0.42 less than the dry GripNumber on average. It was noticeable that the dry GripNumber was fairly uniform for different road surfaces, whereas the standard GripNumber was more variable for different road surfaces. For the surface with the lowest friction, the difference between the standard GripNumber and the dry GripNumber was about 0.50. Figure 6.5 shows an example of a plot of the GripNumber measured on a dry road with the water supply switched OFF.

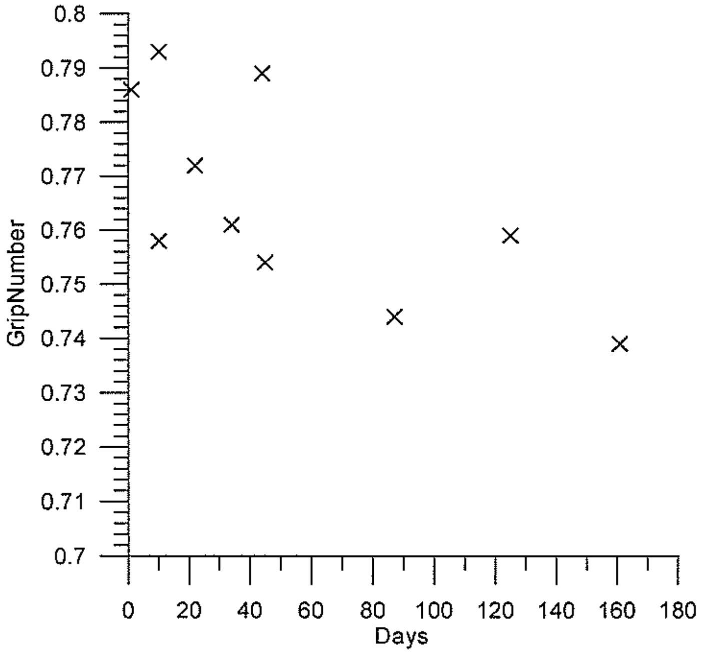


Figure 6.3 GripNumber plotted against days.

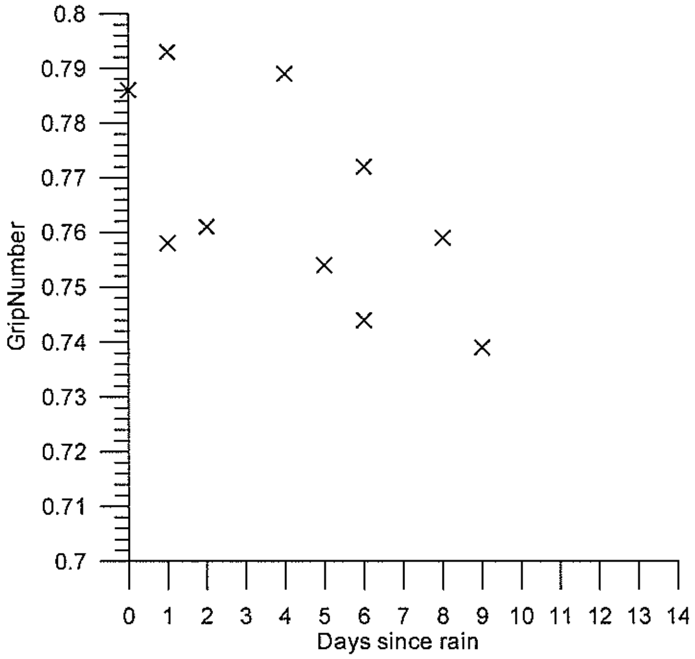


Figure 6.4 GripNumber plotted against days since rain.

Testing on a dry road with the water supply switched OFF is possible, but is not generally encouraged by the manufacturer of the GripTester as this causes higher loads on the drag component of the test wheel's load cell. More importantly, it causes significant heating of the skidding test wheel, and rubber resilience is affected by temperature (Hosking & Woodford 1976). Therefore, GripTester measurements made on a dry road with the water supply switched OFF tend to be more variable than with the water supply switched ON, because there is greater sensitivity to cooling effects brought about by ambient conditions. Rubber resilience increases (i.e. hysteresis losses become smaller) as temperature rises and so skid resistance tends to decrease.

On one occasion a standard GripTester test was performed that resulted in a very low average GripNumber being measured, but this test was done soon after carrying out a test with the water supply switched OFF and so the test has been disregarded due to possible temperature drift effects.

6.3.4 GripTester Measurements on Wet Roads

Tests were done on four days when the road was thoroughly wet because of steady rain (each test consisting of 4 runs). The average measured GripNumber during rain was 0.83. Therefore the average measured GripNumber was 0.06 higher during rain than during dry weather. The GripNumber measured for each test ranged from 0.79 to 0.86.

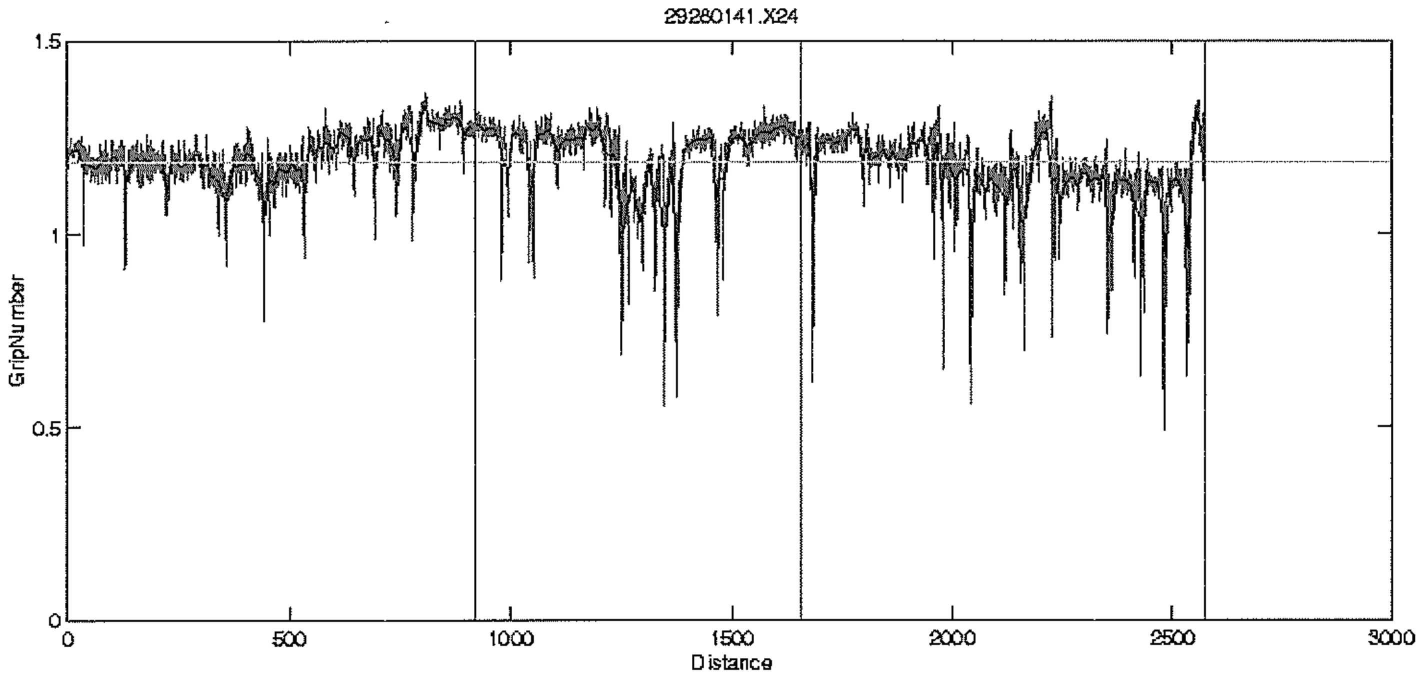
During rain conditions, the difference between GripNumber measured with the GripTester water supply switched OFF and the water supply switched ON was also determined. The GripNumber measured with the water supply switched OFF was 0.01 higher, which is a negligible difference.

6.3.5 GripTester Measurements During the Onset of Rain

Four tests were done during the onset of rain, during the period when the road first became wet. Unfortunately, on three of these occasions, the rain quickly stopped again.

Consequently, whether or not the GripNumber increased because of the effects of continuous rain could not be determined on these three occasions. In fact, what was observed was the GripNumber increasing because the rain became light, and therefore dry patches were forming on the road.

With the water supply switched OFF, the GripTester essentially measures either dry road skid resistance or wet road skid resistance. Therefore for these tests, dry road skid resistance was measured on any length or patch of road that was visibly dry. Wet road skid resistance was measured on any length or patch of road that was visibly wet. Intermediate values between dry road skid resistance and wet road skid resistance were measured where there were both wet and dry patches of road, as typically occurs as a road dries out. The intermediate measure of skid resistance only occurs because of this patchiness.



Test: Summer Ice Project
Date: 14-01-2002 Time: 17:59
Tester: GT074 Operator: PS
Site: Randwick Road Direction: Both Ways
Surface: Various
Road: Dry Weather: Mild,LtNBrz,Dry
Comment: LL RWP

Section	Mean	Min	Max	Std Dev	Records	Length
1 of 3	1.2029	0.7762	1.3655	0.0648	2299	919.60
2 of 3	1.2048	0.5538	1.3322	0.1006	1846	738.40
3 of 3	1.1568	0.4927	1.3544	0.1025	2293	917.20
all of 3	1.1871	0.4927	1.3655	0.0930	6438	2575.20

Figure 6.5 Example output of a test run along Randwick Road, Lower Hutt, performed when the road surface was dry with the GripTester's water supply switched off.

Only one test, on 14th February 2002, showed the GripNumber to change during a period of rain. The GripNumber increased from 0.76 initially to 0.86 after 1 hour, increasing fairly steadily during 8 runs. (There is an apparent minor peak after 30 minutes, but this is probably due to random variation of the GripTester measurements.) This test was done only one day after some significant rainfall. The time history of this series of runs is shown in Figure 6.6.

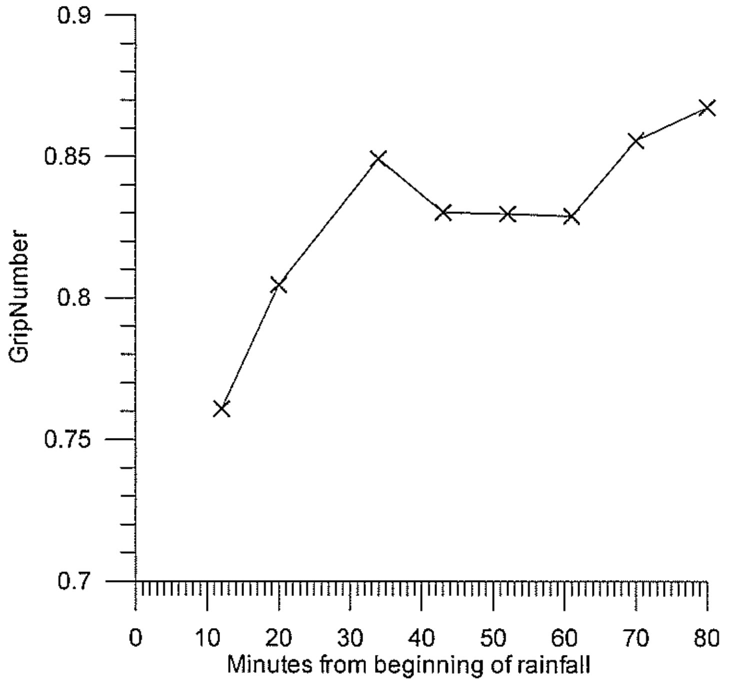


Figure 6.6 Time history of GripNumber measured during the onset of rain.

On another occasion (25th January 2002), during an initial period of rain, a GripNumber of 0.67 was measured for a single run with the GripTester water supply switched OFF. On subsequent runs, the GripNumber was higher because the road was drying. This measurement was done 5 days after previous significant rainfall. The single run measurement of 0.67 compares with the lowest standard test measurement of 0.74.

It proved impossible to complete a test in which a series of GripTester runs were performed during the onset of rain following a sustained dry spell. This was because:

- The study period was characterised by showers at frequent intervals, so that there were few sustained dry spells.
- Rain following the dry spells occurred either at night, or when the GripTester was not available for this study.

Figure 6.7 shows an example of a plot of the GripNumber measured on a drying road with the water supply switched OFF for comparison with Figures 6.2 and 6.5.

6.3.6 Other Observations Concerning the Influence of Rain

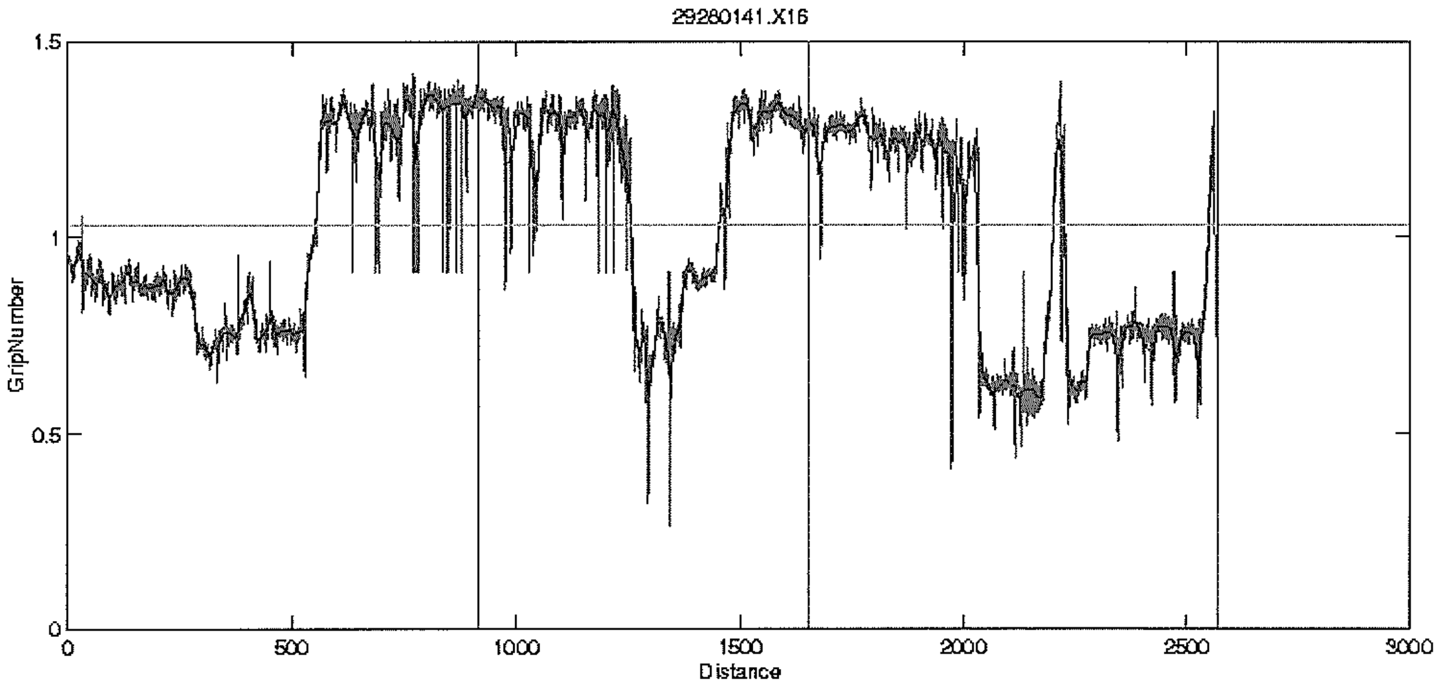
1. When the road is drying, the hot mix dries much more quickly than the chipseal. Considering the situation of a showery summer day, a sudden drop in skid resistance will occur when driving from hot mix onto chipseal, for a period of up to half an hour after a shower. This could lead to a potentially hazardous situation for a driver who may have driven some distance on dry hot mix, and is driving at a speed suitable for a dry road, and suddenly experiences a slippery wet road caused by slow drying of chipseal. Therefore, this phenomenon of differential drying should be brought to the attention of the motoring public.

2. A large part of the data from both 2001 and 2002 consists of standard GripTester runs, tested on a dry road with the GripTester water supply switched ON. There is evidence that this type of measurement does show an effect due to the recent history of previous rainfall.

   However, the degree of skid resistance loss (due to the recent history of previous rainfall) measured by the GripTester, has not been demonstrated to be the same as the friction loss that is experienced by a vehicle during the onset of rain. This is because the mechanism causing the reduction in friction (which consists of a combination of rain and vehicle traffic causing the road contaminants to form a lubricating paste on the road surface) is not fully reproduced by the GripTester (which applies a small amount of water immediately in front of the test wheel). It is conjectured that the actual effect on friction would be greater than that measured by the GripTester in a standard test. That view is supported by the small amount of GripTester data that was obtained during the onset of rain.

3. Dickinson (1989) suggested that it is the proportion of rainy days during the preceding two weeks that has the most effect, rather than the number of days since a significant fall of rain. The GripNumber data acquired has been considered in relation to the proportion of rainy days during the preceding two weeks, and it is apparent that a correlation between rainfall and measured skid resistance does exist, whichever way the rainfall is analysed. However, it is conjectured that the time since a significant fall of rain is the more significant factor. This view is supported by the time history in Figure 6.6, which shows the skid resistance increasing over a period of an hour as the road is washed. The relationship between friction and the dirt build-up model suggested by Cenek et al. (1999) has also been considered, but in this case there appears to be less correlation.

4. A significant fall of rain is considered to be that which is sufficient to thoroughly wash the road in combination with the cleaning effect of traffic action. This may require about an hour of light rain at a rate of about 2 mm/h. Unfortunately, during the study a number of light summer showers lasted only 10 minutes or so. These would only partially wash the road, and would not be counted as significant rainfall in any subsequent analysis.



```
Test: Summer Ice Project
Date: 14-01-2002        Time: 16:39
Tester:   GT074       Operator: PS
Site:     Randwick Road       Direction: Both  Ways
Surface:  Various
Road:     Dry        Weather:  Mild,LtNBrz,Dry
Comment:  LL RWP
```

```
Section  Mean    Min     Max     Std Dev  Records  Length
 1 of 3  1.0176  0.6316  1.4156  0.2421    2292   916.80
 2 of 3  1.1543  0.2647  1.3878  0.2340    1839   735.60
 3 of 3  0.9431  0.4093  1.3989  0.2801    2288   915.20
all of 3  1.0302  0.2647  1.4156  0.2678    6419  2567.60
```

Figure 6.7 Example output of a test run along Randwick Road performed when the road surface was drying following a shower of rain with the GripTester's water supply switched off.

Furthermore, without having a rain gauge immediately adjacent to the test road section for 24-hour monitoring, it was not possible to be even aware that a localised light shower had occurred. Therefore these showers would reduce the apparent effect of rainfall history that was trying to be determined. As a consequence, the data acquired as part of this study is not of sufficient quantity or quality to be of use in determining the influence of a shower of light rain on subsequent skid resistance.

6.4 General Observations of Note

6.4.1 Effect of Chipseal Age on Skid Resistance

Of particular interest in Figure 6.2 is the first 750 m of the run. This shows three distinct lengths of road, each about 250 m long, with distinctly different values of skid resistance. These three surfaces are three lengths of similar chipseal that were laid at different times:

- The first length is 1 year old, laid in March 2001.
- The second length is 5 years old, laid in April 1997.
- The third length is new, laid on 3 March 2002, just 5 days previously.

The progressive reduction in friction with age, caused by traffic wear and weathering of the roading aggregate, is clearly apparent. The measured GripNumber values are:

• New	0.91
• 1 year old	0.76
• 5 years old	0.60

The 5-year old chipseal surface has therefore apparently lost a third of its original skid resistance.

By the completion of the study, 11 weeks after the test shown in Figure 6.2, the skid resistance of the new chipseal was reduced by wear, with the difference in GripNumber between the new and 1-year old surfaces being reduced from 0.15 to 0.06 during this 11-week period.

These results indicate that:

- Skid resistance of the chipseal has progressively reduced with age.
- The rate of reduction of skid resistance has decreased with time.

This issue of wearing of road surfaces has been investigated on previous occasions, but this study shows a clear example of this effect in progress within a single length of road.

Although this example highlights the effects of wearing on the measured skid resistance, it is unlikely to have influenced the findings of this study. This is because, in the context of the average skid resistance over the entire test road section, most of the road surface was a year or more older. Thus the roading aggregates can be regarded as being close to or at the equilibrium phase where environmental rather than traffic factors predominate skid resistance. Therefore the main variation in measured skid resistance is caused by rainfall effects, with relatively little due to wear of the road surface.

6.4.2 Effect of GripTester Bounce

A notable feature of the last 300 m of the test runs in Randwick Road is that there appear to be four evenly spaced humps in the measured GripNumber, at about 65 m intervals. This feature is seen in Figures 6.2, 6.5 and 6.7 at a distance of 2300–2600 m. Inspection of this section of road indicates that there is no visible evidence of any actual variation in the surface skid resistance, but the troughs in the measured GripNumber, between the apparent humps, are caused by servicehole covers in the road. The road roughness due to the servicehole cover causes the GripTester to bounce, and this bouncing is the most likely cause of the reduction in measured GripNumber. The length of reduced measured GripNumber is about 20 m, even though the servicehole cover is less than 1 m long.

It is also possible that the reduced GripNumber is real, caused by traffic bouncing over the bumps and so smoothing the macrotexture of the road surface. However, this is very unlikely as the four evenly spaced humps are also clearly observed in the dry road run shown in Figure 6.5 where differences related to texture and aggregate polishing are expected to be minimal.

6.5 Summary of Findings

A range of GripTester-based skid resistance measurements were obtained that show how the skid resistance of a road is reduced by a preceding period of dry weather, and how the skid resistance is then restored by rain. These measurements provide various indications as to the magnitude of this effect. Unfortunately, none of these indications are very convincing when considered in isolation. However, when examined together, a much more convincing body of evidence results. Also, and significantly, no indications were obtained during the study which demonstrated any opposing evidence.

The various indications that contribute to the body of evidence that skid resistance of roads is influenced by rainfall history are as follows:

1. The 2001 study measured a 0.08 reduction in GripNumber (GN) during the first 10 dry days, from 0.80 to 0.72, corresponding to a rate of 0.008 GN/day.
2. The 2002 study measured a 0.04 reduction in GripNumber (GN) during the first 10 dry days, from 0.78 to 0.74, corresponding to a rate of 0.004 GN/day.
3. The average GripNumber measured during steady rain was 0.83, which was 0.06 higher than the average standard GripNumber of 0.77 measured during dry weather.
4. A single time history was measured during the onset of a period of steady rain. The measured GripNumber increased from 0.76 to 0.87 within a period of 70 minutes. This time history was measured only 1 day after the previous rain day.

5. On another occasion, a single GripNumber measurement of 0.67 was measured during the onset of rain, 5 days after the previous rain day.

From this evidence, and also the widely held impressions of vehicle drivers, the following hypotheses are put forward. However more robust evidence is required to either confirm or refute these hypotheses.

1. The GripTester (for standard measurements on a dry road with water applied in front of the test wheel) measures a reduction in skid resistance after a spell of dry weather. The magnitude of this effect is a reduction in GripNumber of about 0.08 (about 10%) after 2 weeks of dry weather.
2. A similar effect would probably be detected by other vehicle-based skid testers, such as SCRIM and Norsemeter ROAR.
3. This effect is likely to contribute to the well-known phenomenon of seasonal variation of skid resistance. This is because more rain falls during the winter months, and roads consequently typically have a higher level of measured wet skid resistance in winter.
4. The magnitude of the effect experienced by vehicles on naturally wet roads may be greater than is measured by skid testers applying water to dry roads. This is because the combination of road detritus, rain, and vehicle action produce a lubricating paste on the road surface, which the skid testers cannot fully reproduce.
5. Different skid testers are likely to measure the magnitude of this effect differently. This is because the mechanism used to apply water to the road surface may have an important influence on the measurements. For example, a BPT, for which the water is poured onto the road surface by hand, may measure a different effect to a GripTester, for which the water is delivered by means of a pumped system immediately in front of the test wheel to provide a mean film thickness of 0.25 mm on a smooth road surface. These different mechanisms would have a different influence on flushing detritus out of the road pores onto the road surface. Possibly a BPT may not disturb the detritus lodged in the road pores at all, and consequently the effect of the detritus would not be detected by the tester. If this is correct, it could be argued that such a tester would be a better device than mobile skid testers for measuring the inherent skid resistance of the road surface, unaffected by previous rainfall history.
6. A procedure, at least for small areas of road, could be developed which would enable the friction experienced by vehicles to be measured using skid testers that are available in New Zealand without having to wait for the onset of rain. This would involve wetting the road surface, and either letting traffic perform the lubricating action or artificially simulating the role of the traffic.
7. The additional loss of friction experienced by a vehicle during the onset of rain following a dry spell may be about 50% of the difference between dry weather friction and steady rain friction, after 2 weeks of dry weather.

Based on the GripTester results, representative GripNumber values of skid resistance would be:

Dry weather	1.19
Steady rain	0.82
Onset of rain following a dry spell	0.64

8. The rate at which skid resistance reduces during periods of dry weather decreases as the number of days between significant rain events increases, for example:

   GripNumber of 0.82 during steady rain.

   GripNumber of 0.64 during onset of rain after 2 weeks of dry weather.

   GripNumber of 0.46 during onset of rain after 20 weeks of dry weather.

9. Steady rain levels of skid resistance are largely restored after 2 hours of steady moderate rain.
10. Light showers have a partially restoring effect.

Of note is that the above findings and associated hypotheses have been derived from skid resistance measurements performed on straight roads. However, tyre wear is greater on corners than on straight roads because of the greater tyre slip velocities and horizontal forces. The assumption can be made that the build-up of road detritus (which includes tyre rubber particles) is greater on corners than on straight roads. Consequently, the reduction of skid resistance caused by road detritus can be expected to be greater on corners than on straight roads.

In addition to road geometry, the study was unable to quantify or even provide an indication of the influence of the following variables on the variability of skid resistance measurements:

- traffic density during the dry weather;
- proximity to dust sources during the dry weather;
- rainfall intensity affecting the restoration time; and
- traffic density affecting the restoration time.

6.6 Recommendations for Additional Research

On the basis of results of GripTester surveys performed at regular time intervals, the evidence is that skid resistance measurements are significantly influenced by previous rainfall history. Such evidence needs to be better substantiated because the consequences for skid resistance management of roads are likely to be significant. This is because observed changes in the level of skid resistance between one set of measurements and another can be greater than the 0.1 tolerance allowed for in Transit New Zealand's T/10 specification in setting threshold levels for intervention. However, it would be unwise to change current practices without first acquiring further supporting evidence. The way forward is to:

1. Obtain additional information on the causes of variation of skid resistance measurements, with the specific aim being to confirm or refute the current evidence.

2. If the evidence is substantiated, consider how this should influence skid resistance management of sealed public roads.

Specific matters that need to be better understood are:

- Relationships between standard skid tester measurements and previous rainfall history.
- Dependency of these relationships on a skid tester device.
- Extent that different road surface types, road geometries, traffic characteristics and rainfall intensities influence these relationships.

This knowledge is required so that, when interpreting measurements of wet road skid resistance from road surveys, it will be possible to distinguish between what is the inherent skid resistance of the road surface and what is the influence of previous rainfall history.

Addressing the knowledge gaps identified above does not require measurements of skid resistance during the onset of rain, or using a simulation of the onset of rain. This is advantageous, as it was this aspect of the current study that was found to be the most problematical.

In addition, quantification of the tyre–road friction that is actually experienced by motorists during the onset of rain is required. This is likely to be different to the skid resistance measured by skid testers. Such information is required to understand the phenomenon of slippery roads during the onset of rain, and to determine what actions are required to improve road safety during these conditions.

7. Statistical Modelling Studies – Aggregate Characteristics and Skid Resistance

7.1 Experimental Design

The objective of the field study was to investigate the sensitivity of in-service skid resistance performance of chipseal-surfaced sections of state highway to aggregate and texture characteristics under different traffic loadings. To have relevance in a predictive model, the characteristics selected must be capable of being determined in the laboratory before placing on the road, e.g. aggregate PSV, or measured in situ using laser-based profilers, e.g. amplitude and spacing parameters.

Test surface selection is crucial for the outcome of an investigation such as this so that significant correlations are not masked by variances related to random measurement errors. This necessitates the investigated factors to have as wide a range as possible.

7.1.1 Selection of Candidate Test Sites

A search of Transit New Zealand's 2001 RAMM database was carried out to generate a database of candidate test sites that satisfied the following conditions:

- Chipseal surfaces that satisfied Transit New Zealand's recently introduced texture requirements for rural roads (i.e. MPD > 0.9 mm) and showed no signs of bitumen cover either from bleeding, or flushing, or precoated chip.
- A surface age of 3 or more years to ensure that the polishing phase, where skid resistance reduces under the action of traffic, had been passed.
- The road geometry was comparatively straight (i.e. horizontal curvature 300 m or greater) and level (i.e. gradient ±10% or less) to minimise the confounding effect of additional polishing action brought about by accelerating, braking and cornering manoeuvres.
- A homogeneous length of at least 200 m to enable multiple measurements with Transit's Stationary Laser Profiler (SLP) to be made and to minimise any location referencing errors inherent in the RAMM high speed data (HSD) database. The accepted tolerance for recording and reporting survey data is ±(0.3% x D + 10 m) where D is the distance between reference station (RS) markers. This tolerance equates to ±55 m for a typical RS length of 15 km.

The above selection criteria generated around 7500 sites. Where possible, the Polished Stone Value (PSV) of the sealing chip for each site was identified from Transit New Zealand's wall chart of PSV test results for suppliers of surfacing aggregate. This reduced the number of candidate test sites having a known PSV to about 4400.

For each of these 4400 sites, standard 20-m RAMM wheelpath condition (roughness, rutting and surface texture) and 10-m lane geometry (crossfall, gradient and horizontal curvature) were extracted from Transit New Zealand State Highway RAMM tables, together with 10-m SCRIM skid resistance data for the previous surveys conducted in 1995, 1998, 1999, 2000, 2001. The skid resistance data was in terms of Mean Summer SCRIM coefficient (MSSC), which is the estimated mean SCRIM coefficient over the summer period when skid resistance is generally at its lowest.

The extracted data was used to obtain average values for each candidate test site, the averaging length being the entire length of the site.

7.1.2 Preliminary Regression Analysis

The opportunity was taken to perform a regression analysis to identify statistically significant relationships between in-service skid resistance performance and site-averaged road condition, road geometry and traffic data for each candidate site. In-service skid resistance was defined in the following two ways:

- MSSC value based on the 2001 survey results (1-year site-average), and
- MSSC value derived by averaging the 1999, 2000 and 2001 survey results (3-year site-average).

The intent of this analysis was to:

- Establish how well MSSC correlated with the two variables presently used in Transit New Zealand's T/10 specification for predicting in-service skid resistance performance, PSV, and heavy commercial vehicles per lane per day (CVD) (refer Chapter 1, Equation 1.1).
- Identify any other variables stored in RAMM that may be significant predictors of in-service skid resistance to ensure test site selections are conducive to a successful outcome.

In addition, MSSC values from 2000 were regressed against MSSC values from 2001 to establish whether or not existing values of skid resistance are a good predictor of future values. This is typically the case for other road condition variables, roughness in particular.

The results of the regression analysis, in terms of coefficient of determination (r^2), are presented in Table 7.1. The coefficient of determination is the ratio of the explained variation to the total variation. If there is zero explained variation, i.e. the total variation is all unexplained, this ratio is zero. If there is zero unexplained variation, i.e. the total variation is all explained, the ratio is one.

The following comments are made in relation to the r^2 values listed in Table 7.1:

- The degree of correlation in the test site average MSSC values between successive years is about 60%. Given that the surface age of each site is 3 or more years, any inter-year differences are likely to be related to seasonal variations rather than to polishing action of traffic because the equilibrium value of skid resistance should have been reached.

This result confirms that skid resistance is a very variable parameter even when normalising procedures for seasonal effects, such as MSSC are utilised. Therefore, it would be unrealistic to expect that a regression model for skid resistance utilising standard RAMM variables and texture profile variables can result in predicted values that correlate better than 60% with the observed values.

- The two variables in the TNZ T/10 equation for guiding aggregate selection, PSV and CVD, when combined explain only about 12% to 14% of the observed variation in the MSSC values. This low degree of correlation supports earlier New Zealand research reported in Cenek et al. (1998) suggesting that critical variables influencing skid resistance are missing from the T/10 equation.

  However, a possible explanation for the lower than expected r^2 values for these two key variables may be their accuracy. In the case of PSV values, these were inferred rather than measured. The CVD data is even more suspect as values stored in RAMM can either be default or estimated or measured.

  Therefore, in an attempt to improve the quality of CVD data, test sites were selected wherever possible on the basis of proximity to Transit New Zealand's control traffic monitoring sites to ensure that measured CVD values were used.

- The degree of correlation between chip size and MSSC is higher than that between texture depth (MPD) and MSSC. This result indicates that aggregate shape and spacing, two factors which impact on hysteresis losses, have a greater contribution to slow slip-speed skid resistance than texture depth, which impacts on drainage.

- Slightly better correlations have been obtained when the RAMM variables were regressed against site MSSC values that had been averaged over 3 years. This averaging process reduces the influence of year on year variations in weather patterns. For example, MSSC values are expected to be lower during dry summers and higher during wet summers. The 3-year average MSSC value approximates the Equilibrium SCRIM Coefficient (ESC) adopted in TNZ T/10:2002, which is based on a 4-year rolling average.

- No significant correlations between RAMM road geometry data and skid resistance were identified. This was as expected since test site selections were confined to relatively straight and level road geometry.

Table 7.1 Degree that selected RAMM variables correlate with in-service skid resistance for candidate test sites.

Regressed Variable	Coefficient of Determination (r^2)	
	MSSC (2001 Survey)	**MSSC (Average of 1999, 2000, 2001 Surveys)**
Polished Stone Value (PSV)	0.017	0.019
Commercial Vehicles per lane per day (CVD)	0.111	0.130
Horizontal Curvature (m)	0.003	0.005
Road Gradient (%)	0.001	0.002
Crossfall (%)	0.011	0.014
Lane Roughness (NAASRA counts/km)	0.013	0.024
Rutting (mm)	0.023	0.035
MPD Texture (mm)	0.000	0.001
Surface Age (years)	0.003	0.022
Chip Size (ALD, mm)	0.080	0.112
PSV + CVD	0.124	0.144
PSV + Chip Size	0.090	0.128
PSV + CVD + Chip Size	0.177	0.227
MSSC (2000)	0.596	–

Note: ALD = average least dimension

7.1.3 Sites Selected for Surface Profile Measurements

The critical factors used in the site selection were as follows:

1. Chip size
    (a) Coarse, Grade 2
    (b) Medium, Grade 3
    (c) Fine, Grades 4, 5 and 6
2. Traffic
    (a) Low, CVD < 200 v/l/d
    (b) High, CVD > 200 v/l/d
3. PSV
    (a) Low, < 52
    (b) Medium, 53 to 59
    (c) High, > 60
4. Rock Type
    (a) Greywacke
    (b) Basalt
    (c) Gabbro
    (d) Schist – Greywacke
    (e) Andesite
5. Extraction Method
    (a) Alluvial
    (b) Hard rock quarry

A test site selection matrix was developed in discussion with a consulting statistician, as shown in Table 7.2. With reference to Table 7.2, there are 108 possible combinations of variables. Each element comprising the test site selection matrix has been given a unique numerical identifier from 1 to 108. If two test sites were to be found for each matrix element, a total of 216 would be required.

Sorting the 4400 candidate sites into the 108 categories resulted in a significant number of categories not being represented, giving a total of 54 test sites.

The lower than desirable number of test sites was due to:

- the dominance of greywacke aggregate (~80% of all candidate test sites);
- some combinations only being available from a single quarry source;
- the gradual elimination of low PSV aggregate from the highway network resulting from the implementation of Transit New Zealand's T/10 specification; and
- the concentration of most PSV values within a relatively narrow range (47 to 63).

Following on from the RAMM database search, discussions with the consultants responsible for each Transit New Zealand region revealed that some sites had been resealed during the latest sealing season. Consequently, the number of sites was further reduced to 47. The matrix elements satisfied by these 47 test sites have been highlighted in Table 7.2.

The data extracted from Transit New Zealand's RAMM database for 47 test sites is summarised in Appendix A.2 for ready reference.

7.1.4 Laser Profiler Measurements

Detailed surface profile measurements were made using Transit New Zealand's stationary laser profiler (Figure 3.2). It consists of a Selcom^{TM} 32 kHz laser camera that is driven at a constant speed along an approximately 1.6 m-long track.

The laser light spot is 0.5 mm in diameter and allows surface height to be measured to within an accuracy of ±0.03 mm. Therefore, precise vertical cross-section of the traversed surface is provided.

Measurements were made with the stationary laser profiler in the left wheelpath at each of the 47 test sites to allow quantification of macrotexture characteristics in the 0.63 mm to 500 mm wavelength range. Three passes were made over a representative 20 m length of each site. Figure 7.1 shows a representative surface profile obtained for one of the test sites.

Table 7.2 Test site selection matrix with those elements satisfied by one test site highlighted in light grey, and those by two test sites highlighted in dark grey.

Traffic	PSV	Rock Type	Extraction Method	Chip Size		
				Grade 2	Grade 3	Grade 4+
Low Traffic	Low PSV	Greywacke	Alluvial	1	37	73
			Hard Rock	2	38	74
		Basalt	Hard Rock	3	39	75
		Gabbro	Hard Rock	4	40	76
		Schist – Greywacke	Alluvial	5	41	77
		Andesite	Hard Rock	6	42	78
	Medium PSV	Greywacke	Alluvial	7	43	79
			Hard Rock	8	44	80
		Basalt	Hard Rock	9	45	81
		Gabbro	Hard Rock	10	46	82
		Schist – Greywacke	Alluvial	11	47	83
		Andesite	Hard Rock	12	48	84
	High PSV	Greywacke	Alluvial	13	49	85
			Hard Rock	14	50	86
		Basalt	Hard Rock	15	51	87
		Gabbro	Hard Rock	16	52	88
		Schist – Greywacke	Alluvial	17	53	89
		Andesite	Hard Rock	18	54	90
High Traffic	Low PSV	Greywacke	Alluvial	19	55	91
			Hard Rock	20	56	92
		Basalt	Hard Rock	21	57	93
		Gabbro	Hard Rock	22	58	94
		Schist – Greywacke	Alluvial	23	59	95
		Andesite	Hard Rock	24	60	96
	Medium PSV	Greywacke	Alluvial	25	61	97
			Hard Rock	26	62	98
		Basalt	Hard Rock	27	63	99
		Gabbro	Hard Rock	28	64	100
		Schist - Greywacke	Alluvial	29	65	101
		Andesite	Hard Rock	30	66	102
	High PSV	Greywacke	Alluvial	31	67	103
			Hard Rock	32	68	104
		Basalt	Hard Rock	32	69	105
		Gabbro	Hard Rock	34	70	106
		Schist – Greywacke	Alluvial	35	71	107
		Andesite	Hard Rock	36	72	108

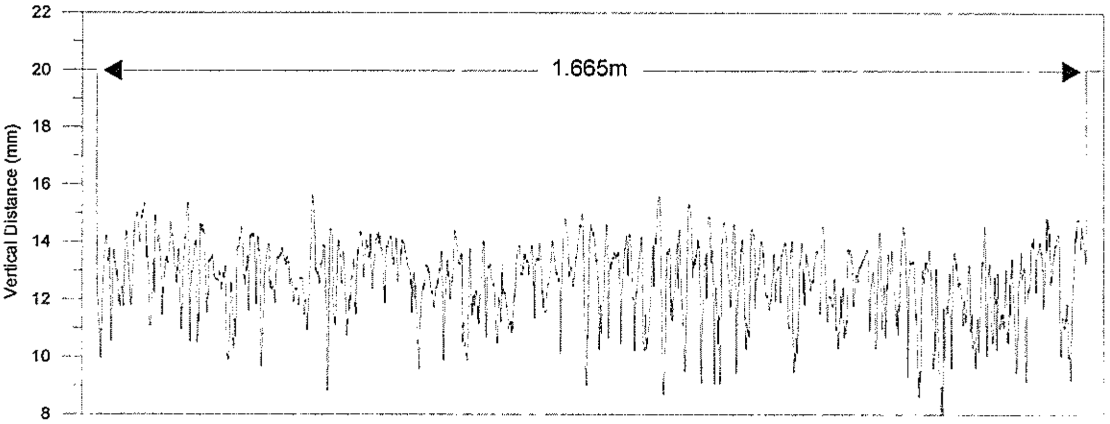


Figure 7.1 Example of a test site surface profile.

7.1.5 Data Processing

The principal objective of this study was to quantify the influence of road surface profile on in-service skid resistance as measured by MSSC. Surface profiles can be divided into three components: roughness; waviness; and form. Accordingly, the acquired road surface profiles were processed to obtain standard measures of surface texture as defined in ISO Standards 4287/1:1984, 4287:1997, 13565-1:1996, 13565-2:1996 and ASME Standards B46.1:1985, B46.1:1995.

These standard measures of surface texture fall into three categories as follows:

- amplitude variables, which are measures of the vertical characteristics of the surface deviations;
- spacing variables, which are measures of the horizontal characteristic of the surface deviations;
- hybrid variables, which are some combination of both amplitude and spacing variables.

Table 7.3 provides a listing of all the surface texture variables that have been utilised in this study. The corresponding values calculated for each of the 47 test sites are tabulated in Appendix A3.

In calculating the surface texture variables listed in Table 7.3, the assessment length was taken to be the track length of 1.67 m and the sampling length one fifth of this i.e. 0.33 m.

Table 7.3 ASME and ISO standardised measures of surface texture.

Surface Texture Variable	Description
Amplitude Variables	
Ra	mean of the absolute departures of the profile from the mean line
Rq	root mean square (RMS) corresponding to Ra
Rt	maximum peak-to-valley height in the assessment length
Rti	maximum peak-to-valley height in one sampling length
Rtm=Rz	mean of all Rti values in an assessment length
Rvi	maximum depth of the profile below the mean line within the sampling length, i.e. maximum profile valley depth
Rvm	mean of the Rvi values obtained for each sampling length within the assessment length
Rpi	maximum height of the profile above the mean line within the sampling length, i.e. maximum profile peak height
Rpm	mean of the Rpi values obtained for each sampling length within the assessment length
Spacing Variables	
S	mean spacing of adjacent local peaks in sampling length (only included if height of peak-to-preceding minima ≥ 1%Rt)
Sm	mean spacing between profile peaks at the mean line, measured over the assessment length (peak = highest part of the profile between crossings of mean line)
HSC	high spot count, i.e. the number of complete profile peaks within the assessment length projecting above the mean line or a line that is some specified distance below the highest peak
Pc	peak count density, i.e. the number of local peaks in an assessment length that project through a selectable band centred about the mean line
Hybrid Variables	
delq	rms slope of the profile for the assessment length
lq	the rms measure of spatial wavelength over the assessment length (gives a measure of average wavelength)
Rmr	material/bearing ratio, i.e. length of the bearing surface (as % of assessment length) at a specified depth below the highest peak
Rku	Kurtosis, i.e. a measure of the sharpness of the amplitude distribution curve for the assessment length
Rsk	Skewness, i.e. a measure of the symmetry of the amplitude distribution curve about the mean line for the assessment length

Note: The amplitude variable, Rz, is equivalent to the sum of the amplitude variables Rp and Rv.

7.2 Regression Analysis of Test Site Data

7.2.1 Averaging Procedure for MSSC Data

The results of the preliminary regression analysis detailed in Section 7.1.2 showed that better correlations were obtained when road condition and road geometry variables were regressed against MSSC values of skid resistance averaged over a number of years, rather than MSSC values for a particular year. This is consistent with the findings from Chapters 5 and 6, which indicated that skid resistance measurements are sensitive to environmental factors such as rainfall frequency and the presence of contaminants such as bitumen film, dust and oil. Therefore, within year and between year variability in MSSC values can be significant because SCRIM surveys of the State Highway network comprise a single pass measurement. Thus some averaging is required to obtain a value of equilibrium skid resistance that can be considered to be truly representative.

The Equilibrium SCRIM Coefficient (ESC) adopted in TNZ T/10:2002 is based on a 4-year rolling average. To provide equivalency with ESC, the dependent variable for the regression analysis was confined to the mean of the 1998, 1999, 2000 and 2001 site-averaged MSSC values whenever the surface age of the test site was 4 years or older. For a surface age less than 4 years (i.e. the surface was constructed after the 1998 SCRIM+ survey), any MSSC values acquired from SCRIM+ surveys over the lifespan of the surface were averaged. This allowed the averaging period to be maximised. Therefore, MSSC data for the last 2 years (2000 and 2001) was averaged for the surfaces just less than 3 years of age, and for the last 3 years (1999, 2000 and 2001) for surfaces with age greater or equal than 3 years but less than 4 years.

The distribution of surface ages for the 47 test site sample is shown in Figure 7.2. The sample is dominated by test sites with surfaces older than 4 years, with only 20% of the test sites having a surface younger than 4 years.

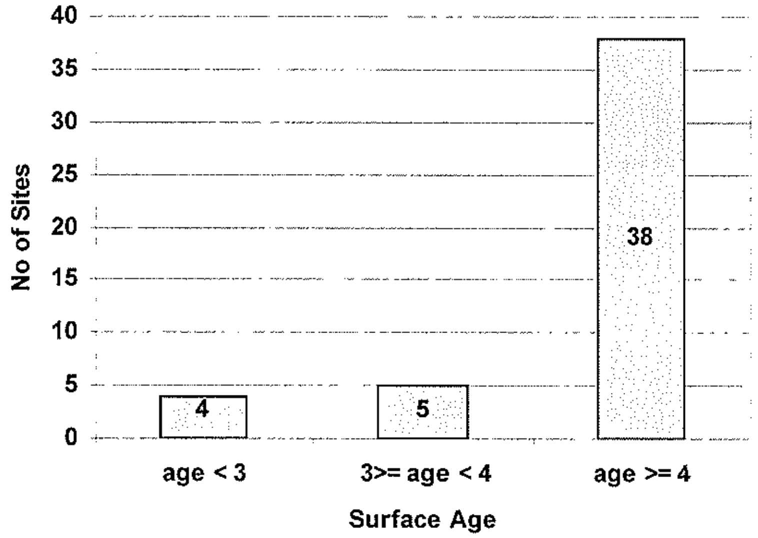


Figure 7.2 Histogram plot of test site surface ages.

7.2.2 RAMM Variables

Confidence that the experimental design would be sufficiently sensitive to identify significant relationships between skid resistance and surface profile characteristics for the 47 test sites selected was desired. To achieve this, the regression analysis detailed in Section 7.1.2 involving RAMM variables was repeated to establish whether or not the resulting coefficients of determination were comparable to those obtained with the population of 4400 candidate test sites.

The results of this repeat RAMM variable regression analysis are summarised in Table 7.4. Comparing the tabulated r^2 with those in Table 7.1, the sensitivities detected with the sample of 47 tests sites are seen to be very similar to those detected with the entire population of 4400 candidate test sites. This confirms the suitability of the experimental design.

Table 7.4 Degree that selected RAMM variables correlate with in-service skid resistance, for the 47 test sites selected for surface profile measurements.

Regressed Variable	Coefficient of Determination (r^2) when regressed against averaged MSSC (1998, 1999,2000, 2001)
Polished Stone Value (PSV)	0.050
Commercial Vehicles per lane per day (CVD)	0.133
Horizontal Curvature (m)	0.076
Road Gradient (%)	0.065
Crossfall (%)	0.005
Lane Roughness (NAASRA counts/km)	0.001
Rutting (mm)	0.036
MPD Texture (mm)	0.032
Surface Age (years)	0.069
Chip Size (mm)	0.164
PSV + CVD	0.183
PSV + Chip Size	0.191
PSV + CVD + Chip Size	0.306

With reference to Table 7.4, the main predictors of in-service skid resistance performance are shown to be heavy commercial vehicle traffic volume (CVD) and average chip size (CS) of the roading aggregate. These two variables when combined separately, or together with PSV, form the basis of the TNZ T/10 equation and of an enhancement to the TNZ T/10 equation proposed by Catt (1983), which incorporates aggregate size.

The r^2 values that result from a multiple regression involving two or more of these variables are very similar to the summation of the simple regression r^2 values for each independent variable used in the multiple regression analysis. For example, a multiple regression of PSV, CVD and CS produces an r^2 value of 0.306, whereas the sum of the individual r^2 values is only slightly greater at 0.347 (i.e. 0.050+0.133+0.164). This indicates that CVD and CS are not explaining the same variance observed in the in-service skid resistance performance of state highways.

The resulting multiple regression models show increasing skid resistance with increasing PSV and decreasing skid resistance with increasing CVD and ALD. These trends appear intuitively correct and replicate trends observed with the in-service skid resistance performance of UK roads reported by Catt (1983). This provided a degree of confidence that the database assembled would be suitable for refining the T/10 equation to provide more reliable predictions of the in-service skid resistance performance of New Zealand chipseal roads.

7.2.3 Surface Profile Variables

A regression analysis of the surface profile data obtained for the 47 test sites was performed to highlight significant relationships between MSSC and amplitude, spacing and hybrid variables of surface texture to assist in the development of a predictive model. Table 7.5 provides a summary of the coefficients of determination (r^2) obtained for each of the surface texture variables that are listed in Table 7.3.

Table 7.5 Degree that standardised measures of surface texture correlate with in-service skid resistance for the test sites selected for surface profile measurements.

Regressed Surface Texture Variables		**Coefficient of Determination (r^2) when regressed against averaged MSSC (1998, 1999,2000, 2001)**
Amplitude Variables:	Ra	0.005
	Rq	0.004
	Rt	0.000
	Rtm	0.002
	Rpm	0.016
	Rvm	0.000
Spacing Variables:	Si (average)	0.000
	Sm	0.050
	HSC	0.039
	Pc	0.145
Hybrid Variables:	delq	0.021
	lq	0.072
	Rmr	0.021
	Rku	0.004
	Rsk	0.091

With reference to Table 7.5, the only surface texture variables that stand out as possibly contributing to MSSC are the spacing variable Pc, which is associated with the number of local peaks over an assessment length of 1 cm, and the hybrid variables lq and Rsk, which are associated with the root-mean-square (RMS) wavelength of the profile and symmetry of the profile (see Figure 7.3) about the mean line respectively. Each of these three surface texture variables has an r^2 value of about 0.1, which, although not particularly good, is comparable to that obtained for the two TNZ T/10 equation variables PSV and CVD when applied to the same dataset.

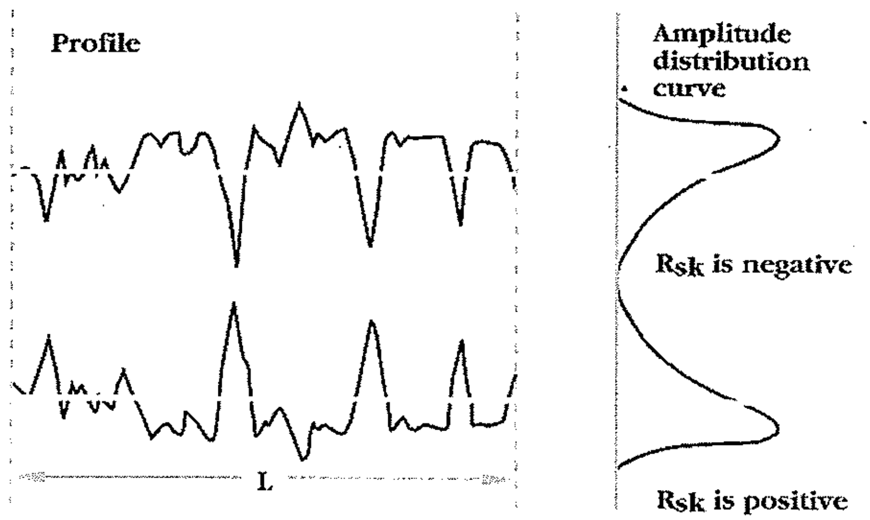


Figure 7.3 Graphical representation of surface texture variable Rsk.

In terms of interpreting the variable Rsk, road surfaces with a positive skewness, have fairly high spikes that protrude above a flatter average, such as that for asphaltic concrete. Road surfaces with negative skewness have fairly deep valleys in a smoother plateau, such as that for open graded porous asphalt (OGPA). More random surfaces such as chipseals have a skew near zero.

7.2.4 RAMM and Surface Texture Variables Combined

The RAMM and surface texture datasets for the 47 test sites were combined and a stepwise regression analysis was performed. Essentially, stepwise regression allows either forward or backward selection to control the entry of variables into the model.

In each step of the procedure, variables are added (forward selection) or removed (backward selection) to obtain a model with a small set of significant variables.

The commercially available software package, STATISTICA by Statsoft (www.statsoft.com), was used to perform the stepwise regression analysis.

The model as derived from the test site data was as follows:

$$\begin{aligned}\mathrm{MSSC_{av}} = {} & (0.0018 \times \mathrm{PSV}) + (-0.05 \times \mathrm{CHCV}) \\ & + (-0.07 \times \mathrm{Rsk}) + (0.15 \times \mathrm{delq}) + (45 \times \mathrm{Rvm}) \\ & + 0.47\end{aligned} \qquad \text{Equation 7.1}$$

where: $\mathrm{MSSC_{av}}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
PSV = polished stone value
CHCV = cumulative heavy commercial vehicle traffic per lane in millions
= commercial vehicle traffic > 3.5 tonnes /lane/day × surface age (years) × operational days per year (=300)/10^6
= 0.0003 × CVD × AGE
Rsk = the skewness of the road profile about the mean line
delq = the root-mean-square (rms) slope of the road surface profile
Rvm = the mean maximum depth of the road profile from the mean line (m)

Detailed statistics of the model constant estimates and goodness of fit of the model are given in Table 7.6. In Table 7.6, the p-level statistic relates to "statistical significance". The higher the p-level, the less the observed relation between variables in the sample can be believed to be a reliable indicator of the relation between the respective variables in the population. Specifically, the p-level represents the probability of error that is involved in accepting the observed result as valid. In many areas of research, the p-level of 0.05 is customarily treated as a "border-line acceptable" error level. On this basis, the two most significant predictors of in-service skid resistance are cumulative heavy commercial vehicle passes, i.e. CHCV and the mean of maximum profile valley depths, i.e. Rvm.

Table 7.6 Model statistics for Equation 7.1.

Model Component	**Model Coefficients**		
	Value	**Standard Error**	**p-level**
PSV	0.0018	0.001	0.145
CHCV	-0.05	0.015	0.002
Rsk	-0.07	0.03	0.03
delq	0.15	0.06	0.02
Rvm	45	16	0.006
Constant	0.47	0.06	1.2E-07
Overall Model Statistics			
Standard Error of Estimation:	0.04		
r^2:	0.43		
No of Observations:	47		

The statistics of the model indicate a standard error of 0.04 in the predicted MSSC and an r^2 of 0.43. Figure 7.4 presents a graphic representation of the model fit. The "95% Confidence Interval" bands shown in Figure 7.4 around the sample regression line represents the confidence limits for an ordinate to the "true" (population) regression line. These confidence limits are less than the prediction interval for an individual value of MSSC, which in practice may be of more interest than the mean value given by the regression line. Based on the standard error of estimation (SE) value of 0.04, the "95% Prediction Interval" is about ± 0.08 and is shown in Figure 7.4.

In comparing model predictions to observed MSSC values, there appears to be a very low bias since the line of regression falls onto the line of equality (i.e. observed = predicted). In addition, the scatter of data points about the regression line is confined to about ± 0.08 MSSC. This is comparable to the expected variability in single pass SCRIM$^+$ measurements. Therefore, despite the regression model given by Equation 7.1 being able to explain only 43% of the observed variation in the average MSSC values, it appears sufficiently reliable to guide the design of chipseal surfaces for skid resistance.

From Table 7.6 the PSV component of the model is seen to have a p-level statistic of 0.145. This is significantly higher than the target value of 0.05 and resulted because the stepwise regression was performed on the basis of forced inclusion of the PSV variable in the regression model. This inclusion was made to preserve the form of the TNZ T/10 equation. Therefore, the other variables incorporated in the model were selected to maximise the model's fit, as determined by r^2, while minimising the p-level of the PSV variable.

The low correlation of the PSV variable with in-service skid resistance ($r^2 = 0.05$) and relatively high p-level could be due in part to inferring PSV values from matching aggregate source information contained in RAMM's surfacing table for each test site, to Transit New Zealand's 2002 wall chart of PSV test results provided for suppliers of surfacing aggregate. Therefore, an improvement in the r^2 and p-level statistics is expected if PSV test results for specimens fabricated from non-trafficked aggregate samples taken from each test site were employed instead.

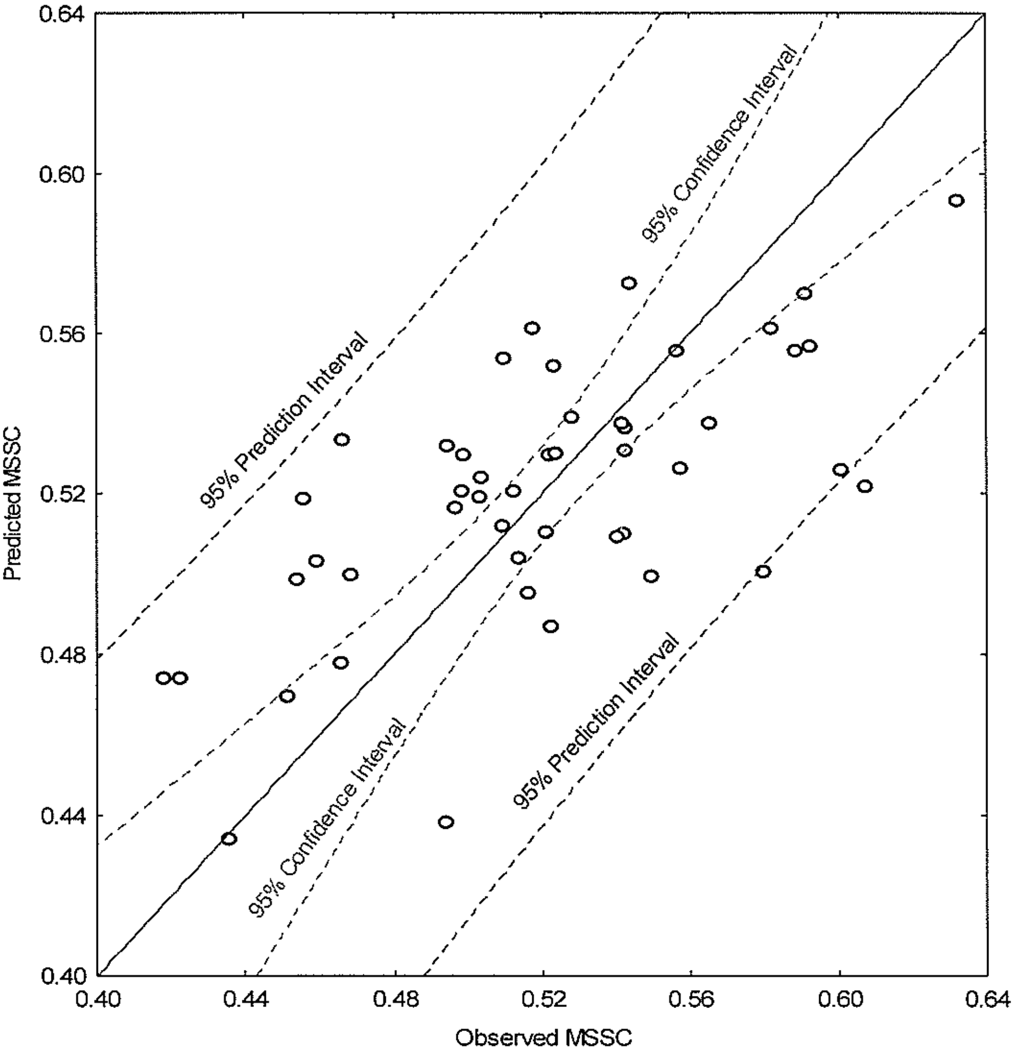


Figure 7.4 Scatter plot of predicted versus observed in-service MSSC.

By comparison, an unconstrained stepwise regression analysis resulted in the following two variable model:

$$MSSCav = (-0.053 \times CHCV) + (0.09 \times Pc) + 0.46 \qquad \text{Equation 7.2}$$

This second regression model had an $r^2 = 0.32$ and S.E.= 0.042. The p-level statistics for CHCV and Pc variables were 0.001 and 0.014 respectively, indicating that these two variables are highly significant.

Features common to both regression models are as follows:

- ***Cumulative Heavy Commercial Vehicle Trafficking***

The equilibrium state of polish of a road surface is assumed to occur after 1 million equivalent standard axle (ESA) passes or after 2 years, whichever occurs first (Kokkalis 1998). It is uncertain from the literature whether the surface age threshold of 2 years is associated with the time expected to reach 1 million ESAs or physical changes to the road surface that occur from weathering.

The 47 test sites were selected on the basis that they had reached their equilibrium state of polish and so no reduction in skid resistance over time related to traffic induced wear was expected as long as traffic volumes remained largely unchanged. Therefore, the identification of cumulative heavy commercial vehicle traffic (CHCV) rather than daily number of heavy commercial vehicles (CVD) as the most significant variable for predicting in-service skid resistance performance of chipseal road surfaces came as a surprise. This age dependency was not as evident in the regression results for the population of 4400 candidate test sites where lightly trafficked sites were not as predominant. Therefore, the conjecture is that equilibrium state of polish is primarily a function of the number of HCV passes (i.e. CHCV) and not exposure to weathering, as all the test sites had surfaces that were about 3 years in age or older.

This hypothesis was tested by determining the threshold value where the variable CHCV ceased to be important (i.e. p-level statistic > 0.05). This threshold value was 1 million HCV passes or approximately 2 million ESA, which is double that of Kokkalis. It is conjectured that differences in road surface type (chipseal versus hot mix), travel speeds, and the use of gritting/de-icing agents over winter between New Zealand and Europe may account for the New Zealand threshold being higher.

From RAMM, the average HCV exposure of two-lane rural state highways is calculated to be 129 HCV/lane/day. Therefore, the equilibrium state of polish can be expected to occur after about 26 years, assuming road transport operations for 300 days per year. By comparison, the average resealing cycle time for state highways is only 7 years. As a consequence, most surfaces on straight sections of state highway are unlikely to reach their equilibrium state of polish unless they carry more than 500 HCV/lane/day.

Both regression models calculate the rate of change in MSSC due to the polishing action of HCV traffic to be of the order of –0.002 MSSC/year. This rate pertains to straight sections of state highway and so can be expected to be significantly higher wherever horizontal tyre forces are greater than for the free-rolling situation, for example when accelerating, braking and cornering.

- ***Key Surface Profile Characteristics***

As expected, Equations 7.1 and 7.2 show that aggregate size, spacing and shape are important determinants of MSSC. From Moore (1975), a mean spacing of 5 to 15 mm between tips of aggregates is considered necessary to satisfy both hysteresis and drainage requirements for speeds on rural state highways. These spacings correspond to values of 2 and 0.67 peaks/cm respectively for the spacing variable "Pc." With reference to Equation 7.2, MSSC increases with increasing Pc implying that, for chipseal surfaces, smaller aggregate sizes (i.e. Grades 4 to 6) are preferable to larger sized aggregates (i.e. Grades 2 and 3) as the mean spacing between aggregates will be less because of denser packing.

The variable Pc ranged from 0.4 to 1.3 over the 47 test sites, indicating that the distribution of aggregate sizes in New Zealand tends to be skewed towards larger sizes than considered desirable by Moore. On the basis of Equation 7.2, this observed variation in Pc translates to a variation of 0.08 in MSSC.

Although Equation 7.2 covers the frequency of contact between the tyre and road surface, it provides little information regarding aggregate shape, which dictates the degree of penetration into the tread rubber. This is addressed by Equation 7.1, which identifies the important shape parameters to be the amplitude distribution about the mean line (Rsk), the root-mean-square of the road profile (delq) and the mean maximum depth of the road profile from the mean line (Rvm).

The relative contribution of these surface profile variables over the range of values measured for the 47 test sites are tabulated in Table 7.7. Compared to the slope/ sharpness of the aggregate and surface profile valley depth, the skewness of the amplitude distribution is shown to have negligible influence.

Table 7.7 Relative contribution of key surface texture variables to MSSC as calculated from Equation 7.1.

Surface Texture Variable	Measured Range		Contribution to MSSC	
	Minimum	Maximum	Minimum	Maximum
Skewness, Rsk	–0.6	0.4	–0.03	0.04
RMS Slope, delq	0.23	1.39	0.03	0.21
Mean Valley Depth,Rvm (m)	–0.006	–0.001	–0.27	–0.05
Sum Total			–0.27MSSC	0.20 MSSC

In practice, the combined contribution of the three key surface profile variables as calculated by Equation 7.1 was found to range between –0.07 MSSC and +0.03 MSSC, and be normally distributed around a mean value of –0.03 MSSC for the 47 test sites. These values are significantly less than the extreme minimum and maximum values of –0.27 and 0.20 MSSC given in Table 7.7, and suggest that the potential for optimising aggregates with regard to their shape and distribution within the surface to maximise skid resistance may be limited. However, an analysis of Equations 7.1 and 7.2 suggests that the ideal road surface profile in relation to maximising MSSC for a given aggregate PSV and HCV traffic volume is as shown in Figure 7.5, the fine angular particles having a tip spacing of 5 mm and a height of between 2 and 3 mm. Such a profile closely resembles that of high friction surfaces, which comprise calcined bauxite chippings in the size range 1.2 to 2.8 mm held in an epoxy-resin binder.

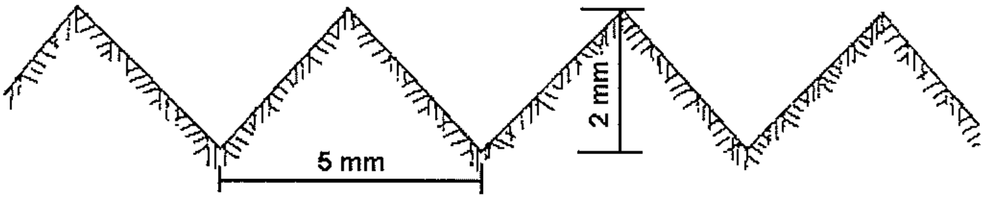


Figure 7.5 Idealised road surface profile for maximising skid resistance.

7.3 Predictive Model Comparisons

The predictive equation given in TNZ T/10 specification can be re-arranged to provide estimates of MSSC as a function of PSV and CVD as follows:

$$MSSC_{av} = 0.01 \times PSV - 0.0000663 \times CVD - 0.026 \qquad \text{Equation 7.3}$$

The regression model represented by Equation 7.1 is considered to be a refinement of Equation 7.3 as it has been formulated to include the variables PSV and CVD, which up to the present time have been believed to be the key variables for the design of skid resistant road surfaces.

In order to assess the predictive ability of both equations, differences between observed average MSSC values and those predicted using Equations 7.1 and 7.3 were calculated. Figure 7.6 is a histogram plot of the results and shows that the median difference is 0 for Equation 7.1 but –0.02 for Equation 7.3. Therefore, the TNZ T/10-based Equation 7.3 tends to overestimate the expected equilibrium level of skid resistance. This is a concern as the functional relationship given by Equation 7.3 has been formulated for sites where polishing stresses are greater than when traffic is rolling freely without braking or turning (WDM 1997). Furthermore, the spread is significantly greater for Equation 7.3 (–0.13 to 0.18) compared to Equation 7.1 (–0.07 to 0.09).

A cumulative frequency plot of the difference between observed and predicted in-service skid resistance is given in Figure 7.7. This plot graphically illustrates the improved predictive ability afforded by Equation 7.1, with the predicted value of skid resistance for 36 out of the 47 test sites (or about 77%) agreeing to within ± 0.04 of the observed average MSSC value.

By comparison, the TNZ T/10 functional relationship represented by Equation 7.3 results in 26 out of the 47 test sites (or about 55%) having predicted values of skid resistance that agree to ±0.04 of the observed average MSSC value.

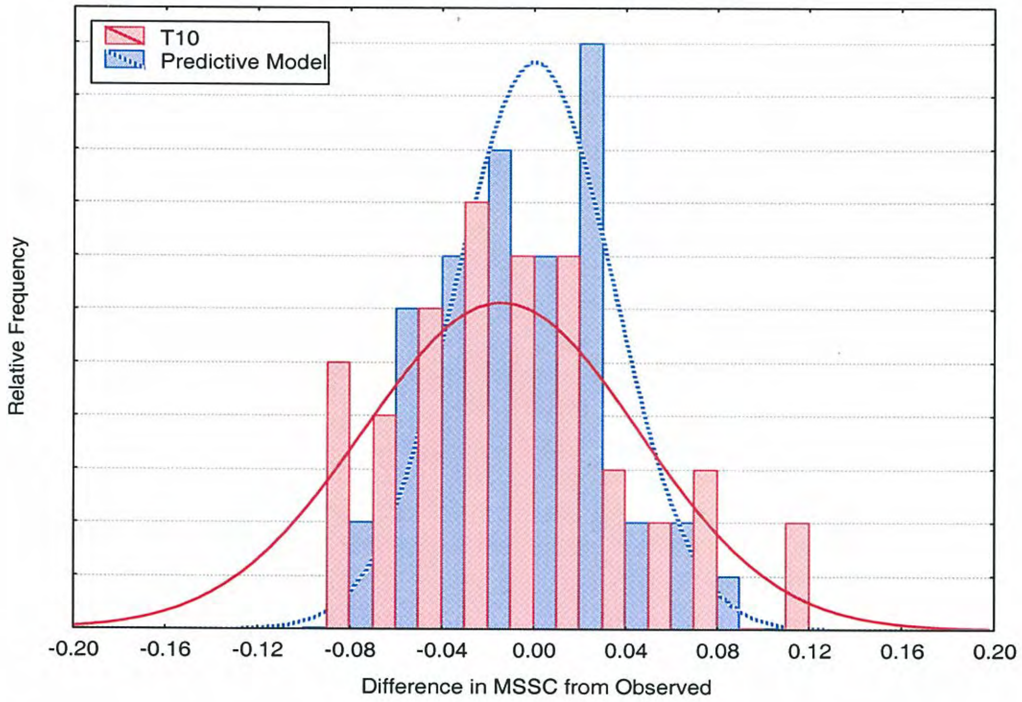


Figure 7.6 **Distribution of differences between observed and predicted MSSCav values for T/10 and proposed predictive model.**

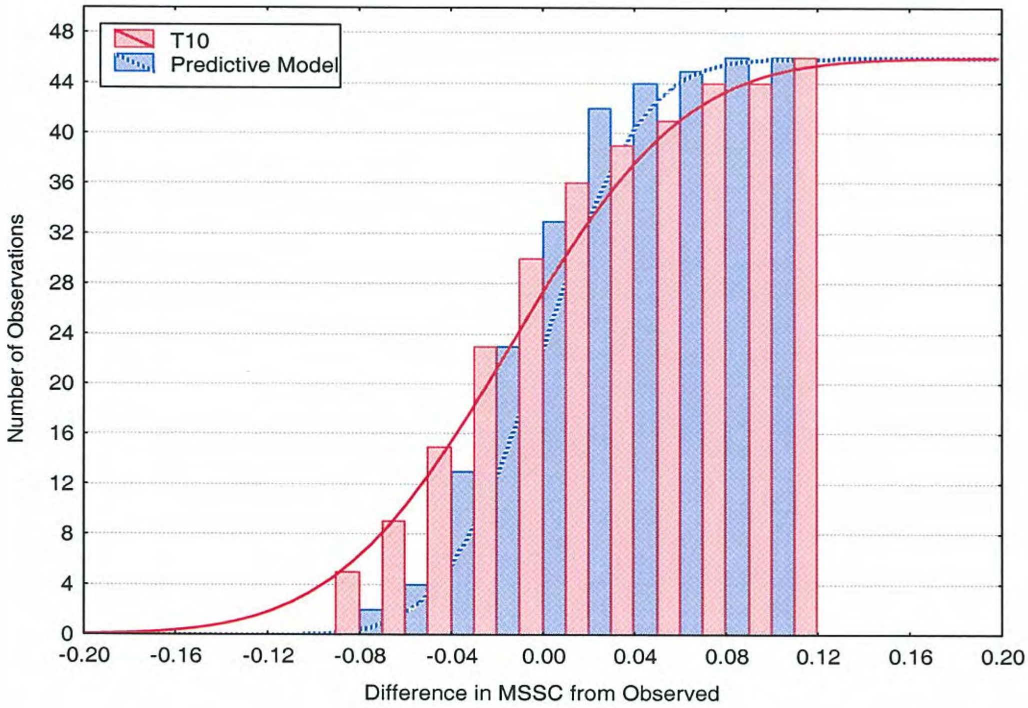


Figure 7.7 **Cumulative frequency plots of the differences between observed and predicted $MSSC_{av}$ values for TNZ T/10 and proposed predictive model.**

A shortcoming of Equation 7.1 that potentially could limit its application in the design of chipseal surfaces is the need for in-situ measurements of the surface profile variables Rsk, delq and Rvm. However, this shortcoming can be readily addressed if a relationship exists between TNZ M/6:2002 requirements for sealing chip, such as average least dimension (ALD), and the three surface profile variables.

Sealing chip characteristics presented in Transit New Zealand's Bituminous Sealing Manual (1993) have been used to derive the following regression equations for relating average chip size to ALD.

$$\text{ALD} = 0.568 \times \text{CS} - 0.142 \quad (r^2 = 0.997, \text{SE} = 0.2) \qquad \text{Equation 7.4}$$

$$\text{CS} = 1.75 \times \text{ALD} + 0.354 \quad (r^2 = 0.997, \text{SE} = 0.54) \qquad \text{Equation 7.5}$$

where:
ALD = average least dimension (mm)
CS = average chip size (mm)

The resulting inter-relationship between grade of sealing chip, CS and ALD assumed for this analysis is given in Table 7.8, along with the median values derived from the 47 test sites for the surface profile variables Rsk, delq, and Rvm.

With reference to Table 7.8, a strong negative linear correlation (coefficient of correlation (r) = –0.94) exists between sealing chip ALD and the combined contribution of the three surface profile variables to skid resistance. Therefore Equation 7.1 can be simplified without significant loss of predictive accuracy by substituting ALD for the variables Rsk, delq and Rvm. The resulting regression model is:

$$\text{MSSC}_{av} = 0.0014 \times \text{PSV} - 0.05 \times \text{CHCV} - 0.007 \times \text{ALD} + 0.52 \qquad \text{Equation 7.6}$$

This regression model has fit statistics of $r^2 = 0.32$ and SE = 0.04. The predicted value of skid resistance agrees to within ±0.04 of the observed average MSSC value for 30 out of the 47 sites (or about 64%) with the spread in difference between predicted and observed average MSSC values being limited to between –0.08 and 0.09. The level of fit, therefore, represents a slight degradation over that achieved by Equation 7.1, but is a reasonable trade-off in order to gain a predictive model that is a significant improvement over the TNZ T/10 Equation (Equation 7.3), and which also utilises input variables that are known at the seal design stage.

Table 7.8 Characteristics of sealing chip conforming to TNZ M/6:2002.

TNZ M/6:2002 Variable		Chip Size (mm)	Median Surface Profile Values			
Grade	ALD(mm)		Rsk	delq	Rvm(m)	Combined contribution to MSSC from Eq 7.1
2	10.75	19	0.00	0.75	-0.0037	-0.056
3	8.75	16	-0.28	0.80	-0.0039	-0.034
4	6.75	12	-0.23	0.71	-0.0034	-0.032
5	5.00	9	-0.09	0.63	-0.0027	-0.021

A feature of Equation 7.4 is that the PSV and CHCV constants are very similar to those of Equation 7.1 and so MSSC sensitivity to these two critical variables is maintained.

Both Equations 7.1 and 7.6 indicate a linear reduction in skid resistance with increasing CHCV passes. Empirical observations confirm that the polishing action of accumulated traffic does indeed cause skid resistance to decay from an initial value (Diringer & Barros 1990). However, the rate of skid resistance loss progressively diminishes, rather than stays constant as indicated by Equations 7.1 and 7.6, and eventually stabilises at a level commonly referred to as the equilibrium state of polish. The typical drop between the initial and equilibrium values of skid resistance is about 40% (Kokkalis 1998). Therefore, deteriorating skid resistance with cumulative polishing over time will be better modelled by an exponential decay than a linear decay. As a consequence, the regression analysis employed to derive Equation 7.6 has been repeated with a negative exponential transformation applied to the CHCV values.

The resulting model is given by Equation 7.7 and the associated statistics of the model constant estimates and goodness of fit tabulated in Table 7.9 for direct comparison with Table 7.6.

$$MSSC_{av} = 0.0013 \times PSV + 0.10 \times e^{-CHCV} - 0.007 \times ALD + 0.44 \qquad \text{Equation 7.7}$$

where:

$MSSC_{av}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
PSV = polished stone value
CHCV = cumulative heavy commercial vehicle traffic per lane (millions)
= commercial vehicle traffic > 3.5 tonnes /lane /day × surface age (years) × operational days per year (=300)/10^6
= 0.0003 × CVD × AGE
ALD = the average least dimension of the sealing chip (mm)

Table 7.9 Model statistics for Equation 7.7.

Model Component	Model Coefficients		
	Value	Standard Error	p-level
PSV	0.0013	0.001	0.312
E^{-CHCV}	0.097	0.030	0.002
ALD	–0.007	0.003	0.03
Constant	0.44	0.08	3.8E-06
Overall Model Statistics			
Standard Error of Estimation:	0.041		
r^2:	0.35		
No of Observations:	47		

The distribution of the differences between observed average MSSC values and those predicted by Equation 7.7 for the 47 test sites are as follows:

- the median difference is 0;
- the range is –0.08 to 0.09;
- 31 out of the 47 test sites (or 66%) have an absolute difference of 0.04 or less.

Both the model statistics and distribution of differences are a marginal improvement over those for Equation 7.6. More importantly, Equation 7.7 provides a decay in skid resistance that is equivalent to Equation 7.6 over the analysis range of cumulative HCV passes (CHCV), while maintaining the same sensitivities to PSV and ALD.

However, it avoids the anomaly of MSSC values decaying to unrealistically low levels should extrapolation to high CHCV values be required, as would be the case for major metropolitan road networks.

For all these reasons, Equation 7.7 is preferable to Equation 7.6 for evaluating the expected in-field skid resistance performance of different chipseal surface designs.

7.4 Application of Model

7.4.1 Sensitivity Analysis

The following two-step process was used to establish the relative sensitivity of MSSC to the three input variables to Equation 7.7 (i.e. PSV, CHCV, and ALD).

Step 1: Median values for the three input variables were derived from the 47 test sites and used to calculate a reference MSSC value from Equation 7.7.

Step 2: The median value of the three input variables was varied by ±20% and applied to Equation 7.7. The corresponding percentage change in MSSC value relative to the reference MSSC value was then computed.

The results of this analysis are summarised in Table 7.10 below. With reference to Table 7.10, the predicted MSSC is influenced most by measurement uncertainty in the PSV values, followed by ALD and then CHCV. However, as a 20% uncertainty in any one of the three input variables causes changes of less than 3% in the calculated MSSC, the model is very tolerant to any imprecision in the input variables, and results because the model constant term of 0.44 is so dominant.

Table 7.10 Sensitivity of predicted MSSC to a 20% uncertainty in each of the model inputs.

Input Variable	Median Value	% Change in Reference MSSC Value of 0.52	
		–20% Uncertainty	+20% Uncertainty
PSV	57	–2.8	2.8
CHCV	0.29	0.84	–0.79
ALD(mm)	8.75	2.3	–2.3

7.4.2 Relative Contribution of Key Variables to MSSC

The relative contribution of PSV, CHCV and ALD to MSSC was investigated by varying their value over the ranges observed for the 47 tests sites. Table 7.11 tabulates the associated change in MSSC level as calculated from Equation 7.7.

This analysis suggests that the expected range of MSSC on straight chipseal sections of state highway should be limited to between 0.43 (heavily trafficked roads) and 0.58 (lightly trafficked roads). The main reason for differences in MSSC values will, not unexpectedly, be cumulative HCV traffic rather than PSV or size of the sealing chip.

Table 7.11 Relative contribution of key variables to MSSC as calculated from Equation 7.7.

Model Variable	Measured Range		Contribution to MSSC		ΔMSSC
	Min	Max	Min	Max	
PSV	43	65	0.056	0.085	0.03
CHCV (10^6 HCV passes)	0.015	1.960	0.014	0.096	0.08
ALD (mm)	5	10.75	–0.075	–0.035	0.04
Sum Total			–0.005	0.146	

With reference to Table 7.11, the maximum contribution of the aggregate variables, PSV and ALD to MSSC is 0.05 and amounts to about 11% of the model constant of 0.44. This result suggests that the scope for seal designers to improve the skid resistance performance of straight road sections through aggregate selection is very limited if New Zealand sourced natural aggregate conforming to TNZ M/6:2002 requirements is to be used.

7.4.3 Transit New Zealand T/10 Specification

Transit New Zealand's policy for skid resistance is contained in its T/10 specification (TNZ 2002a). This specification was introduced in 1998 with the aim of standardising the risk of a wet skid crash across the State Highway network by assigning investigatory skid resistance levels to different site categories, which are related to different friction demands. The investigatory skid resistance is, in effect, a warning level, and is the target equilibrium skid resistance level when designing a road surface. For ready reference, the TNZ T/10 investigatory skid resistance levels are tabulated in Table 7.12.

Table 7.12 TNZ T/10 investigatory skid resistance levels for different site categories.

Site Category	Site Definition	Friction Demand	Investigatory Level (MSSC)
1	Approaches to crossings/intersections	High	0.55
2	Down grades > 10 %, Curves <250m radius	High	0.50
3	Approaches to junctions; Motorway ramps; Down grades 5-10%	High	0.45
4	Undivided carriageway (event free)	Low	0.40
5	Divided carriageway (event free)	Low	0.35

Figure 7.8 shows the decay in skid resistance as a function of cumulative HCV passes as predicted by Equation 7.7. Four design options have been plotted corresponding to minimum and maximum PSV and ALD values that can be expected for New Zealand sourced natural aggregates that conform to TNZ M/6:2002 requirements. The minimum and maximum PSV values are 43 and 61 respectively and the minimum and maximum ALD values are 5 mm and 10.75 mm respectively. These ALD values correspond to Grade 5 and Grade 2 sealing chips (Table 7.8).

With reference to Figure 7.8 and Table 7.12, the following observations are made:

- Small sized (Grade 5) aggregate with low PSV (PSV = 43) provides superior skid resistance performance to large sized (Grade 2) aggregate with high PSV (PSV = 61).
- Skid resistance stabilises at about 2 million HCV passes.
- The stabilised value of skid resistance is typically 82% of the initial value representing a drop of 18%.
- Not unexpectedly, the lowest equilibrium skid resistance level was calculated for the large sized aggregate with low PSV. However, at 0.43 MSSC, it exceeds the TNZ T/10 investigatory skid resistance levels for site categories 4 and 5. Therefore, straight road sections located in site 4 and 5 categories are unlikely to require treatment to address loss of aggregate microtexture due to polishing action of traffic as long as the aggregate PSV is greater than 43.
- The TNZ T/10 investigatory level of 0.55 MSSC for site category 1 cannot be achieved with a Grade 2 chip, irrespective of its PSV value.
- A critical value of CHCV passes exists above which it is impossible to satisfy the TNZ T/10 investigatory levels for the high demand site categories (i.e. 1, 2 and 3) using natural aggregates. This critical value of CHCV passes is significantly less than the 1 million passes required to reach the equilibrium value of skid resistance, and becomes less and less with reducing PSV and increasing aggregate size.

As a complement to Figure 7.8, limiting CHCV passes for T/10 site categories 1 and 2 were calculated for each grade of sealing chip. These are tabulated in Table 7.13. The calculations were confined to a sealing chip with PSV = 61, this representing a higher end value of PSV for natural aggregate sealing chips sourced in New Zealand. Also given in Table 7.13 is the associated daily HCV traffic per lane for a service life of 7 years, which corresponds to the present average recycle time for state highway chipseal surfaces.

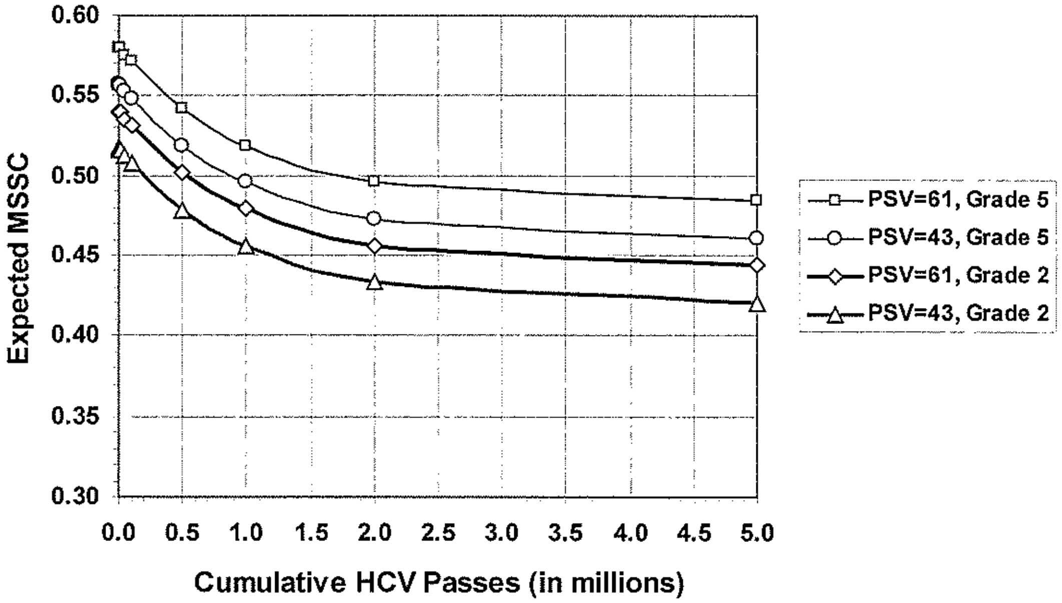


Figure 7.8 Predicted decay in skid resistance with accumulated HCV traffic.

Table 7.13 Limiting cumulative HCV passes to achieve TNZ T/10 investigatory skid resistance levels for site categories 1 & 2 using a sealing chip with PSV=61.

T/10 Site Category	Investigatory Level (MSSC)	Limiting Cumulative HCV Passes (millions)			
		Grade 2	Grade 3	Grade 4	Grade 5
1	0.55	–	0.02 (11)	0.21 (99)	0.37 (178)
2	0.50	0.54 (255)	0.77 (368)	1.22 (580)	1.76 (838)

( ) = corresponding HCV (lane/day) to achieve a service life of 7 years

The maximum expected HCV traffic on chipseal-surfaced rural state highways is 500 HCV per lane per day. Therefore, Equation 7.7 suggests that, for this level of HCV traffic, the useful seal life for high demand site category 1 areas could range from 3 months to 3 years, depending on the grade of sealing chip used. By comparison, the existing T/10 Equation (Equation 7.3) suggests that a PSV = 61 sealing chip should be adequate to achieve an equilibrium skid resistance value of 0.55 MSSC for up to 513 HCV/lane/day. In-the-field experiences suggest that Equation 7.7 better reflects the true situation.

7.5 Research Needs

The following additional research is required to check and refine the models presented for predicting the skid resistance performance of chipseal surfaces.

- ***Contribution of Aggregate Microtexture***

Microtexture is the microscopic surface roughness of the roading aggregates and is mainly a function of aggregate particle mineralogy. Microtexture irregularities typically range from 0.005 mm to 0.3 mm. When microtexture comes into contact with the tyre, an adhesive friction force (commonly referred to as grip) is generated. Under wet conditions, microtexture penetrates the thin water film that remains between the tyre and the road to establish direct contact.

The level of microtexture deteriorates with cumulative traffic polishing. In deriving the skid resistance models presented in this Chapter 7, it has been assumed that aggregate PSV is related to the terminal aggregate microtexture reached in the field. However, only 5 of the 47 test sites had been exposed to 1 million or greater HCV passes and so judged to have reached equilibrium skid resistance value, corresponding to the situation of terminal microtexture. No direct correlation between aggregate PSV and in the field skid resistance could be established for these 5 sites, suggesting that the polishing action of HCV traffic may be different to the polishing action of the PSV test. Furthermore, Kokkalis (1998) has shown that the depth of microtexture is the strongest contributor to the variation of skid resistance. Use of PSV instead of actual microtexture depth may, therefore, be the reason for the low correlation found between PSV and MSSC in the present study.

Further investigation is warranted to establish if:

- Improved model fits will result through use of in-the-field measurements of aggregate microtexture depth made with a stylus profiler instead of aggregate PSV.
- Aggregate microtexture depth can be used for determining equivalency between the cumulative polishing action of traffic and accelerated polishing action of the PSV tests. This will assist in the development of microtexture decay models with respect to cumulative HCV passes for incorporation in skid resistance models from laboratory-measured microtexture decay rates derived from a specified number of hours of PSV test polishing.

- ***Inter-relationship Between Microtexture and Macrotexture***

Moore (1975) suggests that the effectiveness of the microtexture in promoting skid resistance is related in some manner to the sharpness of the aggregate tip. He theorises that the peak pressure on any aggregate increases rapidly and non-linearly with mean slope beyond a point where the elastic pressure is too great to permit the existence of a water film. At this point no microtexture is needed as the high and localised pressure developed between the tyre tread and aggregate ensures physical contact even under the most severe wetted conditions. Conversely, if the tip of the aggregate is predominantly rounded, harsh microtexture is needed to penetrate the thin water film between the tyre and the road to establish adhesion. Therefore, it is hypothesised that the influence of microtexture on skid resistance will be greater for the following situations:

- alluvial aggregates with uncrushed faces, as these are generally characterised by a rounded shape thereby minimising the hysteretic component of skid resistance;
- aggregates that are susceptible to wear, since tips of such aggregates will be predominantly rounded as a consequence of the wearing action of traffic; and
- aggregates which predominantly imbed themselves in a seal so that they lie down on their average greatest dimension (AGD), such as occurs with bituminous mixes, resulting in less slope/sharpness than if they lie down on their average least dimension (ALD).

A preliminary investigation of the data for the 47 sites, of which 24 had chipseal surfaces constructed from alluvial aggregates and 23 had surfaces constructed from aggregates quarried from hard rock, supported this hypothesis. This investigation identified that MSSC sensitivity to PSV was significantly higher for alluvial aggregates (0.008 MSSC/PSV) than for hard rock aggregates (0.0002 MSSC/PSV). Therefore the issue of microtexture/macrotexture interdependency needs further investigation.

- ***Effect of Large Horizontal Tyre Forces***

The effect of traffic is to wear and polish the aggregate, and the cause of this action is the horizontal forces exerted by the vehicle tyre onto the road surface. The higher the horizontal force, the greater the wear and polishing action. This explains why greater reductions in skid resistance values are reported on grades and bends and at intersections where the horizontal force greatly increases due to traction, cornering and braking forces.

The regression-based models for predicting skid resistance have been derived for straight sections of state highway and so pertain to the free rolling situation where horizontal tyre forces will be at their lowest.

Therefore, additional research is required to establish whether or not the rate of skid resistance decay with cumulative HCV passes increases and/or the equilibrium value of skid resistance reduces as a function of increasing horizontal tyre forces.

This can be best accomplished by repeating the regression analysis detailed above for a situation where horizontal forces are expected to be large, say corners with a horizontal radius confined to between 100 m and 200 m. If significant differences in either model form or model coefficients are identified, it may be necessary to derive predictive models for each of the 5 site categories incorporated in the TNZ T/10 specification.

7.6 Summary of Findings

The principal findings of this study to quantify the influence of road surface profile on in-service skid resistance of straight sections of chipseal-surfaced state highways are as follows.

1. The critical surface texture variable is the mean spacing between tips of aggregates, i.e. the smaller the spacing the higher the tyre–road skid resistance.

2. A mean spacing of 5 mm to 15 mm between tips of aggregates is considered necessary to satisfy both hysteresis and drainage requirements for rural state highway speeds. In comparison, the tip spacing measured in the field ranged between 8 mm and 25 mm. This suggests that in New Zealand, sealing chips are produced at sizes larger than considered optimal for skid resistance.

3. The equilibrium state of polish was found to be a function of the number of heavy commercial vehicle (HCV) passes, the threshold value being 1 million HCV passes or approximately 2 million ESA. Therefore surfaces on straight sections of state highway are unlikely to reach their equilibrium state of polish at the end of their service life unless they carry more than 500 HCV/lane/day.

4. A rational model has been developed that:
   - offers a significant improvement over the skid resistance model incorporated in Transit New Zealand's T/10 specification as it has an apparent lack of bias and a significantly larger proportion of the variability observed in the MSSC measures is accounted for;
   - utilises input variables of PSV, HCV traffic, seal age and aggregate ALD, which can all be determined at the seal design stage, thereby enabling the model to be used as a design tool;
   - provides sufficiently reliable predictions of in-service skid resistance to guide design of chipseal surfaces, because it gives a 95% certainty that the predicted value will be within ±0.08 MSSC of the observed value;
   - allows the level of skid resistance to be predicted at any point in time within the service life of the surface.

5. There is a strong indication that the skid resistance deterioration mechanism for alluvial aggregates is quite different to that of aggregates quarried from hard rock.

   For alluvial aggregates, loss of skid resistance is primarily brought about by deteriorating microtexture caused by cumulative polishing by HCV traffic.

   For hard rock aggregates, loss of skid resistance is a combination of rounding and smoothing of the aggregate tips as a consequence of the polishing and wear action of HCV traffic.

   Therefore, the skid resistance of chipseal surfaces constructed from alluvial aggregates show a greater sensitivity to aggregate PSV and less sensitivity to cumulative HCV passes, than surfaces constructed from hard rock aggregates. This finding suggests that separate skid resistance models may have to be derived for alluvial and hard rock aggregates in order to improve predictive accuracy.

8. Conclusions and Recommendations

The ultimate aim of this research was to determine how macrotexture geometry impacts on the skid resistance performance of New Zealand chipseal surfaces, in order to improve chipseal design practices, and to refine existing skid resistance models used for formulating specifications, and the skid resistance management of road networks. This aim has been achieved through a combination of field, laboratory, and statistical modelling studies. The principal conclusions and associated recommendations resulting from these studies have been presented in the body of the report. Therefore, only those of direct relevance to the above aim are presented below.

8.1 Field Studies

8.1.1 Emergency Braking Tests

Emergency braking tests, involving both four-wheel locked braking and ABS (independent anti-lock braking system on all four wheels) were performed on six test sites to obtain accurate measurement of wet and dry stopping distances, and associated average coefficients of friction. These sites comprised 4 chipseal and 2 asphaltic concrete surfaces, and covered a wide range of microtexture and texture depth levels. This range enabled the various aggregate contributions to tyre-road friction to be assessed.

A requirement of the test sites was that they had a comparable level of roughness so that roughness effects on braking distances could be excluded. For each site, mean profile depth (MPD) measurements were made with Transit New Zealand's stationary laser profiler (SLP). Skid resistance measurements were also made with SCRIM, GripTester, Norsemeter Roar and the BPT. These texture and skid resistance measurements facilitated calculation of the International Friction Index (IFI) and comparisons between skid tester output and emergency braking behaviour of vehicles.

The limited emergency braking tests provided evidence that:

1. The reported influence of road surface texture depth on low and high speed friction is negated by vehicles fitted with anti-lock braking systems (ABS) and tyres with adequate tread depth (i.e. ≥ 1.5 mm). Under such operating conditions, wet tyre-road friction appears to be insensitive to both speed over a 25 to 100 km/h range and texture depth.

2. Under locked-wheel braking initiated at typical urban speeds (i.e. ≤50 km/h), wet tyre–road friction reduces with increasing speed but not at the rate predicted by IFI. Again no significant texture effect was observed and so it is conjectured that the tyre tread is providing "extra" texture depth in addition to that provided by the road surface.

3. Skid testers in common use in New Zealand display differing sensitivities to microtexture and macrotexture properties of road surfaces. However, their measurements of skid resistance showed significant correlations ($r^2 \geq 0.8$) with both dry and wet tyre–road coefficients of friction derived from locked-wheel emergency braking. Generally, SCRIM measurements were shown to provide the most reliable estimates

Recommendation

- Improved understanding of the inter-relationships between wet tyre–road friction, volumetric texture depths of tyres and road surfaces, vehicle speed, and water film depth is required before models for the reliable prediction of friction under different wet operating conditions can be developed. In the interim, IFI modelling of wet friction–speed dependencies appears adequate if the volumetric texture depth of the tyre is incorporated in the calculation of the speed number, Sp.

8.1.2 Time Series GripTester Measurements

GripTester surveys were undertaken on public roads to monitor the variation of skid resistance of road surfaces over a prolonged period of time. These surveys established that skid resistance is highest soon after a period of rain and then reduces with time if there is a prolonged dry spell. Measured reductions in GripNumber (GN) ranged between 0.04 and 0.08 over a 10-day dry period following a significant fall of rain, corresponding to a 5% to 10% change in the skid resistance level provided by the road surface. This result highlights the need to take care when interpreting skid resistance measurements to distinguish what is the inherent skid resistance of a road surface and what is the influence of previous rainfall history.

Recommendation

- Some evidence suggests that the rate that skid resistance decays as a function of days since rain will vary with aggregate type (i.e. greywacke, basalt, andesite, etc.). Therefore, further investigation is required to quantify the rate that the skid resistance of a road surface reduces with the length of time since rain as a function of skid tester device, aggregate rock type, sealing chip size, and aggregate microtexture depth. The results from such an investigation will be useful for interpreting and normalising skid resistance survey results, and especially in the selection of sealing chips to achieve a specified level of skid resistance.

8.2 Laboratory-Based Studies

BPT measurements were performed on pavement-core and laboratory-made chipseal samples that had been successively coated with thicker films of bitumen. This allowed the relative contributions of aggregate microtexture and surface texture profile (i.e. aggregate shape and spacing) to be quantified in terms of British Pendulum Number (BPN). The measurements showed that:

1. Aggregate microtexture contributes between 8 BPN (worn surface) and 28 BPN (new surface) to the overall skid resistance of the road surface sample, corresponding to 13% and 30% respectively. These figures were obtained by comparing BPN values for the road samples in their uncoated condition and when covered with a 0.1 mm-thick bitumen film. It was assumed that such a film thickness would be sufficient to completely mask the aggregate microtexture, which typically has a depth of 0.02 mm in a polished (worn) condition and 0.05 mm in the harsh (new) condition.

2. The contribution of macrotexture to overall skid resistance is comparable to that of aggregate microtexture. This was an unexpected result and suggests that, for chipseal surfaces, the hysteresis and adhesion components of friction are similar in magnitude. The estimate of macrotexture, or more correctly surface texture profile, contribution to skid resistance was determined in two ways.

   In the first way, BPN results for a profiled surface (i.e. actual and laboratory-made road surface samples coated with a 0.1-mm thick film of bitumen) were compared with those for a completely flat surface (i.e. bitumen poured molten over a flat plate). The effect of macrotexture was to add 18 to 32 BPN to the 35 BPN measured for the flat reference plate, representing a contribution of between 34% and 47% to the overall skid resistance.

   In the second way, BPN results for the actual road samples were compared with laboratory-made samples with an equivalent mean profile depth so size effects could be discounted. The actual road samples had edges of the aggregates rounded by the wearing action of traffic whereas the laboratory-made samples had aggregates with sharp edges. The measured difference between matched actual and laboratory-made samples was 10 to 14 BPN.

   In all cases, the influence of aggregate microtexture could be discounted as the 0.1 mm-thick film of bitumen should have been more than enough to completely submerge any micro-sized asperities on the surface of the aggregate.

3. The relative contribution of aggregate microtexture to the skid resistance provided by a road surface increases as the macrotexture of the surface decreases.

4. The presence of bitumen film on chipseal road surfaces can result in reductions of skid resistance of between 20% and 30% in situations where the contamination is severe (i.e. bitumen film thickness of the order of 0.1 mm). However, the resulting level of skid resistance is still significantly greater (at least three times) than that provided by a smooth, bitumen-only surface. This suggests that chipseal surfaces in a flushed condition pose a greater safety hazard to motorists in wet conditions than chipseal surfaces that have been blackened by tracked bitumen.

Recommendations

To assist the formulation of skid resistance models, the relative contributions of aggregate microtexture and macrotexture to overall skid resistance should be investigated for alluvial and hard rock sourced aggregates of the rock types commonly used in New Zealand as sealing chips, to identify any significant anomalies.

This can be best carried out by obtaining stylus profile measurements of aggregate microtexture depth and then performing skid resistance measurements before and after a film is applied over the test surface that has a thickness greater than the microtexture depth.

- Safety management of road networks should target the elimination of flushed sections of chipseal surfaces whenever they occur at locations of high friction demand, such as mid curve, and whenever the continuous length of flushed surface in a wheelpath is 20 m or greater, to prevent potentially hazardous braking manoeuvres.

8.3 Statistical Modelling Studies

A regression analysis was performed to investigate the sensitivity of in-service skid resistance performance of chipseal-surfaced sections of state highway to aggregate and texture characteristics under different traffic loading. This regression analysis was performed on a specially assembled database that comprised SCRIM-based skid resistance data from annual network surveys undertaken since 1998, and 18 different standard measures of surface texture derived from stationary laser profiler measurements made on 47 straight and level test sites located on state highways.

Of these 47 test sites, 24 had surfaces constructed from alluvial aggregate ranging in polished stone value (PSV) from 52 to 62 and carrying HCV traffic between 12 and 468 HCV/lane/day. The remaining 23 sites were constructed from quarried rock ranging in PSV from 43 to 65 and carrying HCV traffic between 22 and 380 HCV/lane/day. All surfaces had an age of about 3 years or greater.

The regression analysis revealed that:

1. The model for relating skid resistance, aggregate PSV and HCV traffic contained in Transit New Zealand's T/10 specification gave predictions of skid resistance that correlated poorly ($r^2 = 0.08$) with the measured in-service skid resistance of the 47 test sites. This model tended to overestimate the level of skid resistance, which is a concern as it has been formulated for sites where polishing stresses are greater than when traffic is moving freely without braking or cornering. The predicted mean summer SCRIM coefficient (MSSC) values agreed to ±0.04 of that observed for about 55% of the test sites (26 out of 47).

   The model, as applied, is given below. This is the original model form proposed by Szatkowski & Hosking (1972), which was derived by regressing skid resistance (dependent variable) against PSV and HCV traffic (independent variables).

$$MSSC_{av} = 0.01 \times PSV - 0.0000663 \times CVD - 0.026$$

   where:

   $MSSC_{av}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
   PSV = polished stone value
   CVD = number of HCV/lane/day having a weight of 3.5 tonnes or greater

2. The critical determinants of in-service skid resistance performance of straight, chipseal-surfaced road sections were identified through unconstrained stepwise regression analysis to be:
   - cumulative heavy commercial vehicle (HCV) passes; and
   - the mean spacing between tips of the aggregates, the smaller the spacing the higher the skid resistance.

3. There is a threshold value of cumulative HCV passes which, when reached, results in no further reduction in skid resistance over time due to traffic induced wear. This situation corresponds to the equilibrium state of polish and is calculated to occur after 1 million HCV passes. As the typical resealing frequency for state highways is 7 years, chipseal surfaces on straight sections of rural state highways are very unlikely to reach their equilibrium state of polish unless they carry more than 500 HCV/lane/day.

4. When the stepwise regression was forced to include aggregate PSV as a model input, the following surface texture variables became important predictors of skid resistance:

   Rsk = the skewness of the road profile about the mean line;
   delq = the root-mean-square (rms) slope of the road surface profile;
   Rvm = the mean maximum depth of the road profile below the mean line.

5. In practice, the combined contribution of the surface texture variables Rsk, delq, and Rvm to overall skid resistance was found to range between –0.07 MSSC and 0.03 MSSC with a mean value of –0.03 MSSC. This result suggests that the potential for optimising aggregates with regard to shape and distribution within the surface to maximise skid resistance may be limited. This view was reinforced when a strong linear negative linear correlation ($r = -0.94$) was shown between the average least dimension (ALD) of the sealing chip and the combined contribution to skid resistance calculated from median values of Rsk, delq and Rvm derived for each grade of sealing chip.

6. The regression model that displayed the best compromise between ease of application and accuracy was as follows:

$$MSSC_{av} = 0.0013 \times PSV + 0.10 \times e^{-CHCV} - 0.007 \times ALD + 0.44$$

   where:

   $MSSC_{av}$ = average MSSC derived from 1998, 1999, 2000, and 2001 surveys
   PSV = polished stone value
   CHCV = cumulative heavy commercial vehicle traffic per lane in millions
   = commercial vehicle traffic > 3.5 tonnes /lane/day × surface age (years) × operational days per year $(=300)/10^6$
   = $0.0003 \times CVD \times AGE$
   ALD = the average least dimension of the sealing chip (mm)

7. This regression model represents a significant improvement over the skid resistance model incorporated in Transit New Zealand's T/10 specification achieving:

- no apparent bias;
- model fit statistics of $r^2 = 0.35$ and standard error of estimation (SE) = 0.04;
- a 95% certainty that the predicted value of skid resistance will be within ±0.08 MSSC of the observed value, which is sufficiently accurate to allow the model to be used as a tool to investigate and refine proposed chipseal surface designs;
- ±0.04 agreement between the MSSC value predicted and that observed for 66% of the test sites (31 out of 47).

8. The average HCV exposure of two-lane rural state highways is 129 HCV/lane/day. The expected rate of change in skid resistance caused by the polishing action from this volume of HCV traffic is estimated from the regression model to average out at about –0.003 MSSC/year over the expected service life of a chipseal surface. This can be regarded as being negligible, when compared to short-term variations in skid resistance brought about by spells of dry and wet weather.

9. A critical value of CHCV passes exists above which it is very difficult to satisfy investigatory levels for skid resistance specified in Transit New Zealand's T/10 specification for the high demand site categories (i.e. 1, 2 and 3) using natural aggregates. This critical value of CHCV passes is calculated by the regression model to be significantly less than the 1 million required to reach the equilibrium value of skid resistance and becomes less and less with reducing PSV and increasing aggregate size. The regression model also indicates that the site category 1 investigatory level of 0.55 MSSC is unlikely to be achieved with a Grade 2 natural sealing chip, irrespective of the value of its PSV, for any length of time. This appears consistent with in the field experience.

10. Evidence suggests that the skid resistance deterioration mechanism for alluvial aggregates is quite different to that of aggregates quarried from hard rock. For alluvial aggregates, loss of skid resistance is primarily brought about by deteriorating microtexture because of cumulative polishing by HCV traffic. For hard rock aggregates, loss of skid resistance is a combination of rounding and smoothing of the aggregate tips as a consequence of the polishing and wear action of HCV traffic.

    Therefore, the skid resistance of chipseal surfaces constructed from alluvial aggregates shows a greater sensitivity to aggregate PSV and less sensitivity to cumulative HCV passes than surfaces constructed from hard rock aggregates. This finding suggests that separate skid resistance models may have to be derived for alluvial and hard rock aggregates in order to improve predictive accuracy.

11. By grouping the 47 test sites in terms of alluvial and hard rock-sourced aggregates and performing a separate regression analysis on each grouping, it was possible to obtain an indication of the size of differences in MSSC sensitivities for these two aggregate types to the key variables of PSV, CHCV

passes and aggregate size. Alluvial aggregates were found to be 40 times more sensitive to PSV (0.008 MSSC/ PSV cf. 0.0002 MSSC/PSV), about a third as sensitive to CHCV passes (–0.04 MSSC/CHCV cf. -0.10 MSSC/CHCV) and about a quarter as sensitive to aggregate shape -0.002 MSSC/ALD cf. –0.008 MSSC/ALD) than hard rock aggregates.

These differences in sensitivity are indicative only, given the small sample size of the alluvial and hard rock databases utilised. However, they indicate that selection of alluvial aggregates for skid resistant chipseal surfaces should be predicated on PSV, whereas selection of hard rock aggregates should be predicated on aggregate size (the smaller the better) and ability to withstand tip and edge wear caused by HCV traffic.

Recommendations

- The statistical modelling has shown that, for a given speed, the more often there is contact between the tyre and the road, the higher the skid resistance. For the vehicle speeds expected on rural state highways, a mean spacing of 5 mm to 15 mm between tips of aggregates is considered necessary to satisfy both hysteresis and drainage requirements. In comparison, the tip spacing measured in the field ranged between 8 mm and 25 mm, reflecting the dominant use of Grade 2 to Grade 5 sealing chips. A move to confine the construction of chipseal surfaces to Grade 3 to Grade 6 sealing chips is therefore seen to be desirable for efficient provision of skid resistant roads.
- There is a need is to test aggregates for their ability to maintain their shape under the wearing action of HCV traffic. A possible candidate test is the aggregate abrasion value (AAV), which provides a measure of resistance of the aggregate to surface wear by abrasion.
- Consideration should be given to measuring more surface texture variables than mean profile depth (MPD) during annual high speed condition surveys of the state highway network so that additional information on amplitude, spacing and shape characteristics of the road surface profile can be provided.

  This will lead to an improved knowledge as to how the macrotexture of a road surface wears as a result of both seasonal effects and exposure to traffic. This improved knowledge, in turn, can be used to improve design processes and laboratory test procedures utilised for prequalifying surface course aggregates on the basis of their long-term skid resistance.
- Continued investigation in the following two areas is required to refine the regression model to the stage that it can be incorporated in Transit New Zealand's T/10 specification:
  - Effect of aggregate microtexture depth and abrasion/wear resistance to establish whether or not separate models for different types of sealing chip will be needed, i.e. hard or soft alluvial and quarried rock.
  - Effect of horizontal tyre forces to establish whether or not the rate of skid resistance decay with cumulative HCV passes increases and/or the

  - Effect of horizontal tyre forces to establish whether or not the rate of skid resistance decay with cumulative HCV passes increases and/or the equilibrium value of skid resistance reduces as a function of increasing horizontal tyre forces.

- If the proposed regression-based skid resistance model is to be used for seal design purposes, the constant term should be reduced by 0.08 to 0.36 to account for both short-term weather effects and the model's precision. This will yield conservative estimates of skid resistance for straight road sections.

- The PSV test allows roading aggregates to be ranked according to their ability to resist polishing under standard conditions. However, at the present time, it has not been established whether or not the polishing action of HCV traffic is more or less abrasive than the polishing action of the PSV test. Yet in the present modelling of skid resistance, aggregate PSV is assumed to correspond to the situation of terminal microtexture.

  As depth of microtexture has been shown to be a strong contributor to the variation of skid resistance, the development of microtexture decay relationships for different natural aggregate sources is necessary to advance skid resistance modelling, and also to allow selection of aggregates on the basis of exposure to CHCV passes over the expected service life of the road surface. Therefore, the need is to better understand how the microtexture characteristics of roading aggregates change with respect to CHCV passes and how this can be reliably simulated through laboratory testing.

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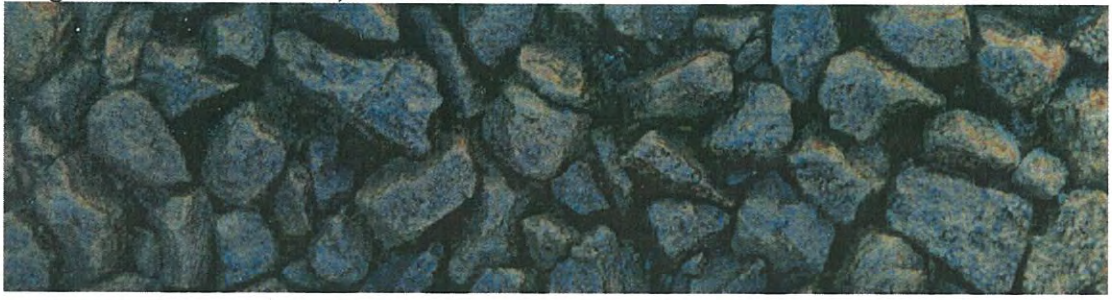
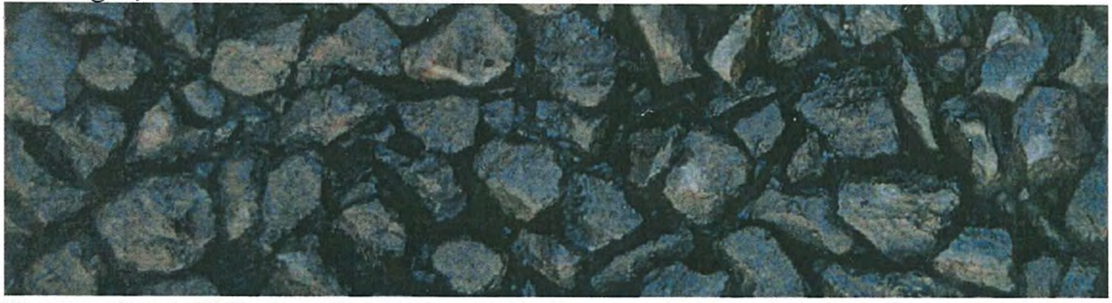
Appendix A1: Bitumen Coated Road Surface Samples

Table A1.1 Sample 1, worn grade 3 greywacke with successive layers of bitumen film.

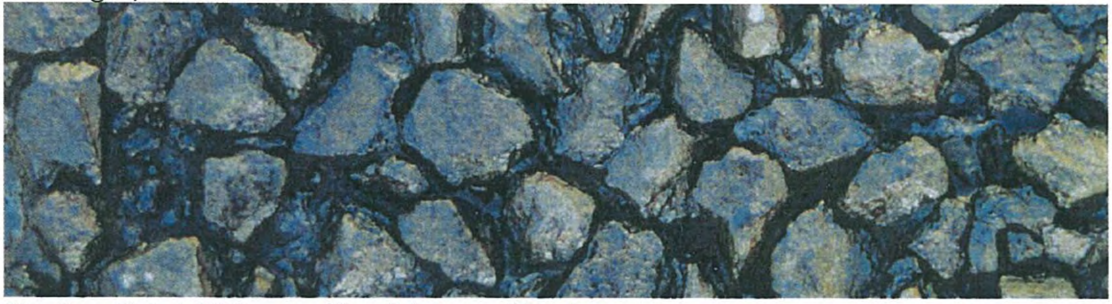
Original surface condition, 3mm MPD



Coating A, total bitumen film thickness 1 micron



Coating B, total bitumen film thickness 4 microns



Coating C, total bitumen film thickness 13 microns

Coating D, total bitumen film thickness 110 microns

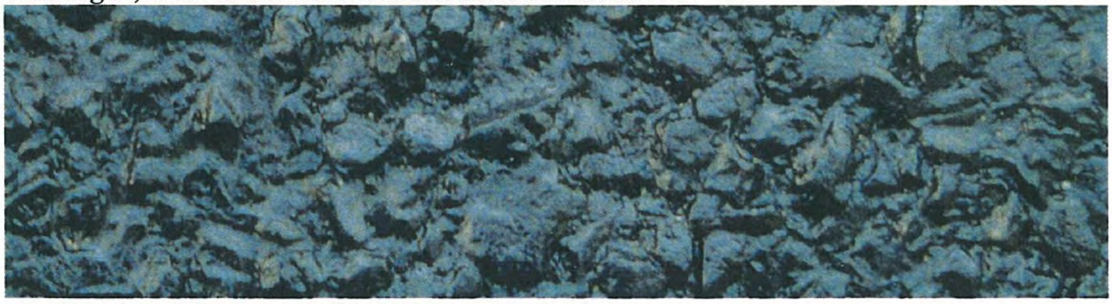
Table A1.2 Sample 2, worn grade 5 greywacke with successive layers of bitumen film.

Original surface condition, 1.6mm MPD

Coating A, total bitumen film thickness 1 micron

Coating B, total bitumen film thickness 4 microns

Coating C, total bitumen film thickness 13 microns



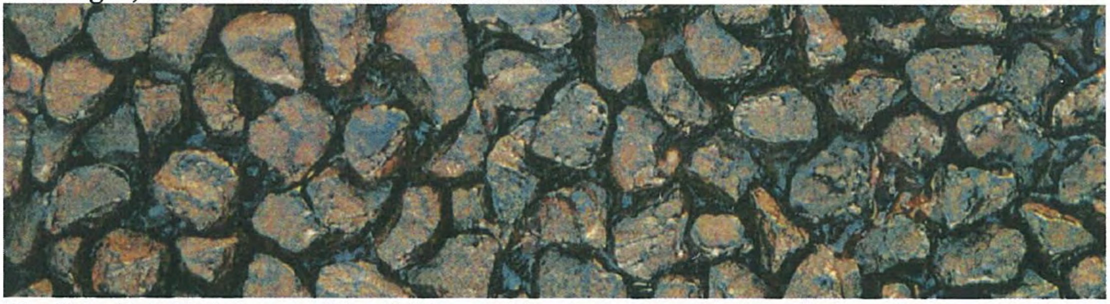
Coating D, total bitumen film thickness 110 microns

Table A1.3 Sample 3, new grade 4 greywacke with successive layers of bitumen film.

Original surface condition, 3.3mm MPD

Coating A, total bitumen film thickness 1 micron

Coating B, total bitumen film thickness 4 microns



Coating C, total bitumen film thickness 13 microns

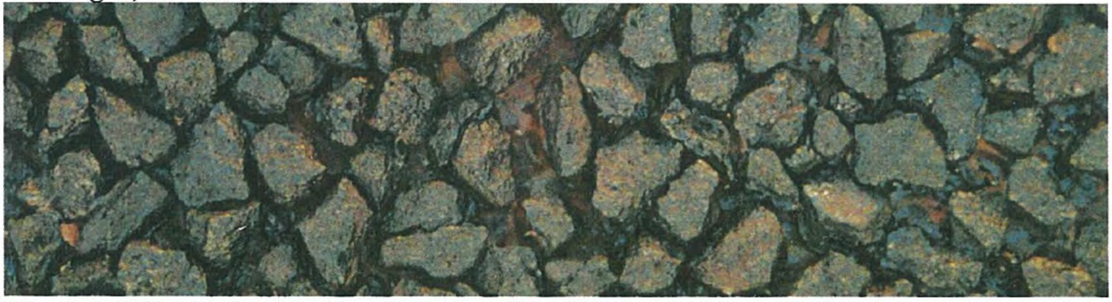
Coating D, total bitumen film thickness 110 microns

Table A1.4 Sample 4, new grade 4 basalt with successive layers of bitumen film.

Original surface condition, 3.5mm MPD

Coating A, total bitumen film thickness 1 micron

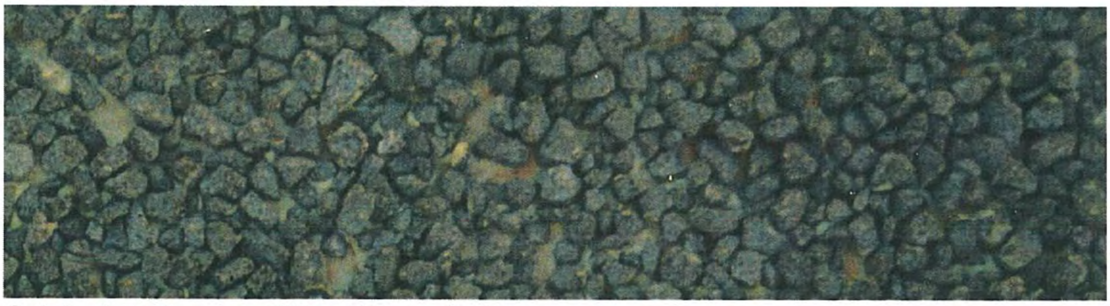
Coating B, total bitumen film thickness 4 microns



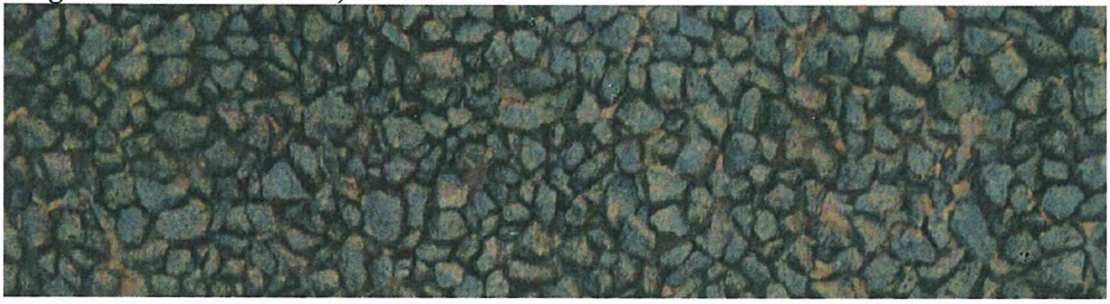
Coating C, total bitumen film thickness 13 microns

Coating D, total bitumen film thickness 110 microns

Table A1.5 Sample 5, new grade 6 basalt with successive layers of bitumen film.

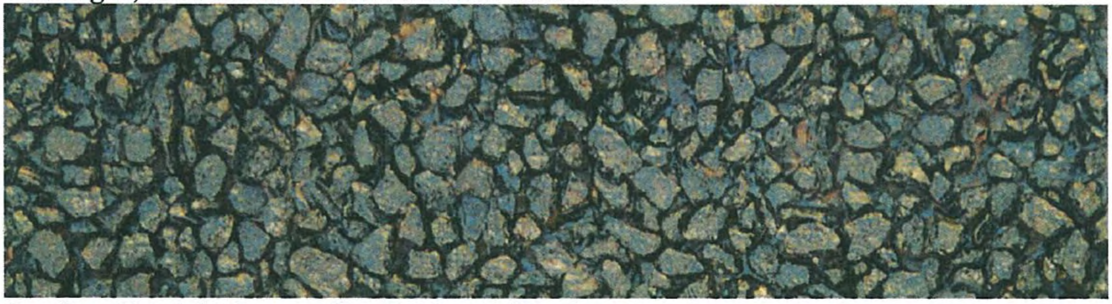


Original surface condition, 2.2mm MPD

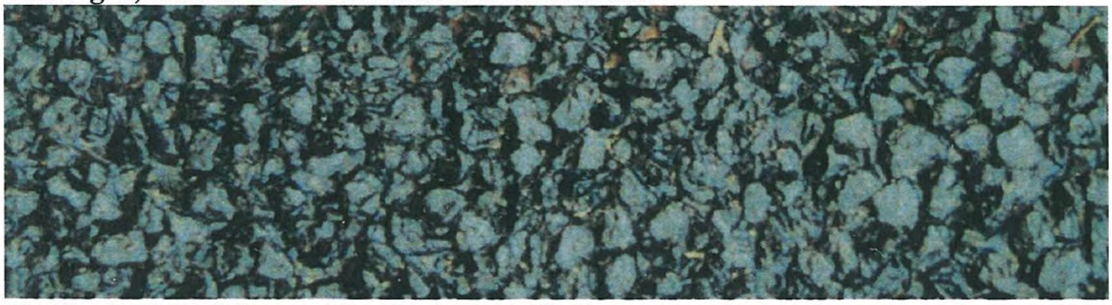


Coating A, total bitumen film thickness 1 micron

Coating B, total bitumen film thickness 4 microns



Coating C, total bitumen film thickness 13 microns



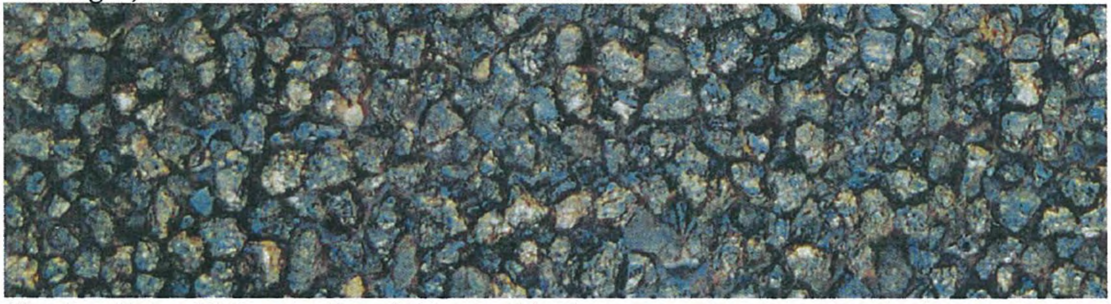
Coating D, total bitumen film thickness 110 microns

Table A1.6 Sample 6, new calcined bauxite with successive layers of bitumen film.

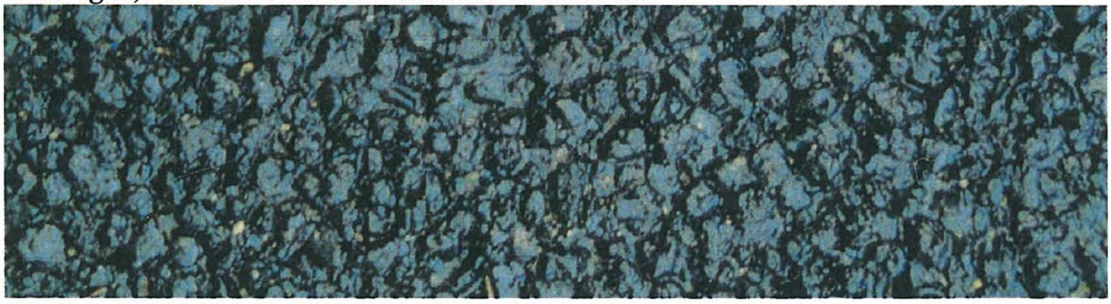
Original surface condition, 2.8mm MPD

Coating A, total bitumen film thickness 1 micron

Coating B, total bitumen film thickness 4 microns



Coating C, total bitumen film thickness 13 microns



Coating D, total bitumen film thickness 110 microns

Appendix A2: RAMM Data for Test Sites

Table Column Heading Abbreviations

SH, State Highway Number
RS, Reference Station Number
ST, Start kilometres from RS
END, End kilometres from RS
LGTH, Test section length (m)
LANE, L1 is lane in increasing direction and R1 is lane in decreasing direction
SOURCE, Quarry
SEAL, RAMM surface type descriptor
CHIP GRADE, Grade of chip, Grade 2 and Grade
AGE, Surfacing age in years
PSV, Polished Stone Value
% HVY, Percentage of ADT that are vehicles with GCW > 3.5 tonnes
ADT, Average daily traffic (vehicles/day)
NO HVY, Number of commercial vehicles per lane per day i.e. CVD term in T/10 equation
CURVE, Horizontal radius of curvature (m)
GRAD., Gradient (%)
CROSSFALL, Crossfall (%)
NAASRA, Wheelpath roughness (NAASRA counts/km)
RUT DEPTH, Wheelpath mean rut depth (mm)
MPD, Wheelpath texture in terms of mean profile depth (mm)
MSSC, Wheelpath mean summer SCRIM coefficient for specified year
Av. MSSC, Variable average MSSC value, calculated from SCRIM$^+$ survey data between 1998 and 2001 that is dictated by age of surface, e.g. a 2-year old surface can only use MSSC data for the last 2 years (2000 and 2001) for averaging whereas surfaces 4 years old or older can use all the 4 year data (1998, 1999, 2000, & 2001).
T/10 Eq., Equilibrium value of skid resistance calculated using the predictive equation given in Transit New Zealand's T/10 specification rearranged to give skid resistance (SR) as a function of PSV and heavy commercial vehicle traffic per lane per day (CVD), i.e.

$$\mathrm{SR} = 0.01 \times \mathrm{PSV} - 0.0000663 \times \mathrm{CVD} - 0.026$$

SITE NO	REGION	SH	RS	ST	END	LGTH	LANE	ROCK TYPE	QUARRY METHOD	SOURCE	SEAL
1	Blenheim	6	0	3470	5250	1780	L1	Greywacke	Alluvial	WAIRAU R	RSEAL
2	Blenheim	01S	18	4030	4290	260	L1	Greywacke	Alluvial	WAIRAU R	RSEAL
3	Blenheim	01S	28	2350	2630	280	R1	Greywacke	Alluvial	WAIRAU R	RSEAL
4	Blenheim	01S	28	6630	7170	540	R1	Greywacke	Alluvial	WAIRAU R	RSEAL
5	Blenheim	01S	43	6030	6680	650	L1	Greywacke	Alluvial	WAIRAU R	RSEAL
6	Blenheim	63	0	200	450	250	L1	Greywacke	Hard Rock	WAIRAU R	RSEAL
7	Blenheim	63	0	7010	7520	510	L1	Greywacke	Alluvial	WAIRAU R	COAT2
8	Blenheim	63	0	11350	11870	520	L1	Greywacke	Alluvial	WAIRAU R	COAT2
9	Central N.I	37	0	1000	1490	490	L1	Greywacke	Hard Rock	ARAPAE	COAT2
10	Central N.I	3	88	13350	13590	240	L1	Greywacke	Hard Rock	OSTERNS	RSEAL
11	Central N.I	31	0	10490	10710	220	L1	Greywacke	Alluvial	OTOROHAN	COAT2
12	Central N.I	30	0	13810	14230	420	R1	Greywacke	Hard Rock	PIOPIO	RSEAL
13	Central N.I	30	14	14450	15210	760	L1	Greywacke	Alluvial	STAPLES	RSEAL
14	Central N.I	30	30	11920	12370	450	L1	Greywacke	Alluvial	STAPLES	RSEAL
15	Central N.I	31	15	14370	14570	200	R1	Greywacke	Alluvial	STAPLES	RSEAL
16	Central N.I	3	65	4720	5730	1010	L1	Greywacke	Hard Rock	TAUHEI	RSEAL
17	Central N.I	3	16	6840	7360	520	L1	Greywacke	Hard Rock	WHITEHAL	RSEAL
18	Central N.I	3	36	1420	2120	700	L1	Greywacke	Hard Rock	WHITEHAL	COAT2
19	Central N.I	3	63	730	1300	570	R1	Greywacke	Hard Rock	WHITEHAL	COAT2
20	Dunedin	87	15	4180	4470	330	L1	Greywacke	Hard Rock	BALCLUTH	RSEAL
21	Dunedin	8	430	970	1510	330	R1	Greywacke	Hard Rock	BALCLUTH	RSEAL
22	Dunedin	01S	729	6530	6890	360	L1	Greywacke	Hard Rock	BALCLUTH	RSEAL
23	Dunedin	01S	729	8410	10770	2360	L1	Greywacke	Hard Rock	BALCLUTH	RSEAL
24	Dunedin	01S	763	0	950	950	R1	Greywacke	Hard Rock	BALCLUTH	COAT2
25	Dunedin	01S	729	12150	13400	1250	L1	Basalt	Hard Rock	BLACKHEA	COAT2
26	Dunedin	01S	635	7070	7360	290	L1	Greywacke	Alluvial	HAREWOOD	RSEAL
27	Dunedin	85	0	1600	3030	330	L1	Greywacke	Alluvial	HILDERTH	RSEAL
28	Dunedin	01S	651	2750	4080	1330	R1	Greywacke	Alluvial	HILDERTH	RSEAL
29	Dunedin	01S	729	50	3000	2950	L1	Greywacke	Alluvial	HILDERTH	RSEAL
30	Dunedin	01S	729	10770	12150	1380	L1	Greywacke	Alluvial	ISAAC	RSEAL
31	Dunedin	85	62	9350	10770	330	L1	Basalt	Hard Rock	LOGAN PT	RSEAL
32	Dunedin	01S	729	3000	5590	2590	L1	Basalt	Hard Rock	LOGAN PT	RSEAL
33	Dunedin	85	105	13800	14850	330	L1	Schist g/w	Alluvial	PARKBURN	COAT2
34	Dunedin	01S	667	9620	9980	360	R1	Schist g/w	Alluvial	PARKBURN	RSEAL
35	Gisborne	2	416	12740	13350	610	L1	Greywacke	Alluvial	AWATOTO	RSEAL
36	Gisborne	35	289	5620	5960	340	R1	Greywacke	Hard Rock	MOUTOHOR	RSEAL
37	Gisborne	35	289	6720	6980	260	R1	Greywacke	Hard Rock	MOUTOHOR	RSEAL
38	Gisborne	2	375	2500	3000	500	R1	Greywacke	Hard Rock	WAIOEKA	RSEAL
39	Gisborne	35	308	0	1330	1330	L1	Greywacke	Alluvial	WAIOEKA	RSEAL
40	Gisborne	2	474	5240	6000	760	R1	Greywacke	Hard Rock	WHITEHAL	RSEAL
41	Manawatu	2	772	13570	13980	410	L1	Greywacke	Alluvial	LONGBURN	COAT2
42	Manawatu	2	772	7870	8470	600	L1	Greywacke	Alluvial	PAHIATUA	COAT2
43	Manawatu	2	772	15060	15770	710	L1	Greywacke	Alluvial	PRENTERS	COAT2
44	New Plymouth	3	203	7570	8040	470	L1	Greywacke	Alluvial	PIO PIO	RSEAL
45	New Plymouth	3	189	8260	8600	340	R1	Greywacke	Hard Rock	WHITEHAL	RSEAL
46	New Plymouth	3	250	2080	2500	420	R1	Andesite	Hard Rock	WIREMU R	COAT2
47	New Plymouth	45	15	3050	3800	750	R1	Greywacke	Hard Rock	WIREMU R	COAT2

Appendix A2: RAMM Data for Test Sites

SITE NO	CHIP GRADE	CHIP SIZE (mm)	AGE	PSV	% HVY	ADT EST	NO HVY	CURVE	GRAD.	CROSS FALL
1	2	19	13.94	60	12	7800	468	4420	0.33	5.10
2	5	9	3.76	60	12	5800	348	4022	0.29	2.65
3	3	16	4.82	60	12	7000	420	2499	0.16	1.18
4	5	9	3.59	60	12	4800	288	4014	0.05	0.93
5	2	19	5.70	60	12	3050	183	2957	0.41	3.08
6	5	9	7.78	60	11	1700	94	2074	0.22	1.40
7	2	19	13.73	60	11	1700	94	2621	0.41	1.29
8	3	16	11.81	60	11	1500	83	3003	2.62	0.68
9	3	16	4.90	52	12	1250	75	805	0.63	3.95
10	3	16	4.72	55	12	2000	120	1691	4.66	3.65
11	2	19	10.78	55	12	1500	90	1847	4.79	4.00
12	3	16	7.99	52	12	600	36	2198	0.87	4.74
13	3	16	8.84	55	12	600	36	1959	0.59	3.90
14	4	12	8.68	55	12	600	36	1106	0.44	2.99
15	2	19	8.73	55	12	250	15	958	2.74	2.42
16	3	16	6.69	54	12	5000	300	2584	0.23	4.12
17	4	12	8.97	54	12	9500	380	739	2.04	4.23
18	3	16	3.00	54	12	5750	345	2381	0.36	3.10
19	4	12	2.98	54	12	5500	330	2516	3.76	2.82
20	3	16	2.95	63	9	540	24	1455	4.90	3.51
21	4	12	4.80	63	13	1300	85	3273	3.44	1.80
22	4	12	7.63	63	10	5450	273	6672	0.23	0.66
23	3	16	2.97	63	10	5450	273	3059	0.33	1.32
24	3	16	9.61	63	10	4820	241	1501	0.28	1.74
25	3	16	9.77	43	10	5450	273	1320	0.60	2.53
26	5	9	8.80	59	17	3180	270	4548	3.96	1.36
27	5	9	7.99	57	13	790	51	3109	1.70	1.12
28	3	16	2.92	57	17	3550	302	3925	0.73	0.92
29	5	9	6.60	57	10	5430	272	3430	0.55	2.23
30	3	16	10.06	59	10	5450	273	3311	0.30	1.31
31	3	16	12.65	45	7	625	22	3177	2.11	2.92
32	3	16	12.89	45	10	5430	272	2876	0.57	1.93
33	3	16	4.03	56	7	351	12	2527	1.09	2.13
34	5	9	7.63	56	6	3936	118	754	0.17	4.63
35	3	16	7.83	55	8	2328	93	4435	0.13	0.38
36	5	9	4.76	65	8	1175	47	978	4.09	3.33
37	3	16	3.99	65	8	1493	60	1105	4.20	3.27
38	5	9	6.69	61	8	840	34	3144	0.82	1.44
39	3	16	9.44	61	8	1809	72	1612	1.06	2.13
40	4	12	3.80	54	15	1316	99	1604	4.02	2.21
41	2	19	6.92	57	12	4800	288	7368	0.31	1.64
42	2	19	6.52	58	12	4950	297	4034	0.49	2.05
43	2	19	5.79	62	12	4800	288	1262	1.50	3.89
44	2	19	15.59	52	14	3750	263	6351	0.85	2.87
45	2	19	9.76	54	14	2500	175	1218	0.41	2.73
46	2	19	13.75	60	8	7232	289	5175	0.89	3.32
47	2	19	5.67	60	8	3110	83	1877	2.47	2.54
Max:	5	19	15.59	65	17	9500	468	7368	4.90	5.10
Min:	2	9	2.921	43	6	250	12	739	0.05	0.38

SITE NO	NAASRA	RUT DEPTH	MPD	MSSC 1998	MSSC 1999	MSSC 2000	MSSC 2001	Av. MSSC	T/10 Eq.
1	65.39	1.75	2.58	0.51	0.52	0.46	0.48	0.49	0.54
2	81.15	4.15	1.55	0.55	0.57	0.54	0.52	0.54	0.55
3	78.57	3.29	2.04	0.58	.	0.52	0.53	0.54	0.55
4	46.37	1.65	1.66	0.52	.	0.58	0.55	0.57	0.55
5	62.56	3.44	2.46	0.57	0.54	0.56	0.53	0.55	0.56
6	38.15	0.62	1.66	0.64	0.63	0.65	0.61	0.63	0.57
7	47.24	1.52	2.89	0.54	0.56	0.56	0.57	0.56	0.57
8	50.85	2.52	2.44	0.57	0.58	0.61	0.61	0.59	0.57
9	79.00	4.35	1.84	0.55	.	0.56	0.52	0.54	0.49
10	96.55	5.68	1.41	0.58	0.49	0.53	0.48	0.52	0.52
11	71.42	2.84	1.78	0.58	0.44	0.54	0.51	0.52	0.52
12	81.18	5.48	1.16	0.47	0.44	.	0.46	0.45	0.49
13	56.07	4.20	3.21	0.46	0.51	0.54	0.48	0.50	0.52
14	58.18	3.04	2.01	0.52	0.50	.	0.48	0.50	0.52
15	100.40	3.97	2.38	0.50	0.48	0.54	0.49	0.50	0.52
16	74.23	3.88	2.51	0.54	.	0.59	0.50	0.54	0.49
17	58.58	4.26	1.89	0.61	0.46	0.47	0.51	0.51	0.49
18	97.98	4.71	2.05	0.51	0.47	0.54	0.47	0.50	0.49
19	74.05	5.41	2.08	0.51	0.51	0.54	0.48	0.51	0.49
20	38.73	3.77	2.19	0.53	.	0.51	0.54	0.52	0.60
21	50.96	2.44	2.08	0.55	.	0.55	0.54	0.54	0.60
22	85.67	1.22	1.49	0.48	0.48	0.52	0.49	0.49	0.59
23	59.46	4.78	2.47	0.49	0.58	0.53	0.49	0.51	0.59
24	54.10	3.32	1.99	0.47	.	0.48	0.46	0.47	0.59
25	50.73	4.56	2.50	0.45	0.45	0.47	0.46	0.46	0.39
26	52.93	5.00	1.48	0.56	0.52	0.51	0.51	0.52	0.55
27	75.11	5.17	2.43	0.54	0.60	0.54	0.54	0.56	0.54
28	69.32	4.09	2.31	0.48	.	0.52	0.51	0.51	0.52
29	59.78	3.96	1.30	0.46	0.45	0.46	0.45	0.46	0.53
30	61.12	5.36	1.72	0.45	0.44	0.46	0.45	0.45	0.55
31	53.43	4.15	1.87	0.60	0.62	0.59	0.62	0.61	0.42
32	59.95	4.51	1.58	0.52	0.51	0.54	0.52	0.52	0.41
33	62.45	3.77	2.46	0.54	0.51	0.52	0.50	0.52	0.53
34	57.01	3.87	1.71	0.65	.	0.57	0.58	0.60	0.53
35	63.23	2.28	1.72	0.51	0.43	0.45	0.46	0.47	0.52
36	81.76	5.38	2.46	0.74	0.59	0.52	0.48	0.58	0.62
37	90.23	1.65	1.88	0.74	0.52	0.61	0.63	0.59	0.62
38	68.16	3.20	2.34	0.68	.	0.54	0.55	0.59	0.58
39	82.00	3.58	2.41	0.59	0.49	0.52	0.52	0.53	0.58
40	66.74	3.74	2.38	0.60	0.51	0.56	0.55	0.54	0.51
41	45.00	2.65	2.12	0.53	0.48	0.49	0.49	0.50	0.52
42	48.27	2.72	1.50	0.52	0.42	0.45	0.47	0.47	0.53
43	43.50	2.28	1.84	0.55	0.50	0.52	0.52	0.52	0.57
44	61.72	3.48	2.13	0.44	0.40	0.45	0.45	0.44	0.48
45	69.77	3.34	1.40	0.46	0.39	0.42	0.40	0.42	0.50
46	59.81	2.95	2.44	0.44	.	0.39	0.44	0.42	0.55
47	74.43	3.43	2.51	0.62	.	0.53	0.59	0.58	0.57
Max:	100.40	5.68	3.21	0.74	0.63	0.65	0.63	0.63	0.62
Min:	38.15	0.62	1.16	0.44	0.39	0.39	0.40	0.42	0.39

Appendix A3: Test Site Surface Texture Characteristics

SITE NO	REGION	SH	RS	ST	END	Ra (m)	Rq (m)	Rt (m)
1	Blenheim	6	0	3470	5250	0.0010	0.0012	0.0077
2	Blenheim	01S	18	4030	4290	0.0008	0.0010	0.0063
3	Blenheim	01S	28	2350	2630	0.0011	0.0014	0.0084
4	Blenheim	01S	28	6630	7170	0.0013	0.0016	0.0094
5	Blenheim	01S	43	6030	6680	0.0010	0.0012	0.0073
6	Blenheim	63	0	200	450	0.0017	0.0020	0.0108
7	Blenheim	63	0	7010	7520	0.0010	0.0012	0.0073
8	Blenheim	63	0	11350	11870	0.0016	0.0019	0.0098
9	Central N.I	37	0	1000	1490	0.0007	0.0009	0.0060
10	Central N.I	3	88	13350	13590	0.0007	0.0008	0.0048
11	Central N.I	31	0	10490	10710	0.0015	0.0019	0.0110
12	Central N.I	30	0	13810	14230	0.0008	0.0010	0.0071
13	Central N.I	30	14	14450	15210	0.0010	0.0013	0.0074
14	Central N.I	30	30	11920	12370	0.0011	0.0014	0.0091
15	Central N.I	31	15	14370	14570	0.0009	0.0011	0.0066
16	Central N.I	3	65	4720	5730	0.0011	0.0014	0.0077
17	Central N.I	3	16	6840	7360	0.0010	0.0013	0.0081
18	Central N.I	3	36	1420	2120	0.0012	0.0014	0.0081
19	Central N.I	3	63	730	1300	0.0011	0.0013	0.0077
20	Dunedin	87	15	4180	4470	0.0011	0.0014	0.0080
21	Dunedin	8	430	970	1510	0.0011	0.0013	0.0082
22	Dunedin	01S	729	6530	6890	0.0011	0.0014	0.0101
23	Dunedin	01S	729	8410	10770	0.0007	0.0009	0.0055
24	Dunedin	01S	763	0	950	0.0015	0.0018	0.0103
25	Dunedin	01S	729	12150	13400	0.0010	0.0013	0.0081
26	Dunedin	01S	635	7070	7360	0.0011	0.0013	0.0075
27	Dunedin	85	0	1600	3030	0.0016	0.0020	0.0110
28	Dunedin	01S	651	2750	4080	0.0006	0.0008	0.0069
29	Dunedin	01S	729	50	3000	0.0010	0.0013	0.0091
30	Dunedin	01S	729	10770	12150	0.0009	0.0011	0.0067
31	Dunedin	85	62	9350	10770	0.0012	0.0015	0.0093
32	Dunedin	01S	729	3000	5590	0.0013	0.0017	0.0097
33	Dunedin	85	105	13800	14850	0.0016	0.0020	0.0110
34	Dunedin	01S	667	9620	9980	0.0006	0.0008	0.0056
35	Gisborne	2	416	12740	13350	0.0010	0.0013	0.0080
36	Gisborne	35	289	5620	5960	0.0007	0.0010	0.0067
37	Gisborne	35	289	6720	6980	0.0009	0.0011	0.0076
38	Gisborne	2	375	2500	3000	0.0009	0.0011	0.0064
39	Gisborne	35	308	0	1330	0.0018	0.0022	0.0126
40	Gisborne	2	474	5240	6000	0.0017	0.0020	0.0118
41	Manawatu	2	772	13570	13980	0.0008	0.0011	0.0072
42	Manawatu	2	772	7870	8470	0.0017	0.0020	0.0110
43	Manawatu	2	772	15060	15770	0.0008	0.0010	0.0049
44	New Plymouth	3	203	7570	8040	0.0012	0.0014	0.0083
45	New Plymouth	3	189	8260	8600	0.0013	0.0017	0.0113
46	New Plymouth	3	250	2080	2500	0.0013	0.0016	0.0087
47	New Plymouth	45	15	3050	3800	0.0017	0.0021	0.0121
					Max:	0.0018	0.0022	0.0126
					Min:	0.0006	0.0008	0.0048

SITE NO	Rt1 (m)	Rt2 (m)	Rt3 (m)	Rt4 (m)	Rt5 (m)	Rtm (m)	Rv1 (m)	Rv2 (m)	Rv3 (m)	Rv4 (m)	Rv5 (m)	Rvm (m)
1	0.0054	0.0056	0.0062	0.0058	0.0053	0.0057	-0.0030	-0.0029	-0.0037	-0.0033	-0.0030	-0.0032
2	0.0040	0.0039	0.0045	0.0043	0.0040	0.0041	-0.0019	-0.0020	-0.0025	-0.0024	-0.0020	-0.0022
3	0.0067	0.0069	0.0078	0.0073	0.0067	0.0071	-0.0037	-0.0036	-0.0042	-0.0042	-0.0035	-0.0039
4	0.0074	0.0071	0.0070	0.0080	0.0068	0.0072	-0.0043	-0.0041	-0.0039	-0.0046	-0.0037	-0.0041
5	0.0054	0.0056	0.0055	0.0053	0.0058	0.0055	-0.0032	-0.0036	-0.0034	-0.0031	-0.0036	-0.0034
6	0.0092	0.0097	0.0094	0.0095	0.0094	0.0094	-0.0055	-0.0057	-0.0055	-0.0058	-0.0058	-0.0057
7	0.0055	0.0057	0.0058	0.0061	0.0062	0.0058	-0.0031	-0.0031	-0.0031	-0.0033	-0.0031	-0.0031
8	0.0085	0.0084	0.0081	0.0082	0.0084	0.0083	-0.0051	-0.0050	-0.0051	-0.0046	-0.0052	-0.0050
9	0.0040	0.0041	0.0043	0.0048	0.0046	0.0044	-0.0021	-0.0023	-0.0025	-0.0025	-0.0023	-0.0023
10	0.0029	0.0031	0.0031	0.0038	0.0031	0.0032	-0.0016	-0.0020	-0.0020	-0.0024	-0.0020	-0.0020
11	0.0083	0.0087	0.0091	0.0093	0.0094	0.0090	-0.0047	-0.0050	-0.0055	-0.0054	-0.0060	-0.0053
12	0.0050	0.0053	0.0056	0.0043	0.0043	0.0049	-0.0030	-0.0028	-0.0034	-0.0021	-0.0022	-0.0027
13	0.0056	0.0053	0.0063	0.0064	0.0056	0.0058	-0.0028	-0.0031	-0.0032	-0.0033	-0.0030	-0.0031
14	0.0071	0.0072	0.0070	0.0074	0.0081	0.0073	-0.0046	-0.0043	-0.0040	-0.0042	-0.0040	-0.0042
15	0.0049	0.0058	0.0051	0.0058	0.0056	0.0054	-0.0030	-0.0033	-0.0032	-0.0034	-0.0031	-0.0032
16	0.0062	0.0069	0.0072	0.0062	0.0063	0.0065	-0.0037	-0.0040	-0.0042	-0.0038	-0.0038	-0.0039
17	0.0068	0.0062	0.0071	0.0069	0.0062	0.0066	-0.0040	-0.0036	-0.0039	-0.0042	-0.0033	-0.0038
18	0.0045	0.0050	0.0048	0.0048	0.0050	0.0048	-0.0029	-0.0031	-0.0028	-0.0028	-0.0032	-0.0030
19	0.0059	0.0068	0.0061	0.0062	0.0056	0.0061	-0.0036	-0.0043	-0.0039	-0.0040	-0.0034	-0.0038
20	0.0058	0.0058	0.0050	0.0060	0.0059	0.0057	-0.0032	-0.0031	-0.0029	-0.0033	-0.0034	-0.0032
21	0.0056	0.0061	0.0068	0.0059	0.0059	0.0061	-0.0027	-0.0028	-0.0036	-0.0027	-0.0028	-0.0029
22	0.0060	0.0089	0.0068	0.0067	0.0077	0.0072	-0.0034	-0.0039	-0.0040	-0.0040	-0.0040	-0.0039
23	0.0033	0.0036	0.0042	0.0038	0.0040	0.0038	-0.0016	-0.0018	-0.0023	-0.0020	-0.0021	-0.0020
24	0.0074	0.0072	0.0075	0.0081	0.0072	0.0075	-0.0034	-0.0033	-0.0036	-0.0039	-0.0035	-0.0036
25	0.0071	0.0070	0.0059	0.0061	0.0061	0.0064	-0.0045	-0.0046	-0.0035	-0.0034	-0.0039	-0.0040
26	0.0054	0.0054	0.0054	0.0065	0.0057	0.0057	-0.0029	-0.0030	-0.0031	-0.0036	-0.0030	-0.0031
27	0.0091	0.0091	0.0096	0.0090	0.0086	0.0091	-0.0055	-0.0053	-0.0055	-0.0052	-0.0047	-0.0052
28	0.0047	0.0049	0.0033	0.0037	0.0037	0.0040	-0.0024	-0.0026	-0.0012	-0.0014	-0.0023	-0.0020
29	0.0065	0.0067	0.0064	0.0069	0.0078	0.0068	-0.0036	-0.0044	-0.0038	-0.0046	-0.0051	-0.0043
30	0.0045	0.0046	0.0045	0.0049	0.0053	0.0048	-0.0027	-0.0028	-0.0026	-0.0028	-0.0027	-0.0027
31	0.0071	0.0072	0.0069	0.0074	0.0084	0.0074	-0.0038	-0.0043	-0.0040	-0.0041	-0.0044	-0.0041
32	0.0080	0.0084	0.0081	0.0074	0.0086	0.0081	-0.0046	-0.0047	-0.0046	-0.0043	-0.0047	-0.0046
33	0.0073	0.0085	0.0079	0.0079	0.0083	0.0080	-0.0043	-0.0047	-0.0047	-0.0046	-0.0048	-0.0046
34	0.0040	0.0044	0.0040	0.0037	0.0042	0.0041	-0.0023	-0.0024	-0.0021	-0.0017	-0.0022	-0.0021
35	0.0059	0.0063	0.0065	0.0058	0.0067	0.0062	-0.0035	-0.0033	-0.0036	-0.0031	-0.0038	-0.0035
36	0.0056	0.0041	0.0055	0.0049	0.0056	0.0051	-0.0032	-0.0022	-0.0032	-0.0025	-0.0030	-0.0028
37	0.0058	0.0050	0.0055	0.0058	0.0056	0.0055	-0.0029	-0.0024	-0.0027	-0.0033	-0.0028	-0.0028
38	0.0052	0.0046	0.0045	0.0050	0.0052	0.0049	-0.0035	-0.0029	-0.0029	-0.0031	-0.0033	-0.0031
39	0.0099	0.0095	0.0090	0.0100	0.0108	0.0099	-0.0066	-0.0060	-0.0054	-0.0062	-0.0060	-0.0060
40	0.0096	0.0088	0.0103	0.0088	0.0090	0.0093	-0.0059	-0.0052	-0.0057	-0.0051	-0.0053	-0.0054
41	0.0058	0.0054	0.0057	0.0060	0.0064	0.0059	-0.0034	-0.0030	-0.0032	-0.0036	-0.0040	-0.0034
42	0.0088	0.0092	0.0099	0.0094	0.0089	0.0093	-0.0050	-0.0049	-0.0056	-0.0050	-0.0049	-0.0051
43	0.0020	0.0024	0.0030	0.0022	0.0025	0.0024	-0.0010	-0.0011	-0.0014	-0.0009	-0.0011	-0.0011
44	0.0068	0.0076	0.0068	0.0077	0.0072	0.0072	-0.0036	-0.0039	-0.0034	-0.0039	-0.0036	-0.0037
45	0.0072	0.0091	0.0080	0.0094	0.0084	0.0084	-0.0038	-0.0042	-0.0045	-0.0043	-0.0041	-0.0042
46	0.0065	0.0066	0.0069	0.0067	0.0068	0.0067	-0.0037	-0.0037	-0.0038	-0.0039	-0.0039	-0.0038
47	0.0086	0.0089	0.0093	0.0080	0.0094	0.0088	-0.0047	-0.0051	-0.0051	-0.0041	-0.0053	-0.0048
Max:	0.0099	0.0097	0.0103	0.0100	0.0108	0.0099	-0.0010	-0.0011	-0.0012	-0.0009	-0.0011	-0.0011
Min:	0.0020	0.0024	0.0030	0.0022	0.0025	0.0024	-0.0066	-0.0060	-0.0057	-0.0062	-0.0060	-0.0060

SITE NO	Rp1 (m)	Rp2 (m)	Rp3 (m)	Rp4 (m)	Rp5 (m)	Rpm (m)	S1 (m)	S2 (m)	S3 (m)	S4 (m)	S5 (m)	Siav (m)	Sm (m)
1	0.0024	0.0027	0.0024	0.0024	0.0023	0.0024	0.0034	0.0033	0.0040	0.0033	0.0034	0.0035	0.0132
2	0.0020	0.0018	0.0019	0.0019	0.0020	0.0019	0.0023	0.0023	0.0025	0.0025	0.0025	0.0024	0.0163
3	0.0030	0.0033	0.0036	0.0031	0.0032	0.0032	0.0032	0.0035	0.0037	0.0038	0.0034	0.0035	0.0143
4	0.0031	0.0030	0.0030	0.0034	0.0031	0.0031	0.0034	0.0033	0.0033	0.0039	0.0037	0.0035	0.0125
5	0.0022	0.0019	0.0021	0.0022	0.0022	0.0021	0.0030	0.0031	0.0033	0.0029	0.0034	0.0031	0.0136
6	0.0038	0.0039	0.0038	0.0038	0.0036	0.0038	0.0042	0.0050	0.0045	0.0047	0.0045	0.0046	0.0143
7	0.0024	0.0026	0.0027	0.0028	0.0031	0.0027	0.0032	0.0031	0.0031	0.0037	0.0033	0.0033	0.0166
8	0.0034	0.0034	0.0030	0.0036	0.0032	0.0033	0.0039	0.0041	0.0037	0.0036	0.0039	0.0039	0.0156
9	0.0019	0.0018	0.0018	0.0023	0.0023	0.0020	0.0025	0.0024	0.0024	0.0026	0.0027	0.0025	0.0115
10	0.0013	0.0011	0.0011	0.0013	0.0012	0.0012	0.0020	0.0019	0.0021	0.0021	0.0021	0.0020	0.0108
11	0.0036	0.0037	0.0036	0.0039	0.0034	0.0036	0.0038	0.0040	0.0042	0.0044	0.0042	0.0041	0.0144
12	0.0020	0.0025	0.0022	0.0022	0.0020	0.0022	0.0025	0.0026	0.0029	0.0024	0.0024	0.0026	0.0140
13	0.0028	0.0022	0.0030	0.0030	0.0026	0.0027	0.0024	0.0026	0.0027	0.0025	0.0023	0.0025	0.0185
14	0.0025	0.0029	0.0030	0.0032	0.0041	0.0031	0.0033	0.0032	0.0032	0.0031	0.0034	0.0033	0.0133
15	0.0019	0.0024	0.0019	0.0024	0.0025	0.0022	0.0028	0.0030	0.0029	0.0035	0.0032	0.0031	0.0123
16	0.0025	0.0028	0.0030	0.0024	0.0025	0.0026	0.0034	0.0036	0.0039	0.0035	0.0032	0.0035	0.0146
17	0.0027	0.0026	0.0032	0.0028	0.0029	0.0028	0.0034	0.0035	0.0030	0.0036	0.0029	0.0033	0.0164
18	0.0016	0.0019	0.0020	0.0020	0.0017	0.0018	0.0024	0.0027	0.0028	0.0026	0.0024	0.0026	0.0183
19	0.0023	0.0025	0.0022	0.0023	0.0022	0.0023	0.0033	0.0036	0.0033	0.0034	0.0034	0.0034	0.0136
20	0.0027	0.0027	0.0022	0.0027	0.0026	0.0026	0.0030	0.0031	0.0032	0.0032	0.0031	0.0031	0.0177
21	0.0029	0.0033	0.0032	0.0032	0.0031	0.0032	0.0033	0.0035	0.0040	0.0034	0.0034	0.0035	0.0184
22	0.0026	0.0049	0.0028	0.0027	0.0036	0.0033	0.0024	0.0031	0.0027	0.0029	0.0030	0.0028	0.0122
23	0.0017	0.0018	0.0019	0.0018	0.0019	0.0018	0.0019	0.0021	0.0022	0.0021	0.0024	0.0021	0.0177
24	0.0040	0.0039	0.0039	0.0042	0.0037	0.0039	0.0028	0.0033	0.0036	0.0029	0.0032	0.0032	0.0199
25	0.0026	0.0024	0.0024	0.0027	0.0022	0.0025	0.0029	0.0035	0.0028	0.0033	0.0031	0.0031	0.0175
26	0.0024	0.0023	0.0023	0.0029	0.0027	0.0026	0.0033	0.0030	0.0035	0.0035	0.0032	0.0033	0.0163
27	0.0035	0.0038	0.0041	0.0038	0.0039	0.0038	0.0041	0.0043	0.0047	0.0047	0.0043	0.0044	0.0152
28	0.0023	0.0023	0.0020	0.0023	0.0013	0.0020	0.0027	0.0030	0.0020	0.0022	0.0020	0.0024	0.0180
29	0.0029	0.0023	0.0025	0.0023	0.0027	0.0025	0.0031	0.0034	0.0033	0.0034	0.0035	0.0033	0.0149
30	0.0018	0.0018	0.0019	0.0021	0.0026	0.0020	0.0032	0.0030	0.0031	0.0030	0.0034	0.0031	0.0118
31	0.0033	0.0029	0.0029	0.0033	0.0040	0.0033	0.0034	0.0036	0.0031	0.0034	0.0035	0.0034	0.0149
32	0.0034	0.0037	0.0035	0.0031	0.0039	0.0035	0.0036	0.0037	0.0043	0.0041	0.0043	0.0040	0.0159
33	0.0031	0.0037	0.0032	0.0034	0.0035	0.0034	0.0032	0.0040	0.0038	0.0037	0.0040	0.0037	0.0182
34	0.0017	0.0020	0.0020	0.0019	0.0020	0.0019	0.0022	0.0022	0.0023	0.0021	0.0021	0.0022	0.0132
35	0.0024	0.0030	0.0029	0.0027	0.0029	0.0028	0.0033	0.0031	0.0030	0.0033	0.0035	0.0032	0.0155
36	0.0024	0.0020	0.0023	0.0024	0.0026	0.0023	0.0025	0.0022	0.0026	0.0026	0.0027	0.0025	0.0113
37	0.0029	0.0027	0.0028	0.0025	0.0028	0.0027	0.0031	0.0027	0.0027	0.0030	0.0031	0.0029	0.0180
38	0.0017	0.0017	0.0016	0.0019	0.0018	0.0018	0.0025	0.0026	0.0026	0.0027	0.0027	0.0026	0.0099
39	0.0033	0.0035	0.0036	0.0038	0.0048	0.0038	0.0048	0.0042	0.0044	0.0040	0.0047	0.0044	0.0153
40	0.0037	0.0036	0.0046	0.0037	0.0037	0.0039	0.0042	0.0041	0.0038	0.0045	0.0041	0.0041	0.0148
41	0.0025	0.0024	0.0026	0.0024	0.0024	0.0025	0.0030	0.0030	0.0027	0.0030	0.0032	0.0030	0.0135
42	0.0038	0.0043	0.0043	0.0045	0.0040	0.0042	0.0049	0.0053	0.0052	0.0041	0.0050	0.0049	0.0154
43	0.0010	0.0013	0.0016	0.0013	0.0014	0.0013	0.0015	0.0014	0.0016	0.0014	0.0015	0.0015	0.0454
44	0.0032	0.0038	0.0034	0.0038	0.0035	0.0035	0.0035	0.0040	0.0032	0.0036	0.0035	0.0035	0.0160
45	0.0035	0.0049	0.0035	0.0050	0.0043	0.0042	0.0033	0.0037	0.0039	0.0043	0.0038	0.0038	0.0174
46	0.0028	0.0029	0.0031	0.0028	0.0029	0.0029	0.0033	0.0034	0.0034	0.0033	0.0034	0.0034	0.0178
47	0.0039	0.0039	0.0042	0.0039	0.0041	0.0040	0.0037	0.0035	0.0034	0.0038	0.0034	0.0036	0.0171
Max:	0.0040	0.0049	0.0046	0.0050	0.0048	0.0042	0.0049	0.0053	0.0052	0.0047	0.0050	0.0049	0.0454
Min:	0.0010	0.0011	0.0011	0.0013	0.0012	0.0012	0.0015	0.0014	0.0016	0.0014	0.0015	0.0015	0.0099

SITE NO	HSC	PC (peaks/cm)	delq	lq (m)	Rmr (% length)	Rku	Rsk
1	1.0	0.9	0.683	0.011	100	3.0	-0.2
2	1.0	0.7	0.471	0.014	100	3.0	-0.1
3	1.0	1.0	0.860	0.010	100	2.9	-0.2
4	1.0	1.1	1.066	0.009	100	2.8	-0.3
5	1.0	1.0	0.722	0.010	100	3.0	-0.4
6	1.5	1.1	1.392	0.009	100	2.8	-0.4
7	1.0	0.8	0.608	0.012	100	2.9	0.0
8	1.0	1.0	1.232	0.010	100	2.7	-0.5
9	1.0	1.1	0.632	0.009	100	3.0	0.0
10	1.0	1.0	0.496	0.010	100	3.0	-0.1
11	3.3	1.0	1.156	0.010	100	2.9	-0.4
12	1.0	0.9	0.536	0.011	100	3.2	-0.2
13	1.0	0.7	0.584	0.014	100	2.9	0.2
14	1.0	1.1	0.943	0.009	100	3.1	-0.3
15	1.0	1.1	0.742	0.009	100	2.9	-0.3
16	1.0	1.0	0.825	0.011	100	2.9	-0.4
17	1.0	1.0	0.845	0.010	100	3.0	-0.3
18	1.0	0.7	0.614	0.015	100	2.6	-0.2
19	1.0	0.9	0.745	0.011	100	3.0	-0.5
20	6.3	0.7	0.604	0.014	99	2.8	0.1
21	1.0	0.7	0.595	0.014	100	2.9	0.4
22	6.7	1.2	1.048	0.008	100	3.3	-0.1
23	1.0	0.7	0.401	0.014	100	2.9	0.0
24	1.0	0.6	0.740	0.016	100	2.5	0.3
25	1.0	0.8	0.643	0.012	100	3.4	-0.3
26	1.0	0.8	0.627	0.013	100	2.6	0.0
27	1.0	0.9	1.153	0.011	100	2.9	-0.4
28	1.0	0.7	0.341	0.015	100	4.7	0.1
29	1.0	0.9	0.742	0.011	100	3.7	-0.5
30	1.0	1.1	0.745	0.009	100	2.9	-0.2
31	1.0	1.0	1.002	0.010	100	3.0	-0.4
32	1.0	0.9	0.945	0.011	100	3.1	-0.5
33	2.7	0.8	0.979	0.013	100	2.7	-0.3
34	1.0	0.9	0.482	0.011	100	3.5	0.0
35	1.0	0.9	0.714	0.011	100	3.0	-0.2
36	1.0	1.1	0.646	0.009	100	3.6	-0.1
37	1.0	0.7	0.507	0.014	100	3.4	0.2
38	1.0	1.3	0.854	0.008	100	3.2	-0.6
39	30.0	1.0	1.339	0.010	90	2.5	-0.6
40	13.3	1.1	1.383	0.009	99	2.8	-0.5
41	1.0	1.0	0.697	0.010	100	3.8	-0.6
42	1.0	1.0	1.237	0.010	100	2.6	-0.2
43	1.0	0.4	0.231	0.027	100	2.6	0.4
44	1.0	0.8	0.758	0.012	100	2.8	0.2
45	2.0	0.8	0.847	0.013	100	3.1	-0.1
46	1.0	0.8	0.762	0.013	100	2.5	-0.2
47	4.7	0.8	0.974	0.013	99	2.6	0.0
Max:	30.0	1.3	1.392	0.027	100	4.7	0.4
Min:	1.0	0.4	0.231	0.008	90	2.5	-0.6